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REEBUILD Integrated Techniques for the Seismic Strengthening and Energy Efficiency of Existing Buildings

Novel technologies for the seismic upgrading of existing European buildings

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Novel technologies for the seismic upgrading of existing European buildings

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Foreword

Our buildings are ageing, posing an urgent need for renovation to align with the goals of multidimensional European and international policies. The built-up area in Europe covers 25 billion square meters, 10 billion of which were constructed before 1960 and 20 billion before 1990. 40% of the European Union (EU) buildings are located in seismic prone regions and were built without modern seismic design considerations. Apart from Member States with moderate and high seismic risk, such as Greece, Italy and Croatia, with a severe impact from earthquakes during the last decades (fatalities, injuries and economic losses), attention should be drawn to regions with lower risk, e.g. in France and Spain. At the same time, buildings stand out as one of the most energy consuming sectors, therefore having a negative environmental impact. In fact, buildings are responsible for 40% of EU energy consumption and 36% of the EU total CO_2 emissions, whereas 75% of the EU existing building stock is considered energy inefficient. The highest amount of energy use in old buildings derives by far from the operational stage of their life (e.g. heating, cooling), resulting in a significant source of carbon emissions with detrimental effects on climate change.

Notwithstanding this negative impact, the building sector provides a unique opportunity to create, through risk-proofed renovation, a safe, sustainable, and resilient built environment which promotes wellbeing and economic growth, and ensures that EU energy and climate targets are met. In this context, the European Parliament entrusted the European Commission's Joint Research Centre with the two-year pilot project "Integrated techniques for the seismic strengthening and energy efficiency of existing buildings" or REEBUILD.

REEBUILD aims to define technical solutions that can reduce seismic vulnerability and increase energy efficiency of existing buildings, at the same time and in the least invasive way. Thereby, increased earthquake resilience and limited environmental impact of buildings is sought by protecting life, economy and the environment. The project has the following key-objectives:

- Define the tools and guidelines to reduce, all at once, vulnerability and energy inefficiency of buildings
- Stimulate the use of integrated solutions
- Create awareness about the topic in the aim of prevention
- Increase resilience of the built environment to seismic hazard and climate change.

The geographical scope of the project covers EU seismic prone regions. However, all EU citizens are potential beneficiaries of the project since it can easily be extended to all EU regions considering the ageing of existing buildings and other hazards, including extreme climatic events.

In a policy context, REEBUILD provides scientific advice to support the development of an action plan, which shall supplement existing European Union policies and initiatives in the field of buildings' renovation. Crucially, the European Green Deal (COM (2019)640) emphasises the need for a Renovation Wave (COM (2020)662), supported by the New European Bauhaus to create sustainable, inclusive and beautiful living spaces. The plans to put the European Green Deal into effect further contribute to the economic recovery following the COVID-19 pandemic. In the Energy Performance of Buildings Directive (Directive 2018/844), besides reducing greenhouse gas emissions, measures related to seismic risk and fire safety are encouraged for planning long-term renovation strategies. The implementation of clean and circular economy principles for the construction sector to achieve a climate-neutral society by 2050 are stressed in the new Circular Economy Action Plan (COM (2020)98) which also addresses the revision of the Construction Products Regulation (Regulation (EU) 305/2011). The new idea for a holistic approach to the renovation of buildings is in line with the Union Civil Protection Mechanism (Decision (EU) 2019/420), with respect to disaster prevention measures and the integration of risk reduction and cohesion policies. Likewise, the Action Plan on the Sendai Framework (SWD 2016/205) encourages investment in disaster risk reduction, integrating "Build Back Better" principles for a more resilient built environment. The European Framework for Action on Cultural Heritage (SWD 2018/491) emphasises the need to safeguard cultural heritage against natural disasters and climate change, and relevant measures are encouraged when planning long-term renovation strategies and national disaster risk reduction strategies. The above policies and initiatives contribute to the implementation of the 2030 Agenda for Sustainable Development (Resolution 2015/A/Res/70/1) and the Sustainable Development Goal 11 "Make cities and human settlements inclusive, safe, resilient and sustainable".

Integrated retrofitting of existing buildings can be seen as a nexus between policies improving the disaster resilience of the EU, encouraging the energy renovation of buildings, promoting circularity within the building sector, and protecting cultural heritage.

Several activities were foreseen to achieve the REEBUILD objectives. EU buildings requiring upgrading were identified, and existing seismic and energy retrofit technologies were assessed in a life-cycle perspective. Combined retrofit solutions were explored based on available technologies and recent scientific developments in the field. A simplified method for the assessment of the combined upgrading was proposed and applied to case studies of representative building typologies retrofitted with the identified solutions. Seismic risk and energy performance of buildings along with socioeconomic aspects were assessed at regional level throughout Europe. Such regional assessments were used to identify appropriate intervention scenarios based on their regional impact and highlight the regions where interventions are of higher priority. National, regional and local authorities, industrial associations and expert communities were involved in enquiries and discussions of relevant implementing measures (legislation, incentives, guidance and standards), technologies and methodologies for the combined upgrading of existing buildings. Dissemination and outreach is further supported by reports, a web platform and public communication material. REEBUILD activities were organised in five main actions:

1. Overview and classification of technologies for seismic strengthening and energy upgrading of existing buildings
2. Analysis of technologies for combined upgrading of existing buildings
3. Methodologies for assessing the combined effect of upgrading
4. Regional impact assessment and contributions to an action plan
5. Stakeholders' engagement.

