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# New Uses of Smart Materials in Civil Engineering for Intelligent, Eco-Friendly Cities

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**Research Article**
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**ABSTRACT**

Structures of all kinds, including buildings, come together to create urban environments. For smart sustainable urbanisation to keep up with the world's continuous growth, smart and sustainable buildings are needed in this area. Materials that can change their properties in response to their surroundings, whether in a passive or active way, are called smart materials. These materials have the potential to make our buildings smarter. Different kinds of smart materials may be used to build buildings. As a field, civil engineering is beginning to pay more attention to smart materials such shape memory alloys (SMAs), piezoelectric materials, fibre optics, magneto-rheological (MR) fluids, electro-rheological (ER) fluids, and magnetostrictive materials. This article delves into the building industry's innovative uses of these materials. We provide the proof of concept demonstrations and give brief explanations of the physical concepts. We outline the benefits and drawbacks of using each material in civil engineering projects and talk about how passive systems work. When it comes to designing buildings to withstand earthquakes, SMAs are the clear winners among the smart materials now on the market. The experimental applicability of SMAs as seismic devices is subsequently confirmed. Materials whose damping and stiffness characteristics are modulated by changes in stress, strain, and acceleration are also shown to be effective for earthquake protection of buildings. These smart materials seem to be increasingly appealing in the field of civil engineering, but their production and use still need more study.

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

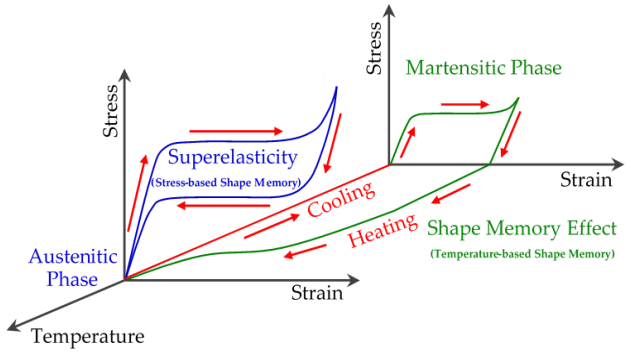
## INTRODUCTION

Civil engineers and urban planners rely heavily on materials. In order to meet the public's needs in metropolitan settings, civil buildings that use the right materials and methods function better. High performance is difficult to achieve in structures made using old-fashioned methods and materials (Cheng et al., 2008). Over the last few years, the primary objective has been to identify novel structural systems and unconventional materials that can meet stringent performance standards (Saadat et al., 2002). When it comes to civil engineering, there is a class of materials known as "smart materials" that may significantly boost performance.

The term "smart" is frequently used in marketing to describe new products (Worden et al., 2003), but in theory, a material can be considered smart if it is self-aware and responds to its surroundings by modifying its properties to create a reversible and beneficial effect or response when excited. This could happen actively or passively, with or without the need in search of energy from other sources. Since all materials respond in some way to their surroundings, the key distinction between smart materials and conventional ones is in the production of a practical and remarkable reaction. Various processes, including changes in crystalline structure, give this exceptional response to an engineering and environmental stimulation type (Schwartz, 2009). Similarly, "smart" systems are those that can adapt their own characteristics to external stimuli, ensuring the safety and reliability of the structure and its service life through the use of materials' inherent qualities or the integrated functions of sensors, actuators, and processors (Otani et al., 2000). Here are some examples of smart materials:

- 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.

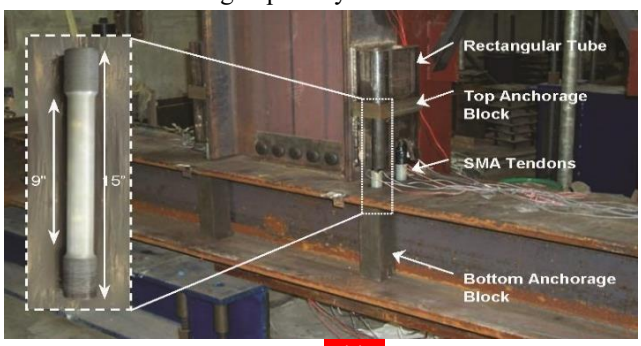
**Shape memory alloys and their applications**

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.

