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Innovative Civil Engineering Applications of Smart Materials for Smart Sustainable Urbanization

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ABSTRACT

Urban areas are formed by buildings and many other types of structures. Smart and sustainable structures in this regard are required for smart sustainable urbanization, to be consistent with the progressive development of the world. Materials possessing a capability of adapting themselves with their environment, either in passive or active conditions, are known as smart materials and capable of bringing smartness into our structures. There are different types of smart materials that can be utilized in the construction of structures. Shape Memory Alloys (SMAs), fiber optics, piezoelectric materials, Magneto-Rheological (MR) fluids, Electro-Rheological (ER) fluids and magnetostrictive materials are the promising examples of smart materials that deserve increasing interest in civil engineering applications. Innovative applications of these materials in construction industry are investigated in this paper. Brief descriptions of the physical principles are provided, and the proof of concept demonstrations are presented. Advantages and limitations of the implementation of each material in civil structures are defined and the effectiveness of passive systems are discussed. It is concluded that SMAs are the best candidates among the available smart materials that can be used for earthquake-resistant design of structures. The suitability of SMAs as aseismic devices is then verified experimentally. It is also shown that materials with damping and stiffness properties changing by changes in stress/strain and/or acceleration are similarly useful for the purpose of earthquake protection of structures. Production and application of these types of smart materials, however, require further research but seems to be more attractive in the civil engineering profession.

Keywords: Smart Materials; Sustainable Urbanization; Civil Structures; Earthquake Protection; Aseismic Devices.

INTRODUCTION

Materials play an important role in civil engineering and urban development. Application of proper materials and systems in civil structures results in improved structural performances that satisfy the public requirements in urban areas.

Structures designed with conventional materials and traditional systems have limited capacities in providing high performances (Cheng et al., 2008). The search for non-conventional materials and non-traditional structural systems to satisfy high performance requirements has been the main task during the past years (Saadat et al., 2002). Smart materials are a category of materials capable of improving the performances of civil structures.

The word smart is often used to market new products (Worden et al., 2003) but in principle a material is smart if it possesses an awareness of its situation and reacts to its environment by changing one or more of its properties to produce a reversible useful effect or response upon receiving an excitation. This can be either active or passive, occurring respectively with or without the need for external sources of energy. The main difference between conventional and smart materials is then in producing the useful and extraordinary response because all the materials react in any form to their environment. This extraordinary response to a form of engineering and environmental excitations (Schwartz, 2009) is provided by different mechanisms such as change in crystallographic structure. Smart systems are similarly defined as systems with a certain level of smartness or autonomy toward structural safety and serviceability as well as the extension of structural service life, relying on inherent properties of materials or embedded functions of added sensors, actuators, and processors that can automatically adjust structural properties in response to excitations (Otani et al., 2000). The various types of smart materials are listed below:

- Shape Memory Alloys (SMAs)
- Fiber optics
- Piezoelectric Materials (PEMs)
- Electro/Magneto-Rheological (ER/MR) Fluids
- Magnetostrictive Materials

Possible applications of smart materials and systems in civil engineering mainly include structural health monitoring, vibration suppression, minimization of vibratory loads, and earthquake mitigation (Chopra and Sirohi, 2014). Effective practical application requires a detailed investigation on physical principles and the study of pros and cons of using these materials in civil engineering structures and urban projects.

In the following sections, innovative applications of smart materials in civil engineering projects are investigated and the proof of concept demonstrations are provided, giving the required details with regard to the physical principles. Advantages and limitations of the application of each material class (SMAs, fiber optics, PEMs, ERs, MRs, and magnetostrictive materials) are discussed and the most useful applications are concluded, addressing also the challenges.

Shape memory alloys and their applications

SMAs are a class of smart materials capable of recovering from large deformations through the application of heat or removal of stress. Recovering capability due to the application of heat is known as the shape memory effect, when the recovery through the removal of stress is referred to as superelasticity (or pseudoelasticity). Figure 1 provides the schematic representation of these two specific behaviors.

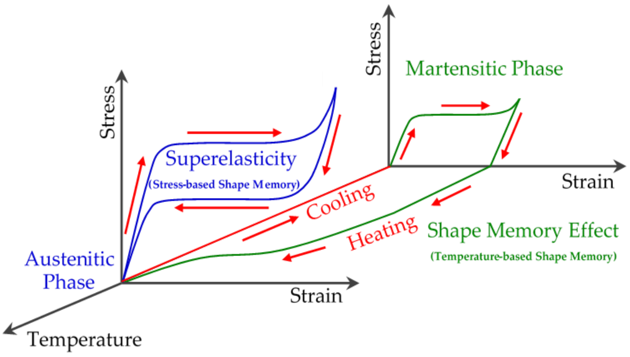

Figure 1. The schematic representation of shape memory effect and superelasticity of SMA materials

These two specific behaviors are caused by the crystalline phase changes between martensitic (twinned or detwinned) and austenitic phases.

SMAs have been used in many different fields of engineering over the past years (Cismasiu, 2010). Application of SMAs in civil engineering relies on unique recovering, energy dissipation, and isolation mechanisms provided by these materials (Dolce and Cardone, 2001). A practical application based on energy dissipation mechanism including also martensitic recovering has been tried by Ocel et al. (2004) using martensitic SMA tendons in the connections of steel frames (see Figure 2a). As it is shown in Figure 2(b), SMA-based Beam-column connections have similarly been recently investigated by Moradi and Shahria Alam (2015). The implementation of SMA braces has also been addressed in the literature (Cardone and Narjabadifam, 2011; Qiu and Zhu, 2017; Narjabadifam and Hejazirad, 2018). Figure 2(c) illustrates the device studied by Qiu and Zhu (2017). As far as the application of SMAs in the role of reinforcements of concrete elements is considered, reference can be given to the studies by Abdulridha et al. (2013), Wang and Zhu (2018), and Wang et al. (2019). Figure 2(d) provides the work presented by Abdulridha et al. (2013).