This report proves an overview of the seismic upgrading techniques that target reinforced concrete, masonry and steel buildings, as such buildings constitute the largest majority of the European building stock. The reviews focuses on novel upgrading techniques, as well as on the specifics of the European Union (EU) territory.

Acknowledgements

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Authors

Thanasis Triantafillou, Dionysios Bournas, Panagiotis Gkournelos

Abstract

The present report provides a review of the seismic upgrading techniques for reinforced concrete, masonry and steel buildings, which constitute the majority of the building stock in the EU. Seismic upgrading techniques are divided in two major categories, depending on the way they "treat" the structure. The first category includes the ones that operate at the element level (local measures), and the second those that operate on the structure as a whole (global measures). Naturally, when it comes to upgrading an actual building, various techniques can and should be combined, addressing its specific characteristics, so that an economic strengthening scheme can be designed. Depending on their age as well as the materials used, seismic upgrading techniques can be divided into conventional and novel ones. The report puts more emphasis on the latter, although it does include short descriptions of the former, for the sake of completeness.

1 General

Undoubtedly, one of the most important risks that structures located in seismic areas have to stand against is that of strong ground motion. In such cases, an earthquake-proof design is necessary, otherwise the risk of seismically-induced structural damage gets uncontrollably high and can lead not only to economic losses, but also and more importantly, to human casualties. It is therefore of outmost importance that countries located in seismically active regions:

- Are able to fully assess the seismic risk and its possible consequences.
- Are always prepared in case a major event takes place.
- Employ strategies to mitigate the seismic risk, e.g. via structural upgrading of existing buildings.

The earthquakes, along with their consequences, have been known to mankind since the ancient times, as ancient Egyptians considered them to be the "God's Hammer" while Greeks attributed their occurrence to the wrath of the God "Egelados". However, they were somewhat underestimated during the early development of most modern cities and the erection of the first structures, which were designed with minimal or without any special considerations at all regarding the earthquake loading. Unfortunately, yet logically, earthquakes did happen, and the failure of several structures gave birth to the field of earthquake engineering which matured during the 20th century. During the same time, seismic codes and provisions where introduced and revised repeatedly, becoming stricter each time, a process that is still undergoing, albeit with a much slower rate. Such revisions would typically take place after major earthquake events which would prove the existing regulatory framework as being in need of improvements.

Taking into account that the maturing process of the seismic codes was gradual and that the rate of constructing new structures is dropping in most places of the developed world, it is a logical consequence the fact that a large number of existing structures is under-designed and thus in need of seismic retrofitting. As a result, over the past decades, more and more academic interest has been focused on developing techniques of seismic upgrading of existing buildings.

The present report aims at providing a review of the seismic upgrading techniques which target reinforced concrete (RC), masonry and steel buildings, as such buildings constitute the majority of the building stock. Both traditional and novel techniques will be discussed, emphasizing on the latter as well as on the specifics of the European Union (EU) territory. A thorough review on the seismic upgrading techniques focusing only on RC (Gkournelos et al. 2021) and masonry (Gkournelos et al. 2022) buildings, was recently published by the authors.

1.1 Policy context

Buildings in Europe are responsible for 36% of the CO2 emissions share, and consume 40% of the EU energy consumption (Directive 2018/844). This huge environmental burden is largely attributed to the low energy performance of old existing buildings, with one-third of them being over 50 years old (Economidou et al., 2011). At the same time, in Southern Europe, collapses or serious damage of existing buildings during strong earthquakes have resulted in significant economic losses and loss of human lives. With demolition and rebuilding being neither an economically viable nor an environmentally friendly solution at large scale, renovation and retrofit strategies are necessary to address the ageing of the EU building stock. Towards this direction, **the European Green Deal** (Communication 2019/640) emphasises the need to engage in a Renovation wave of the existing buildings (Communication 2020/550). Also, the updated Energy Performance of Buildings Directive (EPBD, Directive 2018/844) indicates that, besides reducing greenhouse gas emissions, the Member States should address potential seismic risks when planning their long-term renovation strategies for buildings.

Moreover, the importance of safeguarding the built heritage is also a key outcome of The European Year of Cultural Heritage 2018 (Decision 2017/864/EU). In its follow-up, a European Framework for Action on Cultural Heritage was established (SWD 2018/491), emphasising the need to safeguard our built heritage against natural disasters and climate change. Combined seismic and energy retrofitting of cultural heritage buildings is also explicitly addressed in the Orientation Paper of the Urban Agenda Partnership on Culture and Cultural Heritage (formed in 2019); with reference to the JRC project iRESIST+ in both the SWD and the Orientation Paper. Therefore, it is expected that the future Urban Agenda Action Plan and the Action Plan on Cultural Heritage will recognise the importance of promoting integrated renovation measures.

1.2 Seismicity in the EU

1.2.1 Geophysical information

Seismicity in the European continent can easily be explained by observing its tectonic plates. Europe's mainland is situated on the western part of the Eurasian plate and only Iceland lies on the junction of two plates, the Eurasian and North American (see Figure 1).

The most seismically active region of Europe is the southern Balkan Peninsula. Lying on the junction of three plates, namely the Eurasian, the Anatolian and the Aegean, Greece is the most affected country and experiences moderate to strong earthquakes regularly (see Figure 2). Next to Greece, Italy is a country with high seismicity as well, as a large number of faults exist along the Appennina mountain ridge, which runs along the whole length of the country. Spain, Portugal, Bulgaria, southern France and Switzerland do experience some earthquake activity, but to a much lesser extent. At the other end of the Mediterranean, Cyprus has quite high seismicity, as it is located just above the junction of the Anatolian and the African Plate.