In recent years, SMAs have found use across a wide range of engineering disciplines (Cismasiu, 2010). The special recovery, energy dissipation, and isolation mechanisms offered by SMAs provide the foundation for their use in civil engineering (Dolce and Cardone, 2001). Ocel et al. (2004) examined the use of martensitic SMA tendons in the connections of steel frames as a practical application based on energy dissipation mechanism, which includes martensitic recovery (see Figure 2a). Similarly, Moradi and Shahria Alam (2015) have recently examined SMA-based beam-column couplings, as seen in Figure 2(b). The introduction of The use of SMA braces has also been discussed in previous works (e.g., Narjabadifam and Hejazirad, 2018; Qiu and Zhu, 2017). The gadget that was examined by Qiu and Zhu (2017) is shown in Figure 2(c). Research by Abdulridha et al. (2013), Wang and Zhu (2018), and Wang et al. (2019) might be consulted about the use of SMAs as reinforcements in concrete elements. The study of Abdulridha et al. (2013) is shown in Figure 2(d).




(a)

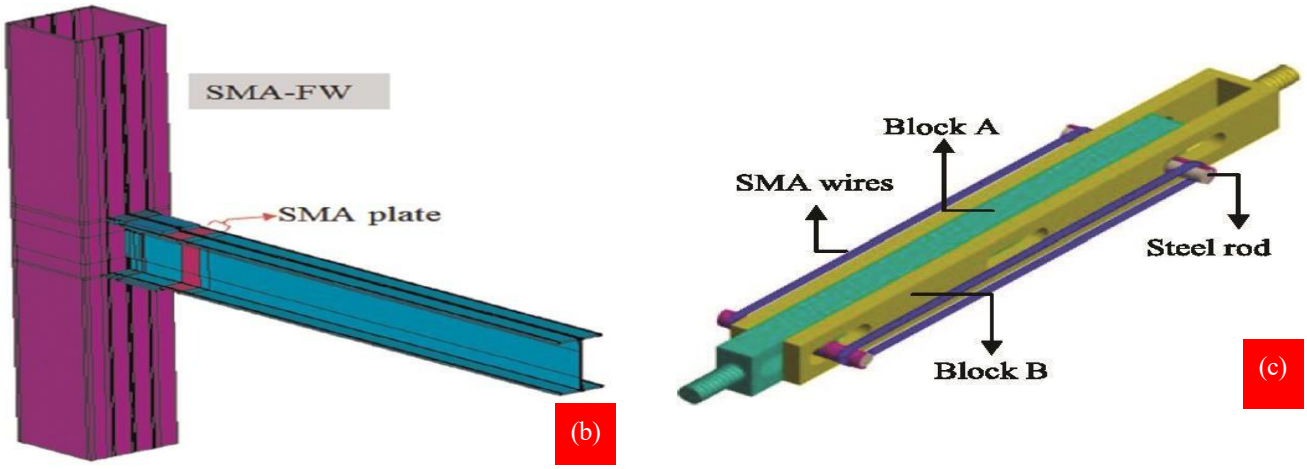
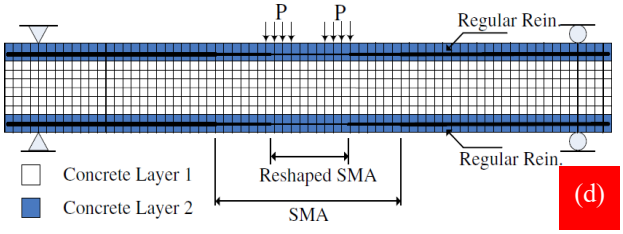
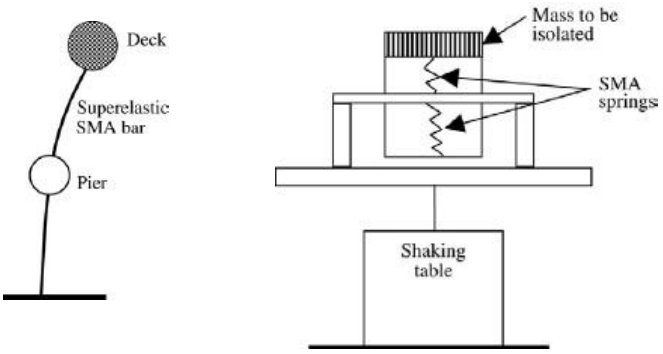