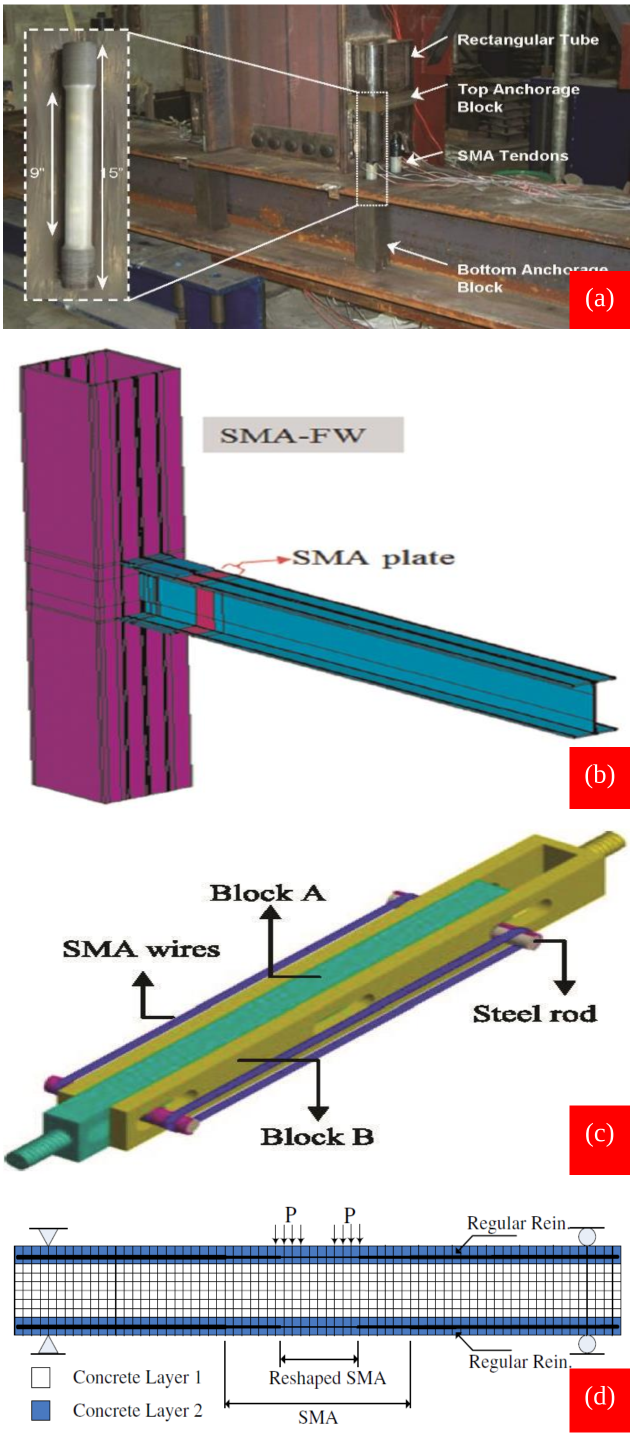

Figure 2. Civil engineering applications of SMAs in the forms of (a) martensitic beam-column connections (Ocel et al., 2004), (b) austenitic beam-column connections (Moradi and Shahria Alam, 2015), (c) braces (Qiu and Zhu, 2017), and (d) rebars (Abdulridha et al., 2013).

The most favorable application of SMAs, however, is the application of these materials as isolation devices. The first attempt to use SMAs as isolation devices has been carried out by Dolce et al. (2000). Several systems are then proposed by different researchers including Wild et al. (2000), Khan and Lagoudas (2002), Cardone et al. (2003), Casciati et al. (2007), Attanasi et al. (2008), Cardone et al. (2009), Ozbulut and Hurlebaus (2010), Khodaverdian et al. (2012), Hedayati Dezfuli (2013), Ozbulut and Silwal (2014), Huang et al. (2014), Fang et al. (2015), and Narjabadifam (2015). Figure 3 provides a brief history of SMA-based aseismic isolation systems.