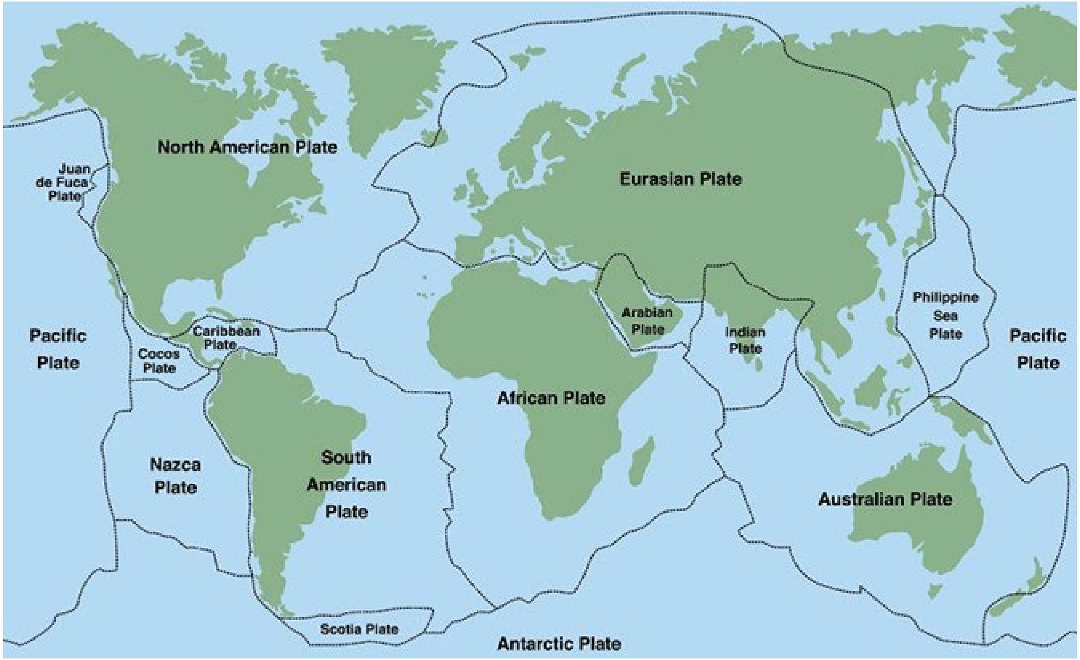
Another seismically active part of Europe is the Vrancea region located in eastern Romania, near the Carpathian mountains. Earthquakes in this region are not as frequent, but they are of significant intensity. Last, but not least, Iceland is a country of high volcanic and seismic activity, as it gets divided by the border of the Eurasian and North American plate.

Another cause of seismicity in the EU is the extraction of gas, which causes small-magnitude earthquakes in the Netherlands.

Figure 3 shows all the recorded earthquakes in Europe since 1998 of magnitude at least equal to or greater than 4. Here, it is obvious that the Balkan Peninsula, Italy, Cyprus, Romania and Iceland are those regions within the European continent that are most affected by earthquakes.

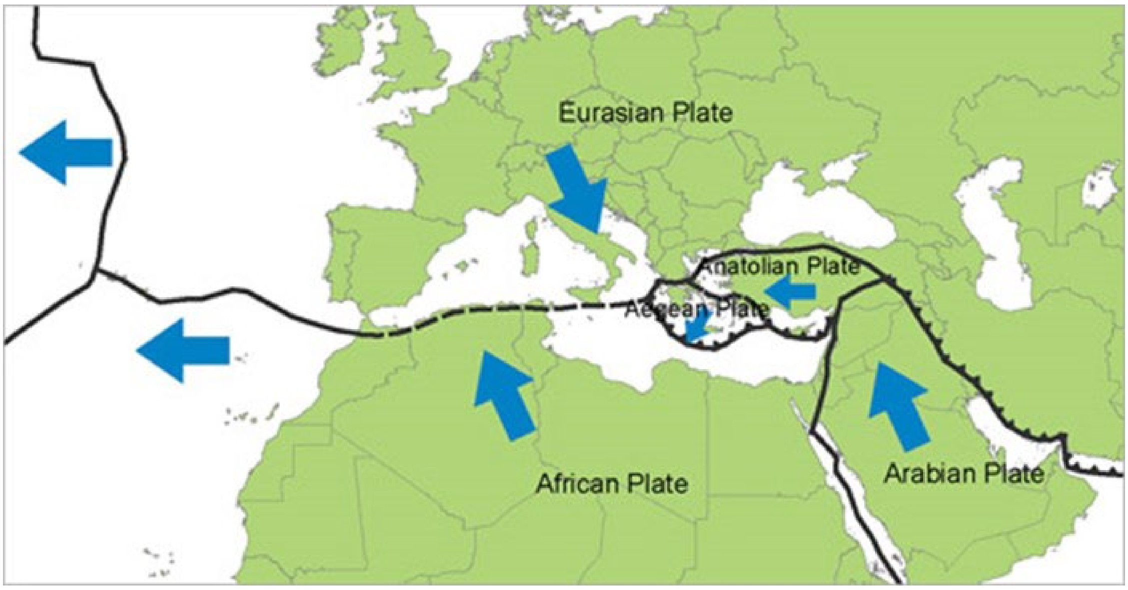
Figure 4 shows the expected peak ground accelerations (PGA) with 10% exceedance probability in 50 years in Europe including Turkey. The regions with the highest seismicity identified above, are the ones that are expected to experience the strongest ground shaking in terms of PGA values as well.