**Figure 2**. Civil engineering applications of SMAs in the forms of (a) martensitic beam-column connections (Ocel et al., 2004), (b) austenitic beam-column connections (Moradi and Shahria Alam, 2015), (c) braces (Qiu and Zhu, 2017), and (d) rebars (Abdulridha et al., 2013).




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.

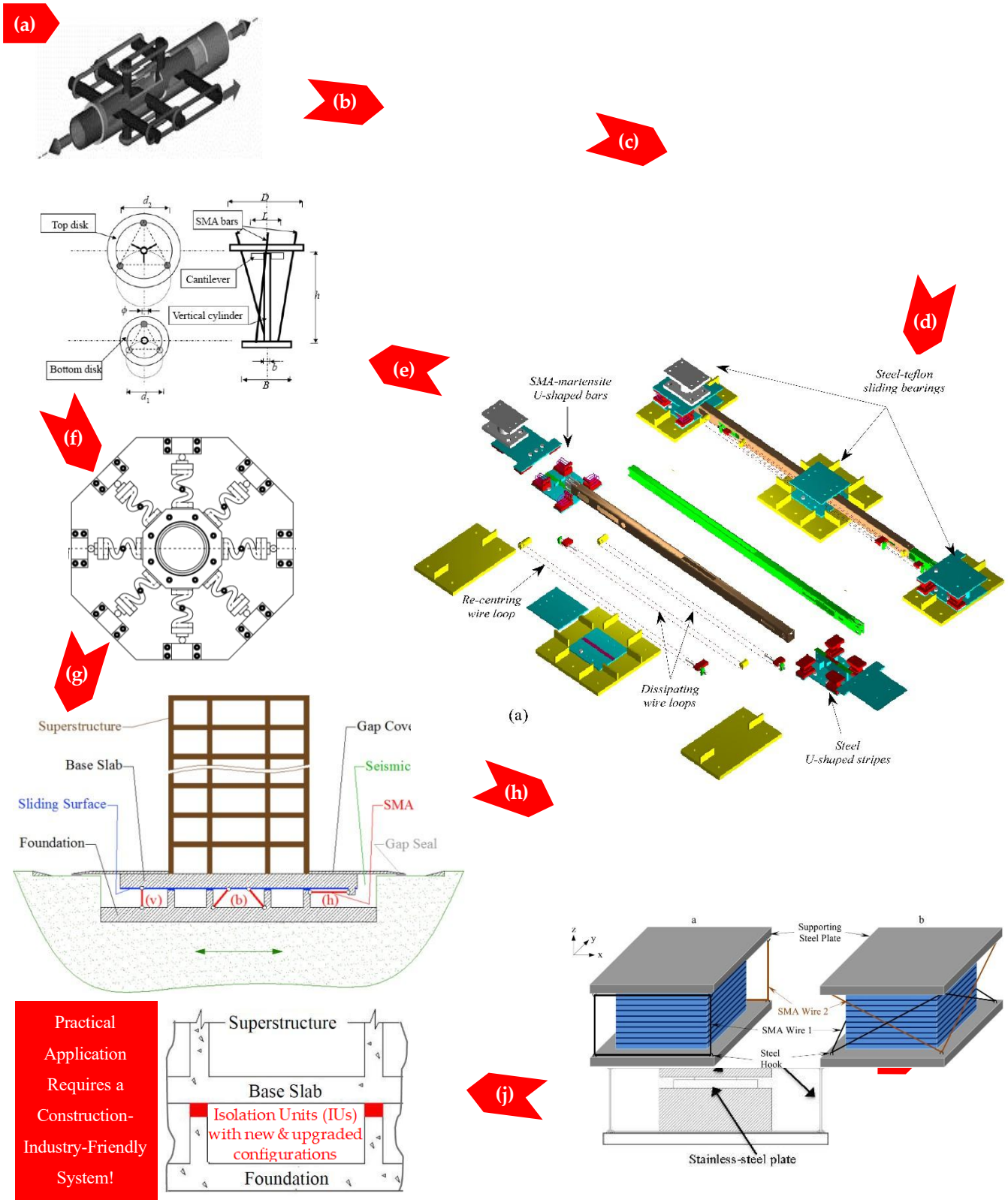



**Figure 3**. The SMA-based aseismic isolation systems: (a) Dolce et al (2000); (b) Wild et al. (2000); (c) Khan and Lagoudas (2002); (d) Cardone et al. (2003); (e) Casciati et al (2007); (f) Attanasi et al. (2008); (g) Cardone et al. (2009); (h) Hedayati Dezfuli and Shahria Alam (2013); (i) Ozbulut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