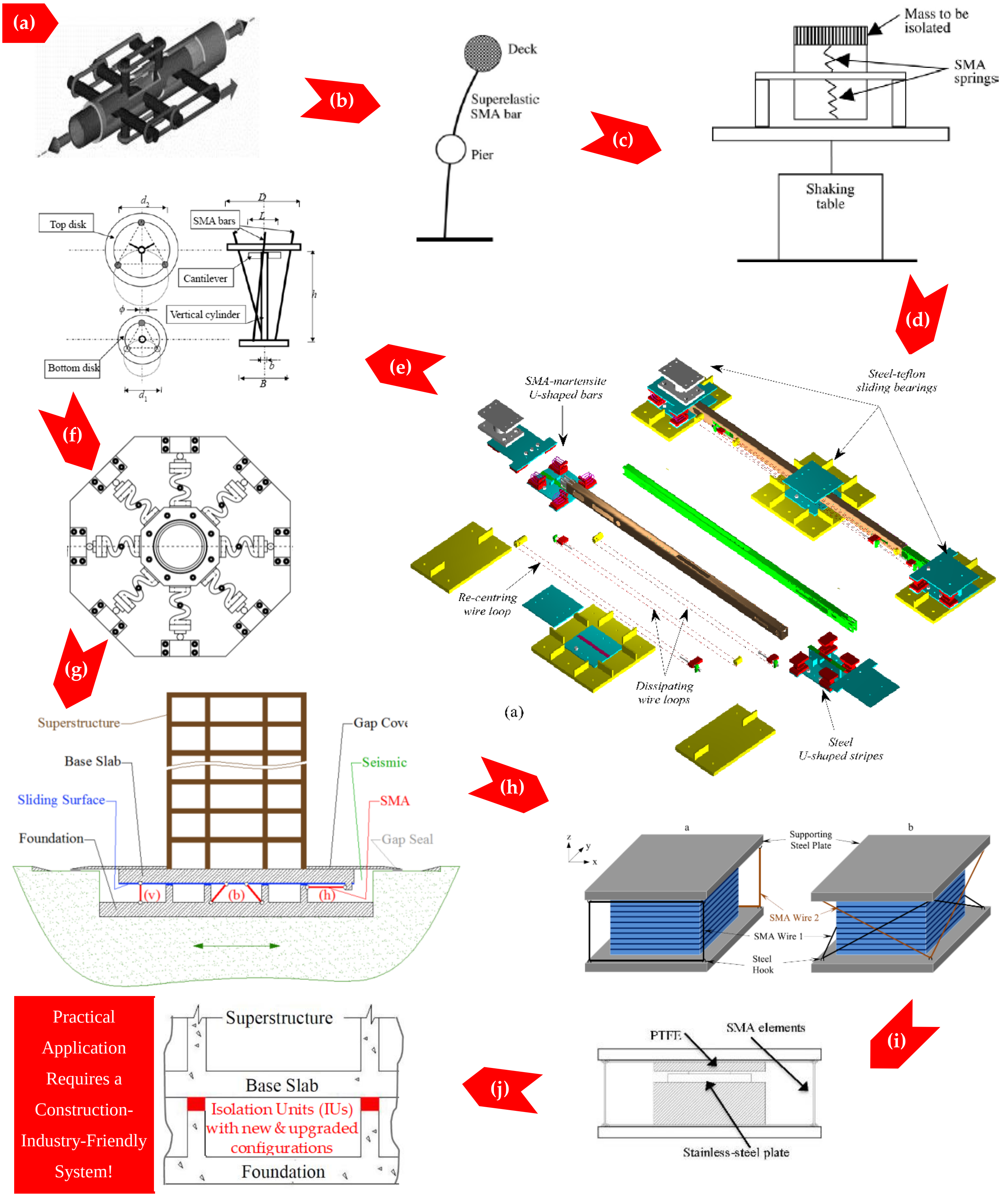

Figure 3. The SMA-based aseismic isolation systems: (a) Dolce et al (2000); (b) Wild et al. (2000); (c) Khan and Lagoudas (2002); (d) Cardone et al. (2003); (e) Casciati et al (2007); (f) Attanasi et al. (2008); (g) Cardone et al. (2009); (h) Hedayati Dezfuli and Shahria Alam (2013); (i) Ozbulut and Silwal (2014); (j) Narjabadifam (2015).

Fiber optics and their applications

The early application of fiber optics in civil structures was reported in 1990s by embedding them in concrete for sensing purposes (Chopra and Sirohi, 2014). Up to date, different applications have been reported or discussed by Akhras (2000), Habel and Krebber (2011), Mikami and Nishizawa (2015), Barrias et al. (2016), Joe et al. (2018), and Wu et al. (2018 a,b). Figure 4 provides some examples for the applications of fiber optics in civil engineering projects.

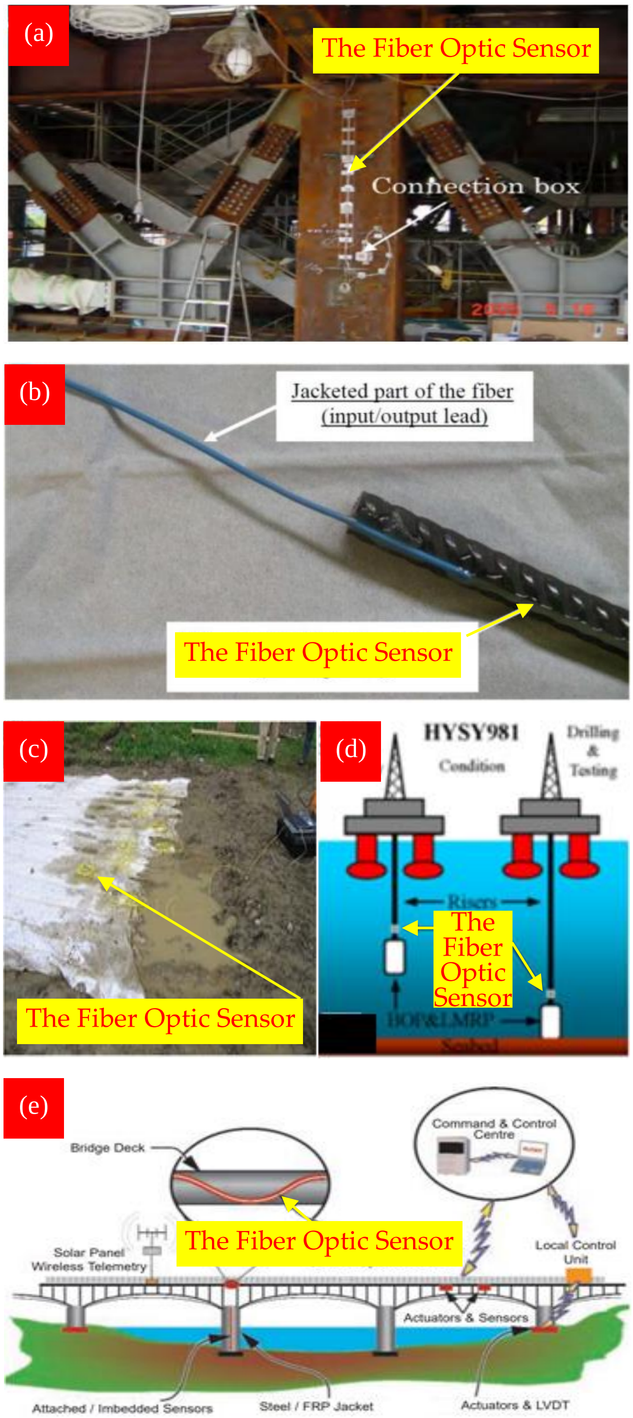

Figure 4. Fiber optics in civil structures: (a) Mikami and Nishizawa (2015); (b) Barrias et al. (2016); (c) Habel and Krebber (2011); (d) Joe et al. (2018); (e) Akhras (2000).

Figure 4(a) shows the application of fiber optics for the purpose of health monitoring of a high-rise building in Japan. Figure 4(b) aims at the same but in the concrete structures. In figure 4(c) the application in geotechnical engineering is represented and figure 4(d) is an example of the application in offshore environmental engineering. The application in bridges is also shown in figure 4(e).

Piezoelectric materials and their applications

Piezoelectric materials are popular smart materials discovered in the year 1880 by Pierre Curie and Jacques Curie (Schwartz, 2009). The word "piezo" is a Greek word meaning "to press". Piezoelectricity means, in this regard, electricity generated pressure (πιεζειν, in Greek language). Piezoelectric materials respond very quickly to changes in voltages. They can be used to generate precise motions with repeatable oscillations. Piezoelectric materials can be natural or man-made. The most famous material that naturally exhibits piezoelectric effect is quartz, but man-made materials are more efficient. From a theoretical point of view, the piezoelectric effect is a phenomenon involving electromechanical interconversion between mechanical strain and electrical charge in piezoelectric materials. Their relationship can be generally expressed on the basis of linear coupling equations based on stress, strain, electric field, elastic stiffness coefficient, electrical displacement, piezoelectric stress coefficient, and the dielectric permittivity for constant stress (Cheng et al., 2019).