Figure 1. Tectonic plates of the globe



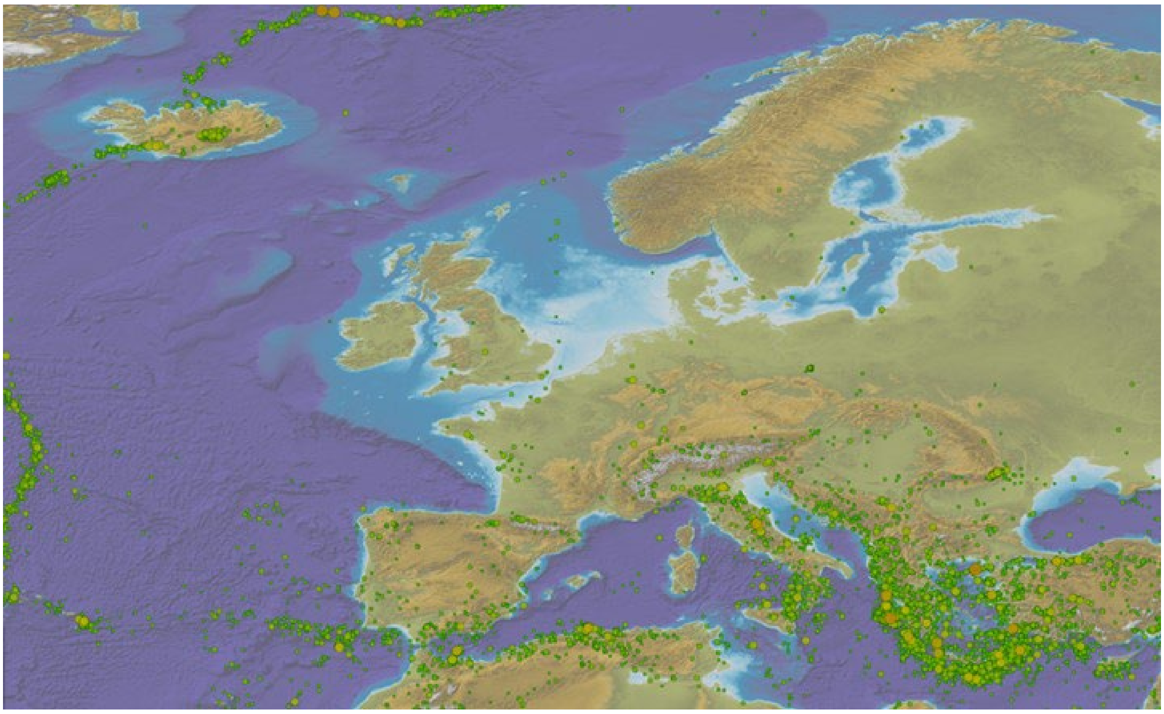
Source: https://www.worldatlas.com.

Figure 2. Tectonic plates of southern Europe



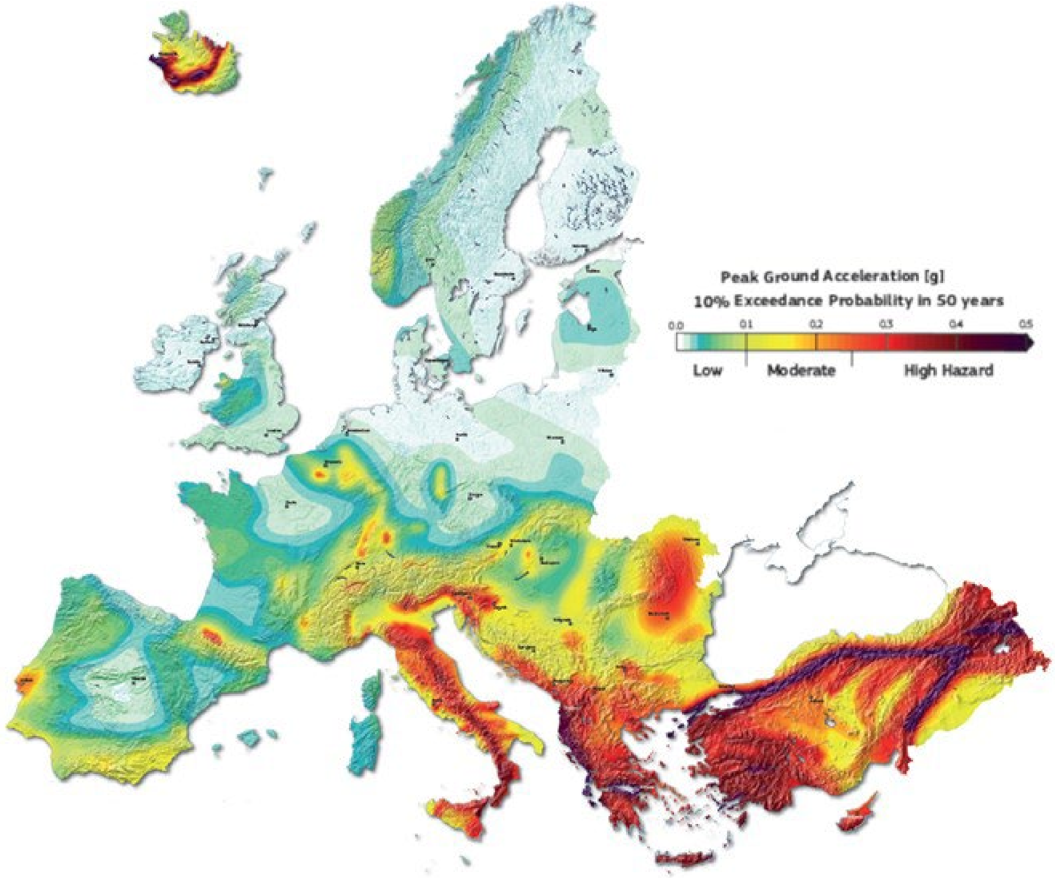
Source: http://eurasiatectonics.weebly.com.