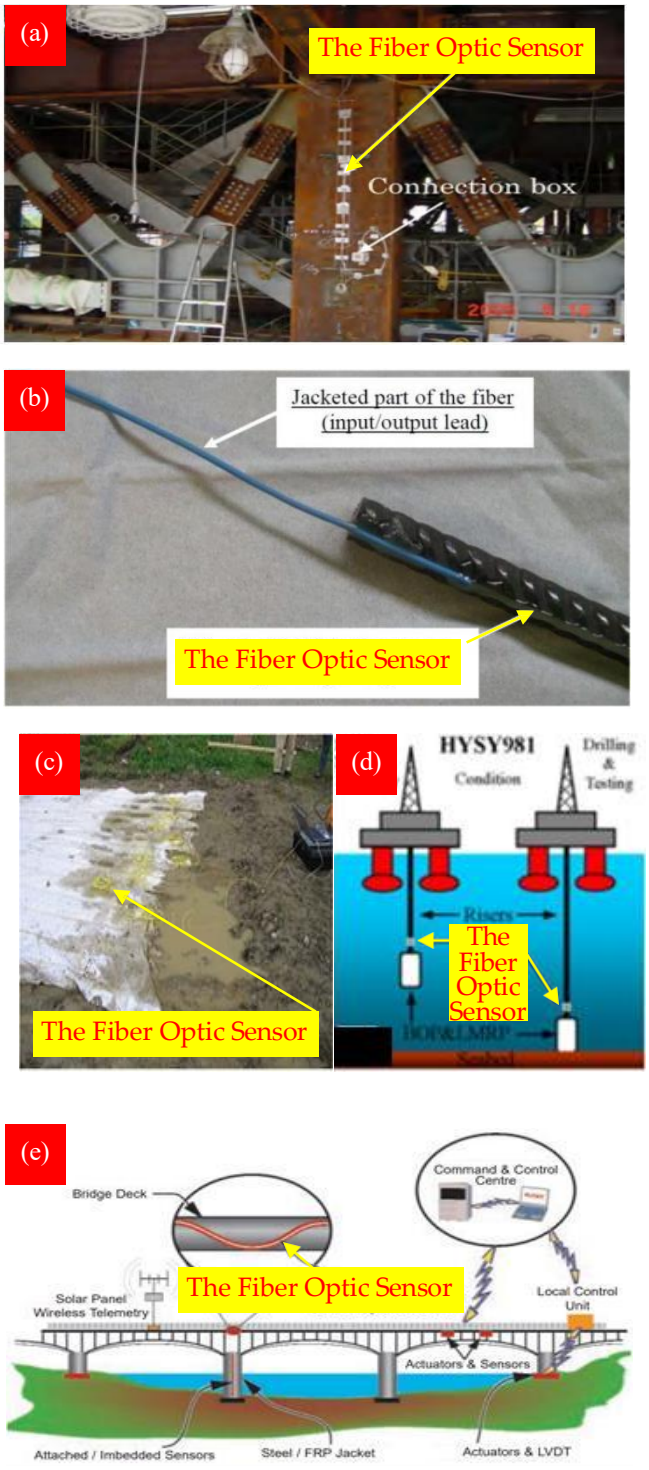



**Figure 4**. Fiber optics in civil structures: (a) Mikami and Nishizawa (2015); (b) Barrias et al. (2016); (c) Habel and Krebber (2011); (d) Joe et al. (2018); (e) Akhras (2000).

**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.

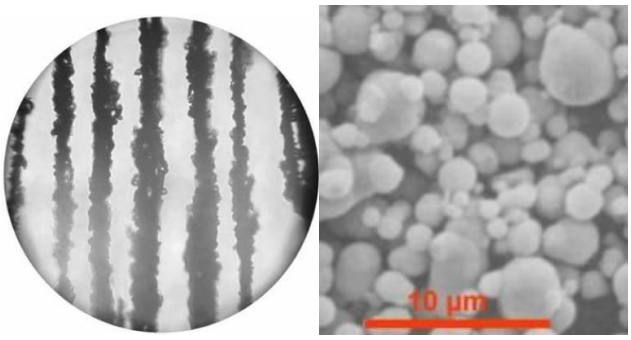



**Figure 7**: The micrography of a MR fluid subjected to magnetic field (left), compared