A piezoelectric material is indeed a substance that produces an electric charge when a mechanical strain or stress is applied, producing also a mechanical deformation when an electric field is applied. The former is termed direct piezoelectric effect and the latter is known as inverse (converse) piezoelectric effect (Worden et al., 2003). These effects are formed in the crystalline structure of the material. To explain these effects, the molecular structure of the crystals should be investigated. Each molecule in this structure has a polarization, in which one end is more negatively charged and the other end is positively charged. This situation results in a dipole. The polar axis can be considered as the imaginary line that runs through the center of both charges on the molecule. The arrangement of these polar axes is the source of the piezoelectric effects. The piezoelectric materials are naturally found with random polar axes within a polycrystalline structure. This polycrystalline structure can be changed to the monocrystalline structure with polar axes arranged in the same direction, when the material is subjected to mechanical stress or electric field. Figure 5 shows a schematic representation of the basic polycrystalline structure near to a sample of natural quartz and illustrates both the direct and the inverse piezoelectric effects paying the attention on the dipoles and the changes in the dimensions in a general shape.

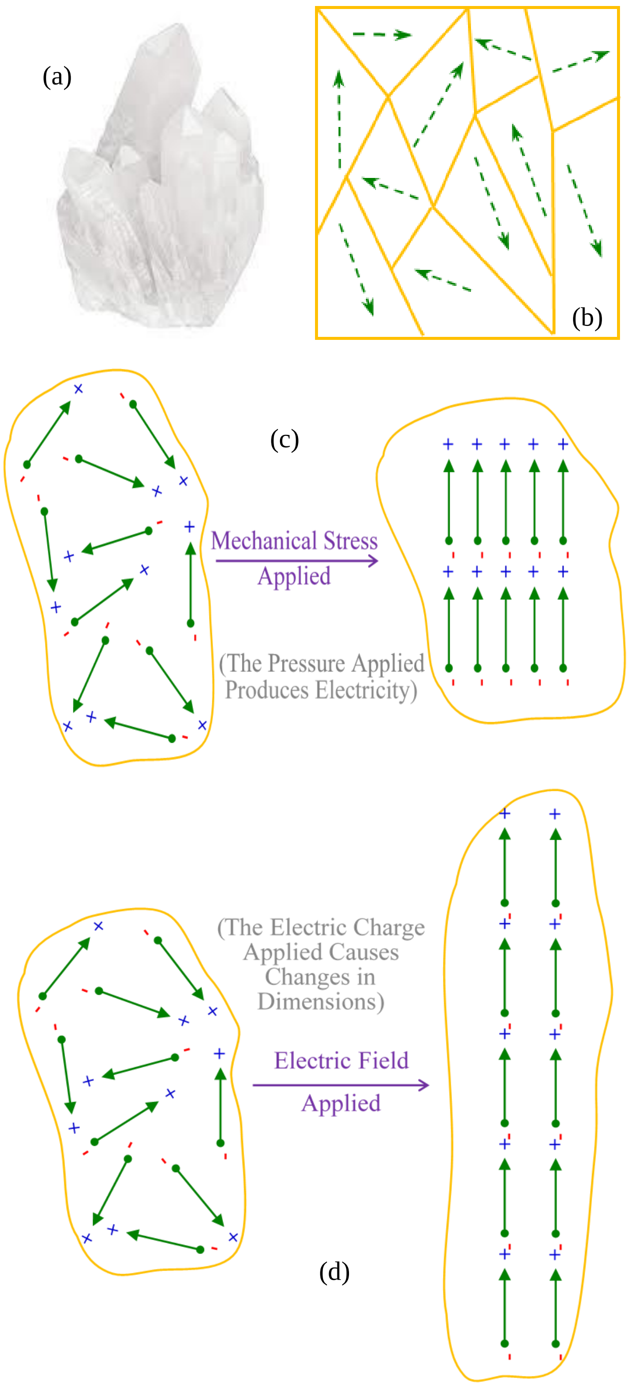

Figure 5: Piezoelectricity: (a) the natural quartz; (b) Schematic representation of the basic polycrystalline structure with the random polar axes; (c) the direct piezoelectric effect; (d) the inverse piezoelectric effect

Civil engineering applications of piezoelectric effects include mainly health monitoring of structures, repair, and energy harvesting. As shown in figure 6(a), they can also be used as dampers (Chen et al., 2019). Figure 6(b) shows the application for health monitoring of a bridge (Shimoi et al., 2012), figure 6(c) represents the application for the purpose of repair (Duan and Wang, 2010), and figure 6(d) shows the studies for energy harvesting applications in buildings (Elhalwagy et al., 2017) and highways (Jiang et al., 2014).