Figure 3. Map of earthquakes with magnitude >4



Source: https://www.seismicportal.eu/.

Figure 4. Seismic Hazard map of Europe



Source: *EU-FP7 project Seismic Hazard Harmonization in Europe (SHARE).*

1.2.2 Earthquakes in the EU

The European territory has been struck numerous times in the past by earthquakes, which have led to extensive damage to the infrastructure as well as to human casualties. Most events were of magnitude less than 7.0, yet due to the poor design of buildings as well as the low quality of the construction materials, their effects proved to be devastating. The next paragraphs list the countries that have experienced the heaviest damage and casualties by earthquakes in Europe's recent history, since 1900.

1.2.2.1 Italy

Despite not being the most seismically active country, Italy has experienced the greatest by far human losses in modern European history. Since 1900, more than 39 deadly earthquakes have occurred, claiming the lives of more than 110,000 people. The average magnitude of those earthquakes has been 5.8, an admittedly low number, which exposes the structural deficiencies and the lack of seismic design in the Italian building inventory.

By far, the deadliest event was the 1908 Messina earthquake (magnitude 7.1), in which at least 80,000 lives were lost, followed by the 1915 Avezzano earthquake (magnitude 6.7), which took the lives of 30,000 people. During the more recent years, Italy has, among others, experienced the following shocks:

- 1968 – Western Sicily, an M5.5 earthquake kills almost 300 people.
- 1976 – Friuli, the main event of M6.5, along with the two aftershocks of M5.7 and M5.9 kill more than 900 people.
- 1980 – Irpinia, an M6.9 event claims the lives of almost 3,000 people.
- 2009 – L'Aquila, an M6.3 event kills 309 people.
- 2016-2017 – Central Italy earthquake, two main events of M6.0 and M6.5 kill 299 people (Di Bucci et al., 2021).

1.2.2.2 Romania

Romania has experienced a much smaller number of earthquakes, but almost all of them have been of high magnitude. In total, 5 deadly events have taken place since 1900, in which more than 2,500 people have lost their lives. The average magnitude of these events was 7.0, an admittedly high one, but thanks to the low people density of the affected regions, the death toll was not higher.

The most seismically active part of the country, Vrancea county, has had four out of the five major events mentioned above, which are listed below:

- 1940, an M7.7 event kills 1,000 people.
- 1977, an M7.4 event kills more than 1,500 people.
- 1986, an M7.1 event kills 2 people.
- 1990, an M6.9 event kills 14 people

The last and most recent seismic event in Romania, took place in Banloc, Timis County (western part of Romania), and cost the lives of 2 people.

1.2.2.3 Greece

The most seismically active country of Europe, Greece has had a total of 18 deadly earthquake events since 1900. These events had an average magnitude of 6.6 and costed the lives of a little short of 1,500 people.

The deadliest events of the last century were the 1932 Ierissos earthquake (M7.0 and almost 500 casualties), the 1953 Kefalonia earthquake (M6.8 and almost 500 casualties) and the 1999 Athens earthquake which killed 143 people. Other milestone events were those of Thessaloniki in 1978 (M6.2, 49 dead), Kalamata in 1986 (M6.0, 23 dead) and Aegion in 1995 (M6.5, 26 dead).

1.3 The EU building inventory

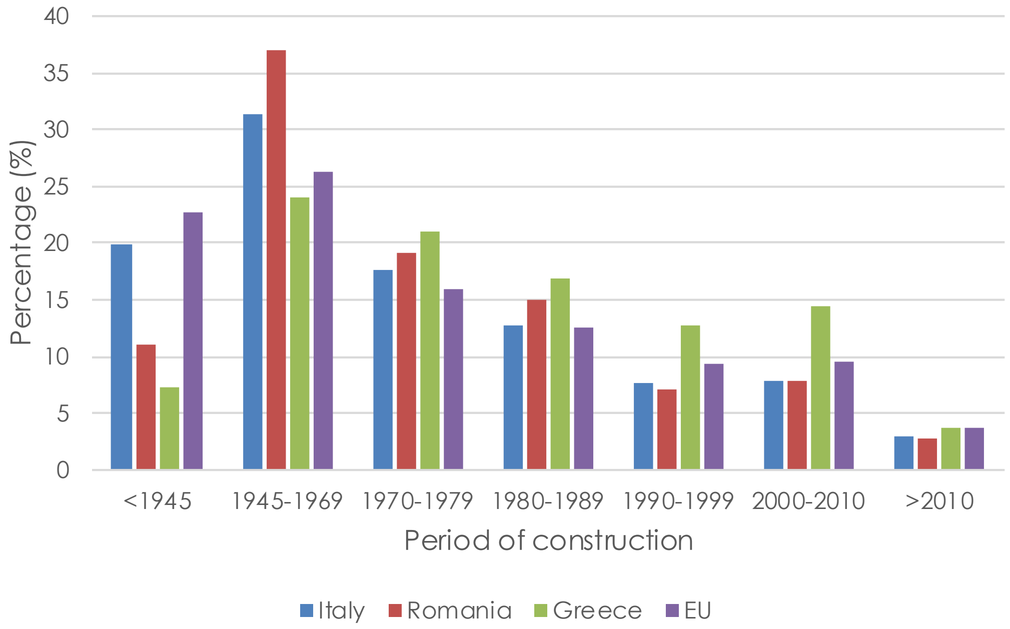
1.3.1 Building demographics

According to the EU Buildings Observatory of the European Commission, around 75% of the existing buildings are used for residential purposes, with an actual percentage that varies from country to country and ranges from 61.6% up to 91.2%.