with the micrography of the fluid without magnetic field (Spaggiari, 2013)

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.

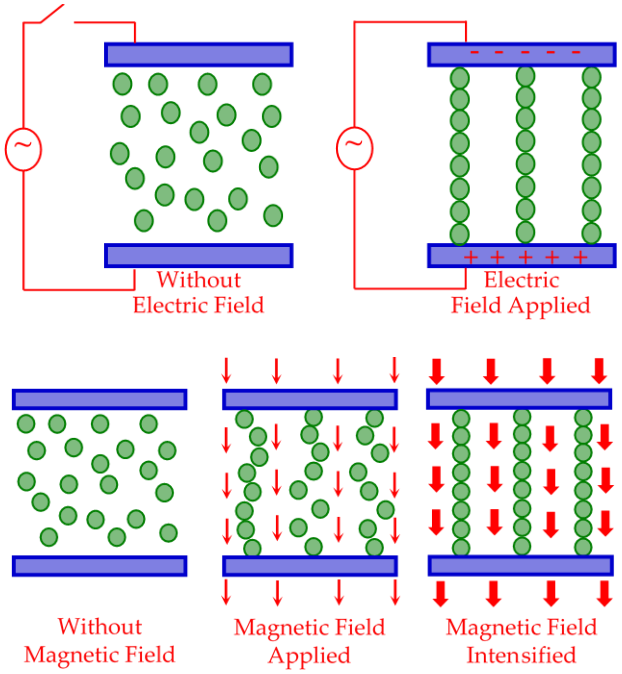


**Figure 8**: Schematic representations of the arrangement of the suspended particles in ER (up) and MR (down) fluids, subjected to respectively electric and magnetic fields

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.