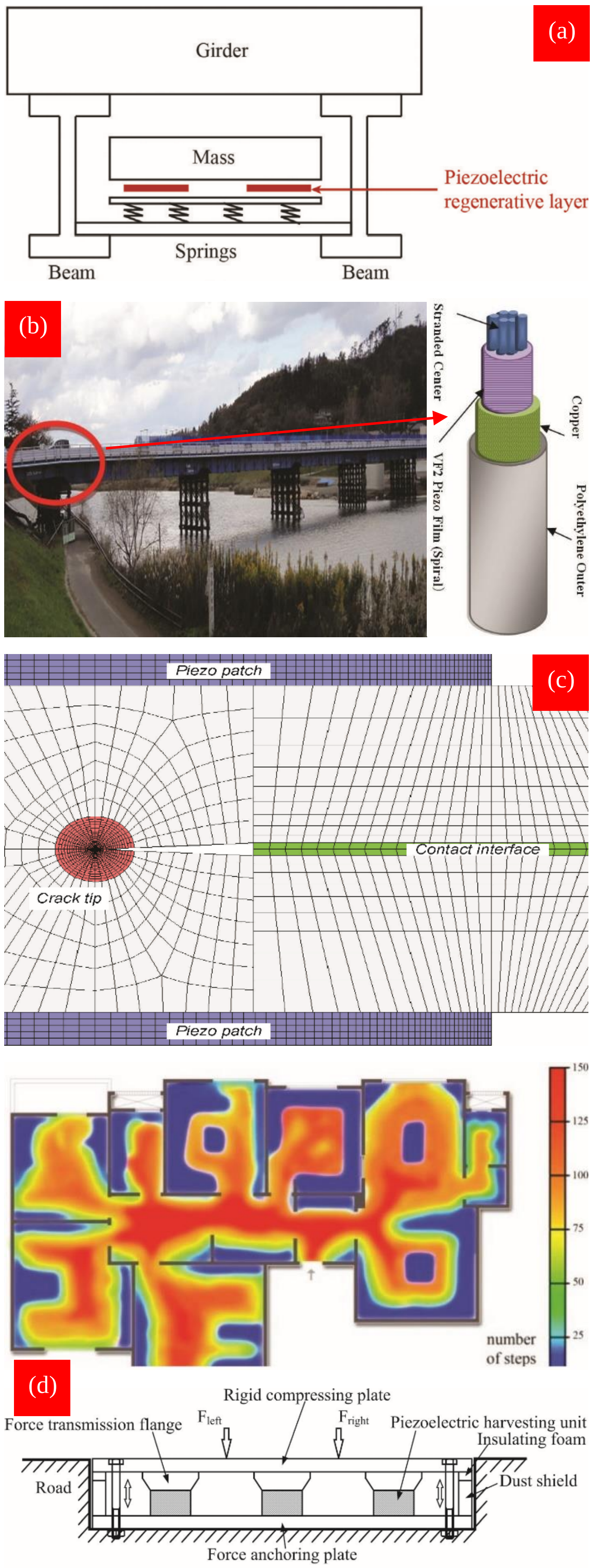

Figure 6. Civil engineering applications of piezoelectricity: (a) as dampers (Chen et al., 2019); (b) for structural health monitoring (Shimoi et al., 2012); (c) for the purpose of repair (Duan and Wang, 2010); (d) as energy harvesting devices (Elhalwagy et al., 2017 and Jiang et al., 2014).

Electro/magneto-rheological fluids and their applications

Electro-Rheological (ER) and Magneto-Rheological (MR) fluids are known as smart fluids because they can change their states from liquid to gel or semisolid and vice versa with response times on the order of milliseconds. The basics of ER and MR fluids were discovered in the late 1940s and early 1950s, when most of the initial research was focused on ER fluids (Chopra and Sirohi, 2014). The higher attention on ERs, however, was because of that devices based on ERs have a very simple geometry and are easy to construct when compared with MR devices.

As it was mentioned above, the key characteristic of ERs and MRs is indeed an easy-to-obtain significant change in fluid viscosity with the application of electric or magnetic field respectively for ER and MR fluids. This specific property owes to the presence of the suspended particles that are sensitive to electric and magnetic fields. The suspended particles are randomly distributed in the fluid if there is no field (electric or magnetic) available, but in the presence of electric or magnetic field the suspended particles form chains. This is shown in figure 7 representing the micrography of a MR fluid under the effect of a magnetic field, in comparison with the micrography of the fluid with no magnetic field (Spaggiari, 2013). As a result of the creation of the chains inside the fluid, the rheological properties change under the effect of the applied field.

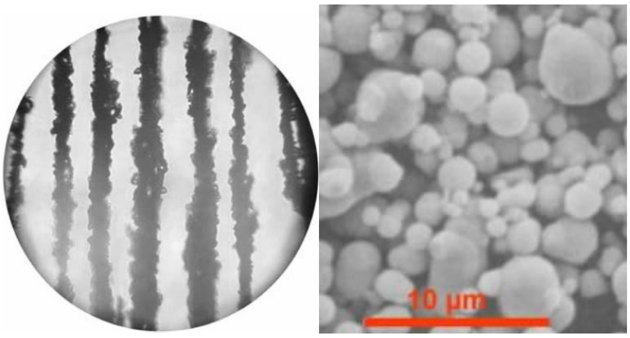

Figure 7: The micrography of a MR fluid subjected to magnetic field (left), compared with the micrography of the fluid without magnetic field (Spaggiari, 2013)

ER and MR fluids are very similar in terms of their composition and behavior. ER fluids change their properties in response to an electric field, while MR fluids respond to a magnetic field. Both the responses are schematically shown in figure 8. ER and MR fluids are, however, different in terms of their density, yield stress, and other mechanical properties. The yield stress of MR fluids is an order of magnitude higher than that of ER fluids. MR fluids are, in addition, much more tolerant to impurities and can be operated by low voltage power supply. This low voltage is much safer to work, compared to the high voltage required for ER fluid devices.

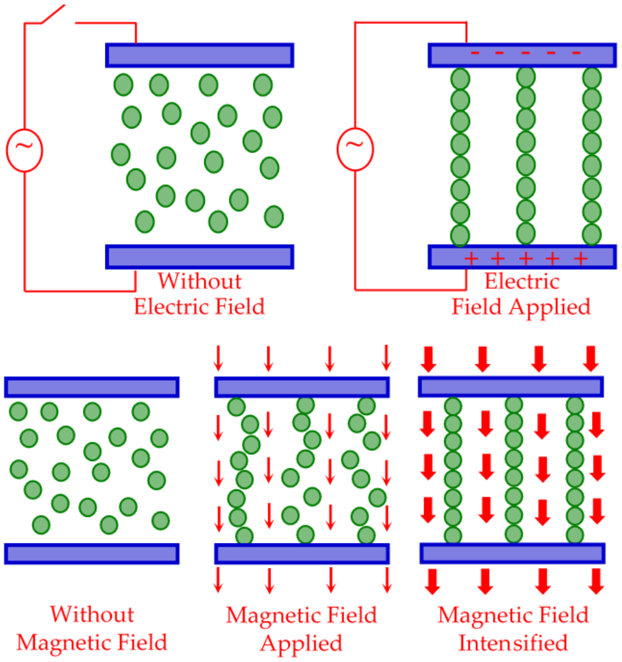

Figure 8: Schematic representations of the arrangement of the suspended particles in ER (up) and MR (down) fluids, subjected to respectively electric and magnetic fields

As far as the application is considered, both ER-based and MR-based devices can be produced and used in civil engineering projects (Makris et al., 1996; Choi and Wereley, 2002). MRs, however, are preferred to ERs because of three main limits of ERs: (i) very limited yield stress (maximum 5–10 kPa) of ERs, (ii) common impurities that might be introduced during manufacturing and may reduce the capacity of ERs, and (iii) high-voltage (about 4000 V) power supply required to control ERs, resulting in safety, availability, and cost issues (Cheng et al, 2008). Figure 9 shows the schematics of both ER and MR dampers to represent the working principles of them.