Concerning their age, most buildings were built during the post-war period 1945-1969 and almost half of today's standing structures are already 50 years old. This means that a very large percentage of the EU building inventory has already exhausted the conventional service life that buildings are normally designed for.

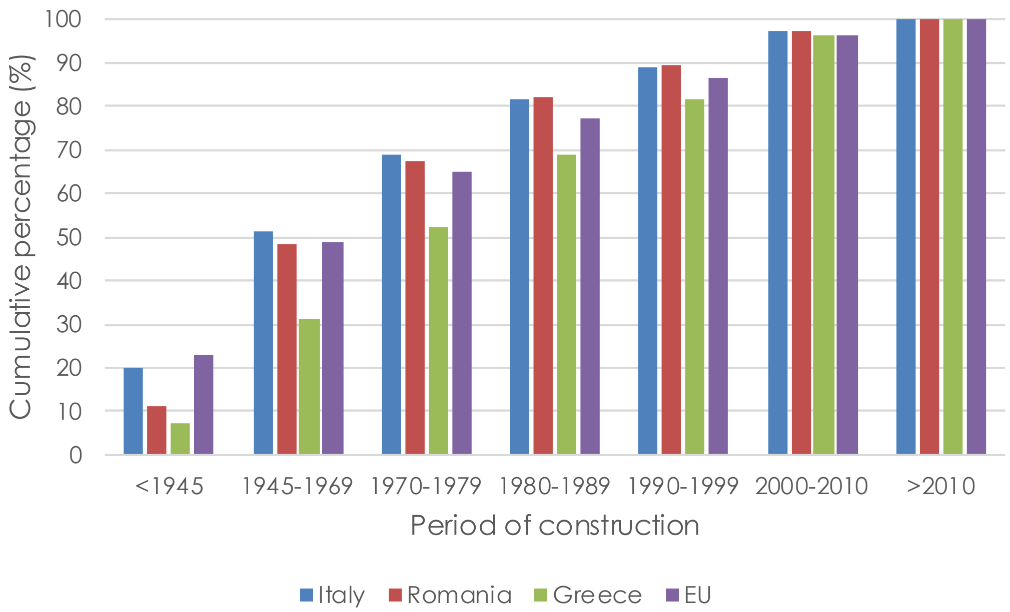
Figures 5 and 6 show the percentages and cumulative percentages respectively, of buildings constructed at various time intervals. The EU average is given along with the specific values for the three seismic countries discussed earlier, and as it can easily be seen, the trend is roughly the same for all four cases. Here, it becomes obvious that there is a very large amount of existing buildings which, apart from being old and close to the end of their service life, have been constructed using outdated seismic provisions (see Section 1.2.2) and are therefore potentially vulnerable against future ground motions.

Figure 5. Bar chart of EU building ages



Source: *EU Buildings Observatory.*

Figure 6. Cumulative bar chart of EU building ages



Source: *EU Buildings Observatory.*

Taking the above into consideration, it is not surprising that roughly half of the total construction budget in the EU is expected to be consumed in the repair and maintenance of the existing infrastructure (European Parliament 2016).

1.3.2 Seismic standards for buildings

The field of earthquake engineering is a relatively young one, as it was practically born after the strong earthquakes of the 20th century, which rendered its existence necessary. During the same time, the first seismic codes started to be issued and employed in practice, yet they were inadequate to tackle the earthquake problem efficiently. Therefore, they went through a history of numerous revisions, each time getting stricter until today that they have "matured" to a large extent. The next paragraphs describe briefly the seismic code history in Italy, Romania and Greece, the EU countries with the highest seismicity, as examples.

1.3.2.1 Italy

Interestingly, the first purely engineering recommendations for seismic analysis were made in Italy in 1909, following the 1908 Messina earthquake. At that time, the equivalent static analysis using a percentage of the building's total mass was suggested, a process that dominated until the mid-1970s. The design spectrum was introduced in 1974 and an up-to date seismic code was adopted. Ever since, the seismic zonation has changed various times, reaching today, that a comprehensive probabilistic seismic hazard model exists for the whole country.

1.3.2.2 Romania

In Romania, the first seismic zonation was done after in 1941, after the 1940 Vrancea earthquake, and identified a seismic and a non-seismic area of the country. Then, the first actual seismic regulation appeared in 1963, and was upgraded three times, in 1977, 1990 and 2006. The latest and current regulation was inspired by Eurocode 8, and the country's zonation was based on a probabilistic seismic hazard assessment.

1.3.2.3 Greece

In Greece, the first seismic provisions appeared only in 1959, a few years after the 1953 Kefalonia earthquake. This code, which was based on the equivalent static forces method, was slightly enhanced in 1984 with some additional clauses. Then, the first modern standards were introduced in 1995, just after the Aegion earthquake, and were extended in 2000, when the latest code came into force (called EAK2000). Since 2014, the Eurocodes can be used (if selected so) instead of the national standards, with an aim to fully adopt them in the near future.