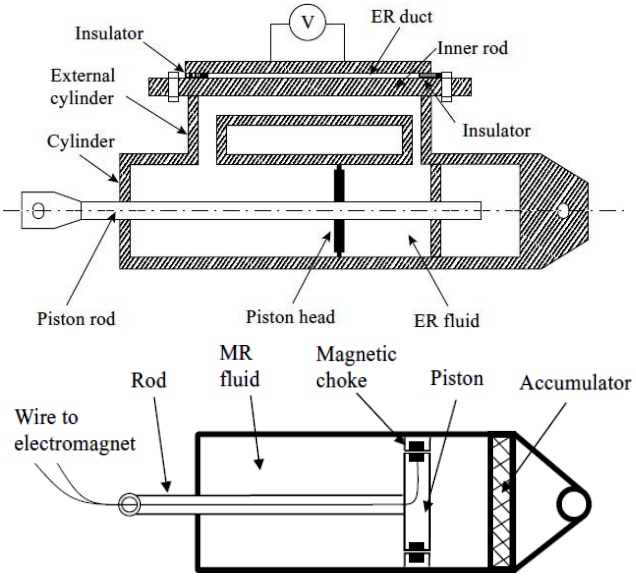



**Figure 9**: Schematics of ER (up) and MR (down) dampers (Cheng et al., 2008), representing the working principles of these two smart dampers

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.

(a)

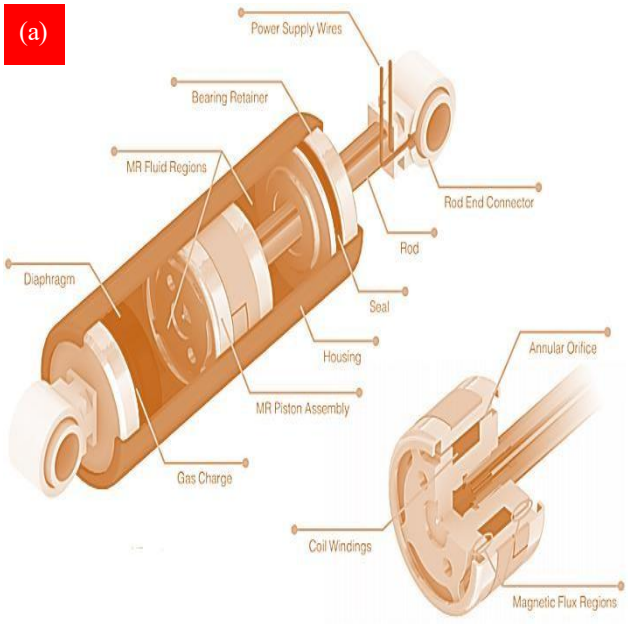





**Figure 10**. Implementation of MR dampers in structural control of a bridge: (a) the detailed 3D schematic of the prototype; (b) the photograph of the damper right after installation (Weber et al., 2006)

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.

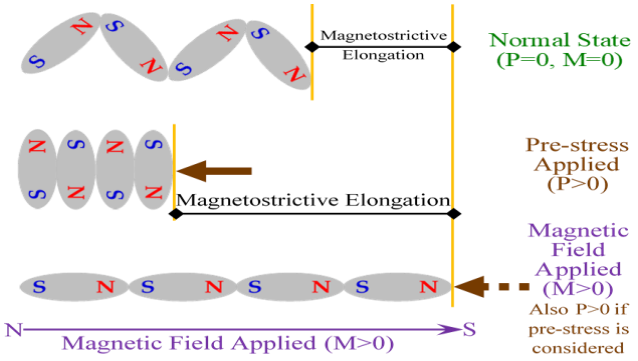



**Figure 11**. Schematic representation of the magnetostrictive effect (normal state and pre-stress added) described by the ellipsoid model.

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).