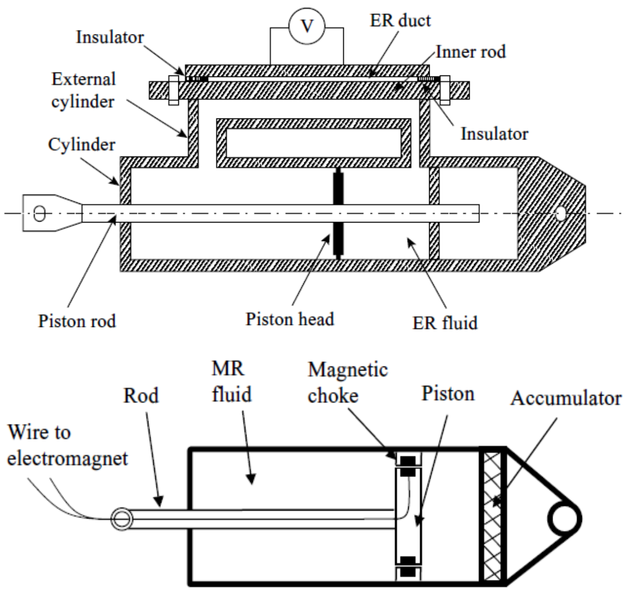

Figure 9: Schematics of ER (up) and MR (down) dampers (Cheng et al., 2008), representing the working principles of these two smart dampers

A more detailed prototype schematic of the MR damper, which is more attractive for seismic protection of civil engineering structures, is also shown in figure 10, providing at the same time its application in a bridge (Weber et al., 2006). It should be noted that the application is displayed right after installation in a bridge near Kampen city in Netherlands, and thus without a protective cover.

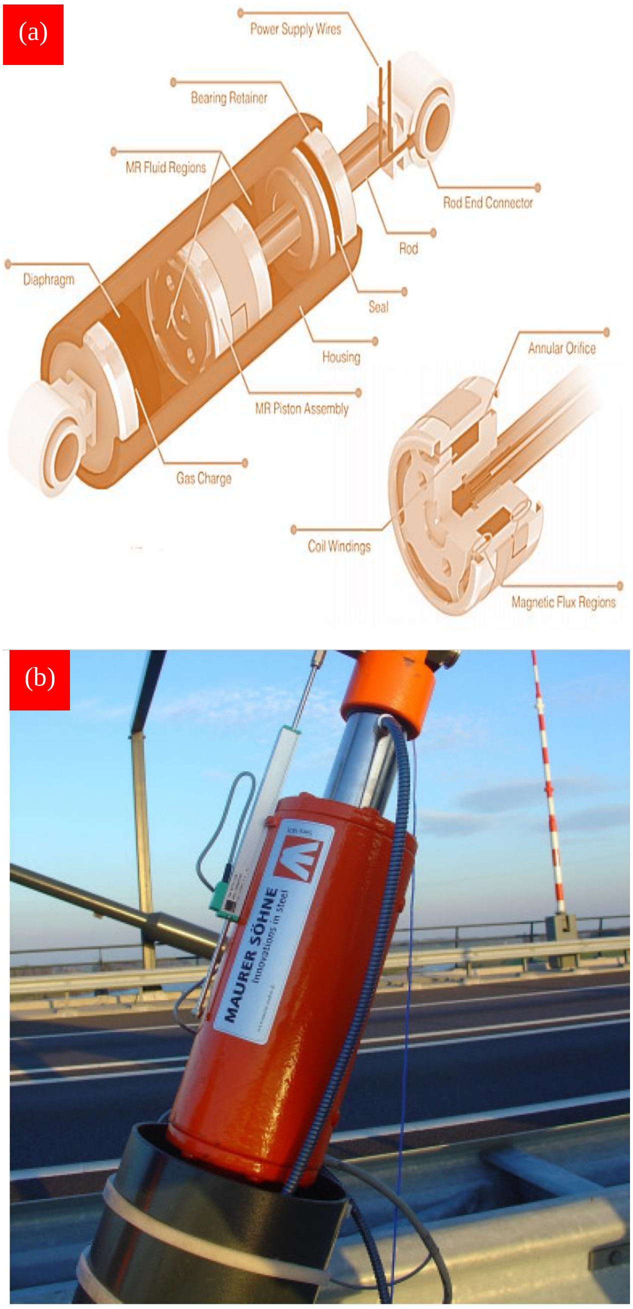

Figure 10. Implementation of MR dampers in structural control of a bridge: (a) the detailed 3D schematic of the prototype; (b) the photograph of the damper right after installation (Weber et al., 2006)

Many other applications and investigations have also been reported, up to date. Application of MR dampers in base isolation systems (Oliveira et al., 2018) and the study of ageing effects (Caterino et al., 2018) are the most recent examples.

Magnetostrictive materials and their applications

Magnetostriction is a smart property of some ferromagnetic materials which causes them to expand or contract in response to a magnetic field. This smart effect indeed allows magnetostrictive materials to convert electromagnetic energy into mechanical energy, which is attractive for engineering purposes and can also be useful in civil engineering applications. Once a magnetic field is applied to a magnetostrictive material, its molecular dipoles and magnetic field domains rotate to align with the field. This causes the material to strain and elongate. The magnetostrictive effect was first discovered by James Prescott Joule in 1842, when he was observing a sample of iron that resulted in definition of the concept of magnetostriction. This effect, for this reason, is also known as Joule’s effect (Ghorbanpour Arani and Khoddami Maraghi, 2016).

Terfenol-D (an alloy of the formula $Tb_xDy_{1-x}Fe_2$ (x~0.3), initially developed in the 1970s) is the well-known material that possesses magnetostrictive properties, with the highest magnetostriction exhibited among other materials (Dong et al., 2011; Yang, 2016).

The most popular and simple model to explain the magnetostriction behavior is the ellipsoid model. This model is demonstrated in figure 11. In this model, the magnetic boundaries are represented by ellipsoids with predefined magnetic directions. Under magnetic field, ellipsoids rotate and cause a change in dimension. The change in dimension due to the magnetostrictive effect can be increased if a pre-stress is applied before. The ellipsoid model can also be used to explain the effect of pre-stress on magnetostriction, which is included in figure 11. Applying a pre-stress make the ellipsoids rotate away from the stress direction. Then if a magnetic field is applied in the direction of the applied stress, the resulting elongation will be larger than that without pre-stress.