1.3.3 Performance in past earthquakes

Over the past years, a number of building damages or even failures and collapses have been observed during strong ground motion events. These failures can be attributed to various reasons, like the use of poor-quality materials, the design using old standards, the use of over-simplified structural models etc.

With regards to **RC buildings**, the following types of damage and structural deficiencies have been observed repeatedly:

- Shear failures of columns and walls, due to lack of capacity design in shear and/or due to minimal shear reinforcement.
- Short/captive columns that fail in shear, because of partially infilled frames.
- Shear failure of joints, due to insufficient reinforcement passing through them.
- Lack of column capacity design, leading to weak column-strong beam frames and reduced redundancy.
- Open ground-storey buildings (pilotis type) – soft-storey mechanisms.
- Pull-out of poorly anchored bars and rebar buckling in areas of low confined concrete.
- Indirectly supported beams.
- Staircase-related damage, due to the introduction of torsional effects, short columns etc.
- Infill wall failure out-of-plane due to their previous in-plane damage and lack of engineered resistance.

Unreinforced masonry (URM) as a building material is very similar to unreinforced concrete, as it has a considerable compressive capacity, but negligible tensile one. This lack of tensile reinforcement is the reason behind many structural deficiencies and failures observed in URM buildings, especially during earthquake events. Various different members and damage types can be identified in this figure, like for instance:

- In-plane flexure and shear of pillars (column-like elements).
- In-plane flexure and shear of lintels (beam-like elements).
- In-plane shear of walls.
- Out-of-plane flexure of walls.
- Separation of walls.

In-plane (IP) actions in masonry result mainly in cracking. These cracks can be unacceptable from a serviceability point of view, but in most cases do not compromise the overall stability of a building. On the other hand, the out-of-plane (OOP) response of walls is a much less predictable phenomenon with far more dangerous possible outcomes, including partial collapses.

Although **steel** (and steel-concrete composite) **structures** are increasingly considered as a suitable solution for buildings in high seismicity areas (due to the very good strength and ductility exhibited by steel, the high quality assurance guaranteed by the industrial production of steel profiles and the reliability of connections), they have suffered significant damage in past earthquakes. Damage was varied and widespread in many elements, ranging from columns, braces, beams, and beam-to-column connections.

The above-mentioned damage types that have been observed over the years, along with the numerous experiments that have been conducted in various laboratories around the academic world, have provided a great insight to our understanding about the response of RC, URM and steel buildings to earthquakes. These failures have led to the birth of earthquake engineering and in turn to the modern seismic codes we use today in our societies.

The poor past performance of the building inventory has made it clear that old structures located in seismic areas are in urgent need of seismic retrofitting. It is therefore of outmost importance that the involved member states invest funds and resources towards mitigating the seismic risk in the near future.

1.4 Seismic upgrading strategies

The damage and failures that occurred during the earthquakes of the recent past, rendered necessary the development of seismic retrofitting techniques, so that vulnerable buildings could be protected against possible future earthquakes. As a result, the academic field of seismic strengthening was born and since then has attracted a lot of interest both in the academia as well as in the everyday engineering practice.

Seismic upgrading techniques can be divided in two major categories, depending on the way they "treat" the structure. At first, there are the ones that operate at the **element level (Local measures)** and then those that operate on the **structure as a whole (Global measures)**. Obviously, when it comes to upgrading an actual building, various techniques can and should be combined, addressing its specific characteristics, so that an economic strengthening scheme can be designed. Depending on their age as well as the materials employed in each technique, they can also be divided to conventional and novel ones.

Figure 7 illustrates the goals of structural strengthening interventions. When only the deformation capacity of a building needs to be enhanced, then local measures are typically sufficient without generally affecting the building's strength and stiffness, or they affect it marginally. However, if the load capacity and stiffness also need to be increased, global measures will most likely have to be employed, as achieving a much higher lateral load capacity in a structure via local measures alone would be an uneconomical option. Lastly, in cases that both the capacity and ductility of a structure are in need of improvement, then a combination of global and local measures should be employed.

Instead of increasing a building's lateral strength, there is also the alternative of decreasing the earthquake-induced forces, which can be achieved by reducing the mass and/or reducing the lateral stiffness of the structure. Mass reduction can be realized through the use of lighter partition walls, floor removal etc., while stiffness reduction is achieved via the employment of base isolators and energy dissipation systems. In some cases, mass reduction may lead also to stiffness reduction, e.g. when replacing masonry infills by lighter partition walls.

Figure 7. Seismic strengthening goals

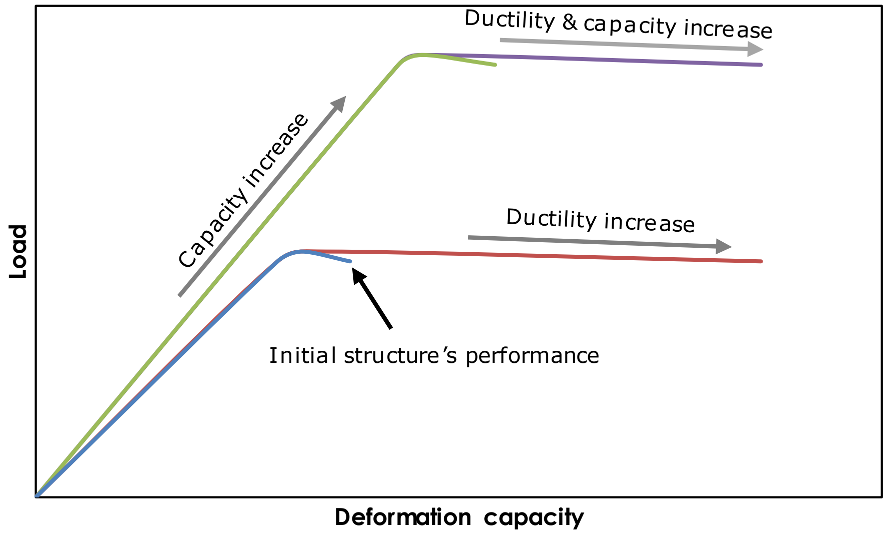


Figure 8 summarises the main categories of seismic strengthening schemes targeting RC buildings. The most common measures are given in Table 1, together with the properties they affect. The symbols + and – indicate a possible beneficial or detrimental effect, respectively, the extent of which will depend on the specific case. More details on most of these measures are described in the next chapters of this report.