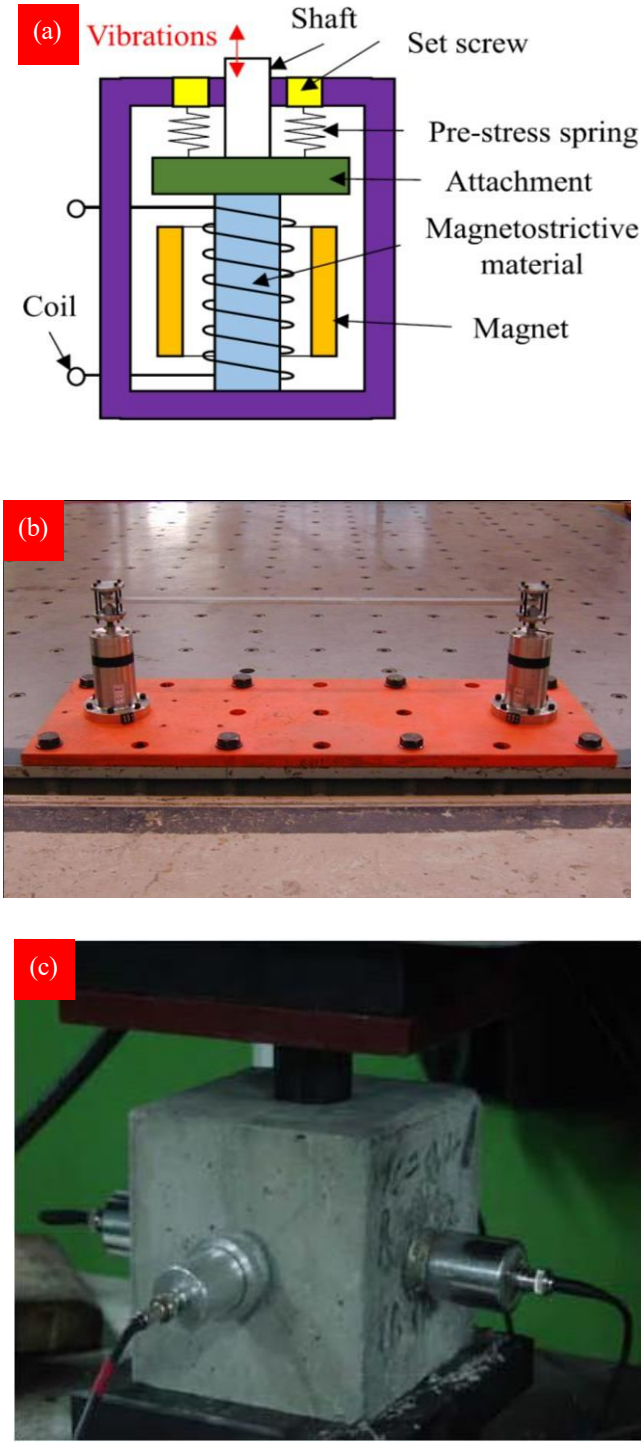



**Figure 12**. Civil engineering applications of the magnetostrictive materials: (a) schematic of a magnetostrictive actuator (Deng and Dapino, 2018); (b) vibration control of a beam (Moon et al., 2005); (c) non- destructive evaluation (Dong et al., 2011)