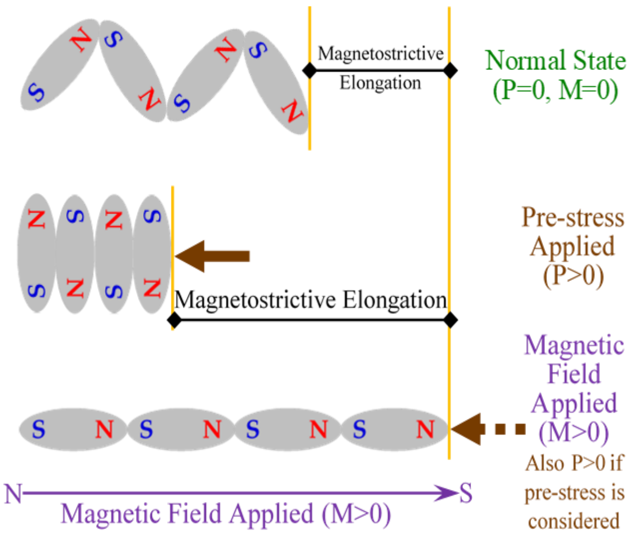

Figure 11. Schematic representation of the magnetostrictive effect (normal state and pre-stress added) described by the ellipsoid model.

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Magnetostrictive materials can be used as sensors and/or actuators for the purposes of vibration control or non-destructive evaluation of civil engineering structures. Figure 12(a) shows the schematic of a magnetostrictive actuator that can be used in vibration control (Deng and Dapino, 2018) and figure 12(b) is the photograph of a setup for the experimental investigation of magnetostrictive actuators in vibration control of a beam (Moon et al., 2005), and figure 12(c) demonstrates the application of magnetostrictive sensors in non-destructive evaluation of concrete structures (Dong et al., 2011).

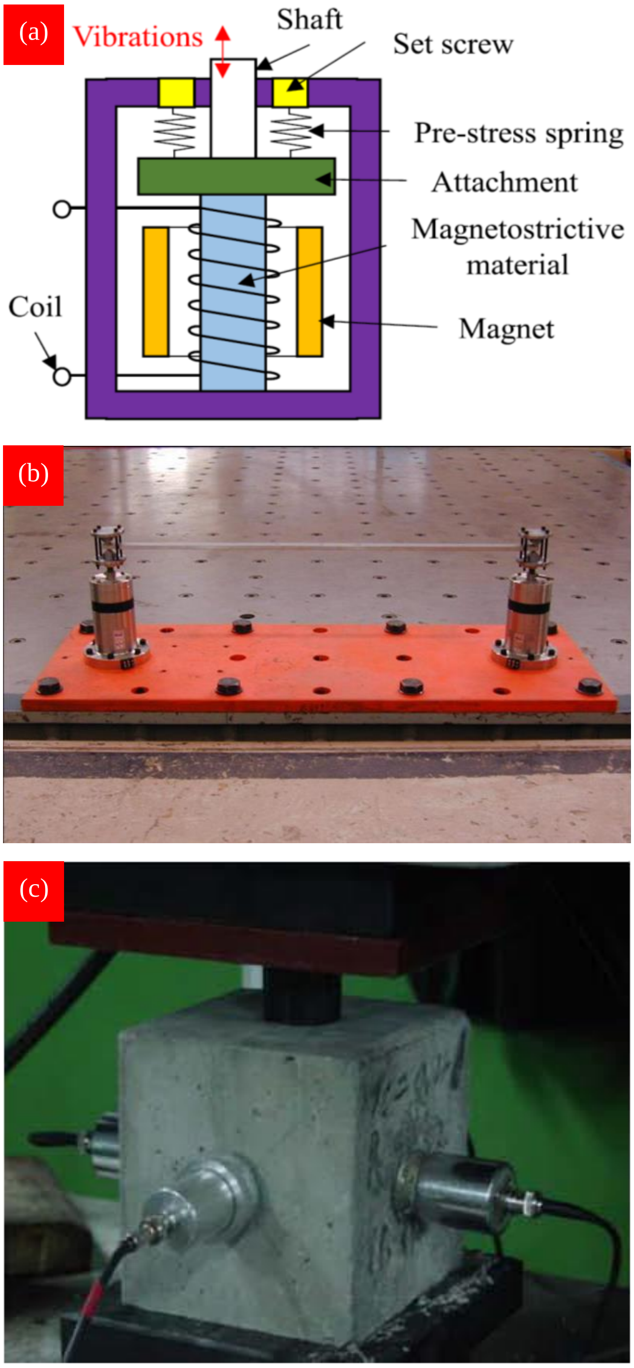

Figure 12. Civil engineering applications of the magnetostrictive materials: (a) schematic of a magnetostrictive actuator (Deng and Dapino, 2018); (b) vibration control of a beam (Moon et al., 2005); (c) non-destructive evaluation (Dong et al., 2011)

ADVANTAGES AND LIMITATIONS OF THE APPLICATION OF EACH MATERIAL

As it was discussed in the previous sections, the smartness of smart materials can be either active or passive. The smartness in civil engineering can then be achieved by active, passive, semi-active, or hybrid smart systems (Cheng et al., 2008). Active systems require external sources of energy with large control efforts that may cause control-induced instability. They work also generally based on some complicated devices, which are not available always in practice. Passive systems, on the other hand, are generally simple-structured and consume no addition energy but sometimes not fully adaptive to the possible uncertainties. Semi-active and hybrid systems lift typically the limitations and the drawbacks but remain rather complicated again to obtain widespread application in civil engineering projects. Construction industry, in this regard, is more interested in the passive smart systems being also robust and cost-effective in addition to the above-mentioned merits.

Civil engineering structures, in general, are subjected to large forces. Earthquakes are one of the most important sources of these large forces. Smart earthquake-resistant design of civil engineering structures requires large-scale smart devices. Some of the smart materials, however, fail to satisfy this requirement. This will be evident if one compares the orders of magnitudes of the forces generated by different smart materials. The discussion provided in the relating previous section to compare ER dampers with MR dampers is an example of this. SMAs are more suitable for this purpose, compared to the other smart materials. The unique superelastic behavior exhibited by the austenitic form of these alloys is the most favorable characteristic of them for earthquake protection of structures. A simple experimental verification of this effectiveness is provided in figure 13, showing the behavior exhibited by a 1mm diameter SMA wire subjected to cyclic loading, in addition to the proofs available in the literature (Dolce and Cardone, 2001; Saadat et al., 2002; Cardone et al., 2011). The wires used in this study were supplied by a French company (nimesis technology: a leading company in the development of SMA-based devices, www.nimesis.com) and the alloy type was NiTi, which is the most famous SMA but rather expensive. Many other alloys, however, can be used and the performances are similar. Iron-based alloys have recently been proposed to provide better performances at a lower cost (Cladera et al., 2014; Wen et al., 2014; Sakon, 2018). Various structural elements, in addition can be produced by SMAs. Wires, wire bundles, bars, films, and most recently wire ropes are some examples. Bars and wire ropes are the most suitable elements for large-scale civil engineering structures, when the wire ropes are preferred in practice with regard to some metallurgical difficulties included in the production of the bars

(Reedlunn et al., 2013; Mercuri, 2014; Carboni et al., 2015; Kitamura, 2016; Ozbulut et al., 2015; Biggs, 2017).