## 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).

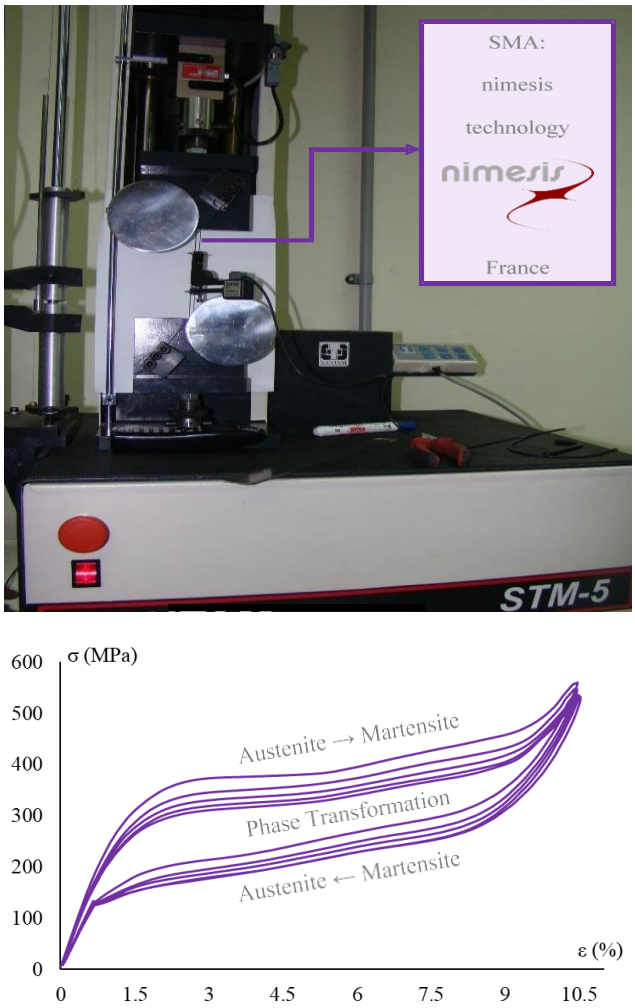
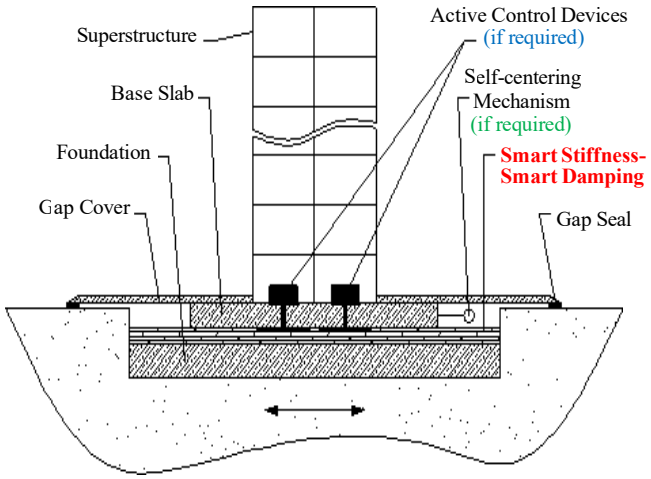



**Figure 13**: Experimental verification of the suitability of SMAs for structural earthquake engineering applications: (up) the test

apparatus; (down) the superelastic behavior exhibited by the tested SMA wire under cyclic loading

By observing their repeatable hysteretic behaviour and appropriate energy dissipation characteristic, it is clear that these materials may achieve a high reversible strain. These characteristics are well-suited for use in earthquake engineering. Making materials whose damping and stiffness characteristics alter in response to changes in stress, strain, and acceleration is one way to advance smart materials research and its potential uses in civil engineering constructions. Structures made of these types of smart materials may be used to withstand earthquakes, as seen in figure 14. Since they are the most widely used and reliable technique of earthquake control, they may serve as a means of separation for most of the civil architectural frameworks. As said before, it is best to have a passive approach, although an active control might also work. Although these smart materials seem more appealing in the civil engineering profession, their production and use pose a problem in this area and need more study.

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




## CONCLUSION

By analysing their underlying principles of operation and looking at examples of their inventive use, researchers looked into the potential of smart materials in civil engineering projects. A first step in the project was to examine Shape Memory Alloys (SMAs). It was shown that SMAs have several uses in civil engineering projects because to their shape memory effect and superelasticity. The potential of fibre optics as sensors for a variety of building types' health monitoring was assessed. Devices for energy harvesting, structural health monitoring, repair, and damping were all discovered to benefit from piezoelectricity. Due to ERs' limitations, such as their low yield stress and the high voltage power supply needed to produce the control effect, Magneto-Rheological (MR) fluid dampers are better suited for use in civil engineering applications than Electro-Rheological (ER) fluid dampers. After delving into the concepts of magnetostriction, it became clear that these materials had potential as sensors and actuators in fields such as vibration control and non-destructive structural assessment. The benefits and drawbacks of using each smart material in civil engineering projects were further covered. It was determined that SMAs are necessary for civil engineering constructions due to their unique demands, the most critical of which being the necessity for large-scale components in terms of earthquake protection. for civil engineering constructions that are designed to be resistant to seismic activity. The field of materials engineering faces a challenge due to the high level of interest in civil engineering, but it has been demonstrated that smart stiffness and damping properties that are sensitive to acceleration or strain can be useful in civil engineering. These properties provide an effective isolation mechanism, for example.

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