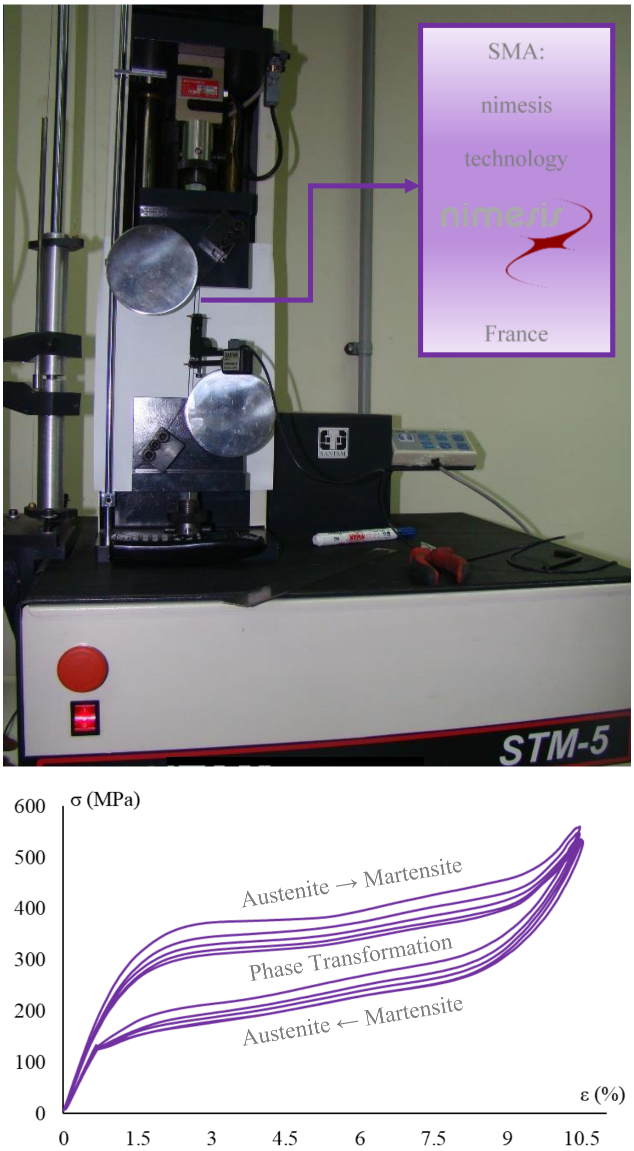

Figure 13: Experimental verification of the suitability of SMAs for structural earthquake engineering applications: (up) the test apparatus; (down) the superelastic behavior exhibited by the tested SMA wire under cyclic loading

As it can be seen, a high reversable strain within a repeatable hysteretic behavior providing also an acceptable energy dissipation property can be obtained by these materials. These features are indeed suitable for the application in aseismic design.

Further developments in the field of smart materials regarding their applications in civil engineering structures can be addressed in the production of materials with damping and stiffness properties changing by changes in stress/strain and/or acceleration. As it is shown in figure 14, these kinds of smart materials can be used for the purpose of earthquake protection of structures. They can provide an isolation mechanism, as the most popular and effective method of aseismic control for most of the civil engineering structures. This would be preferred to be passive, as discussed above, but an active control is also applicable. Production and application of these types of smart materials, however, form a challenge in this field and require further research but seems to be more attractive in the civil engineering profession.

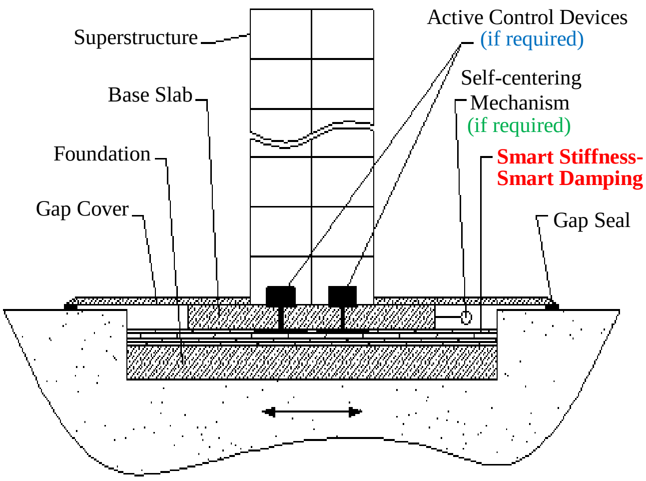

Figure 14: Acceleration/strain-sensitive smart stiffness and smart damping properties can be useful in civil engineering

CONCLUSION

The applications of smart materials in civil engineering projects was investigated based on the evaluation of their working principles and the review of previous innovative applications. The investigation was started with the study of Shape Memory Alloys (SMAs). It was shown that SMAs find lots of applications in civil engineering projects, based on both superelasticity and shape memory effect. Fiber optics were evaluated as the useful sensors for structural health monitoring of a wide range of structures. Piezoelectricity was found to be useful for damping devices, for structural health monitoring, for the purpose of repair, and for the energy harvesting devices. Electro-Rheological (ER) fluid dampers were compared to Magneto-Rheological fluid dampers and it was shown that MRs are more suitable for civil engineering applications because of some drawbacks of ERs such as their very limited yield stress and the high-voltage power supply required to provide the control effect. The principles of magnetostriction were investigated and it was shown that magnetostrictive materials can be used as actuators and sensors in vibration control and non-destructive evaluation of structures. A discussion was then provided on the advantages and limitations of the application of each smart material in civil engineering projects. Based on the specific requirements of the civil engineering structures, in which the need for large-scale elements is the most important of them specifically when the earthquake protection is considered, it was concluded that SMAs are the most useful materials for aseismic design of civil engineering structures. It was also shown that acceleration or strain -sensitive smart stiffness and smart damping properties can be useful in civil engineering, providing an effective isolation mechanism, for example, which form a challenge in the field of materials engineering motivated by a high degree of interest in civil engineering.

DECLARATIONS

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Authors' contributions

Authors of this research paper have directly participated in the planning, execution, or analysis of this study and have read and approved the final version submitted.

Conflict of interest statement

We hereby state that, there is no conflict of interest whatsoever with any third party.

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