Figure 8. Taxonomy of seismic upgrading techniques

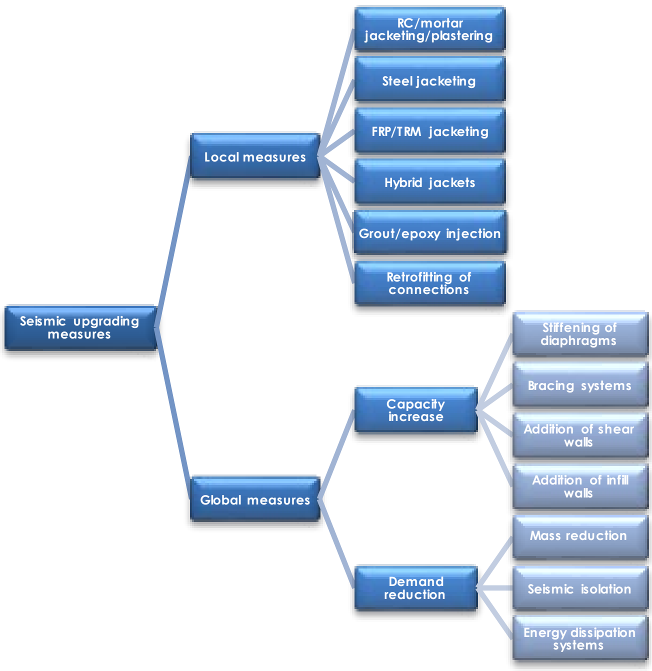


Table 1. Effect of local and global retrofit measures on building properties (partially based on Tsionis et al. 2014).

		Strength	Stiffness	Ductility	Irregu-larity	Force demand	Deformation demand
Local measures	RC/mortar jacketing	+	+	+		-	+
	Steel jacketing	+		+			+
	FRP/TRM/ Hybrid jacketing	+		+			+
	Grout/Epoxy injection	+					
	Retrofitting of connections			+			+
Global measures	Diaphragm stiffening				+		
	Bracing systems	+	+		+	-	+
	Shear walls	+	+		+	-	+
	Infills	+	+		+	-	+
	Mass reduction					+	+
	Seismic isolation					+	-
	Energy dissipation		+			+	+

2 Local measures

Local strengthening comprises measures applied to individual structural elements of a building, in order to improve their mechanical characteristics. By adding for instance, external reinforcement to the existing building member, the strength (e.g. flexural and/or shear) and deformation capacity of the latter increases. Traditional techniques make use of conventional materials like concrete and structural steel are out of scope of this report, whilst novel ones employ more innovative materials like Fiber Reinforced Polymers (FRP), Textile Reinforced Mortars (TRM) etc., and will be described herein.

2.1 FRP-based systems

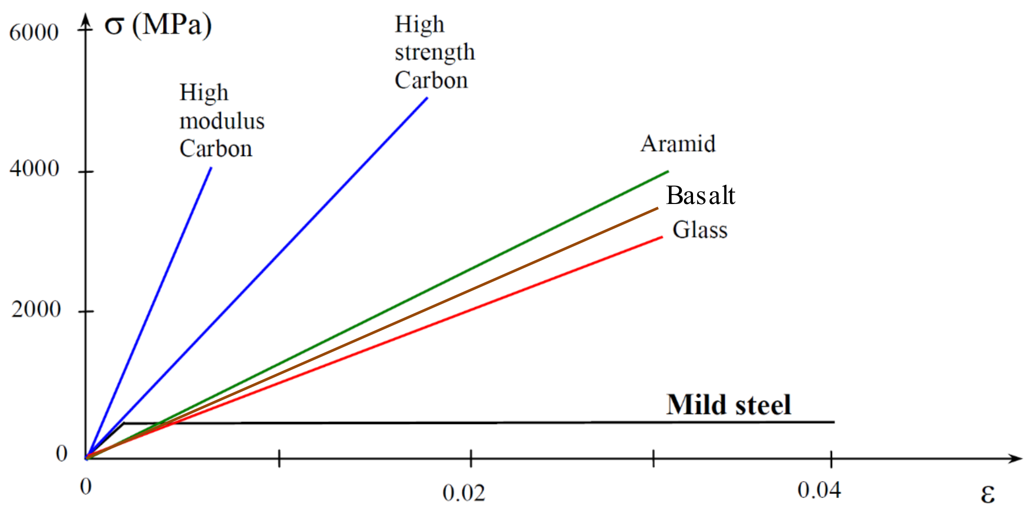
2.1.1 General

Fiber-reinforced polymer (FRP) composites are formed by embedding continuous fibers in a polymeric resin matrix, which binds the fibers together, and comprise today one of the most popular techniques for the seismic upgrading of individual RC, URM and steel elements. When compared to traditional retrofitting methods, FRP are a very competitive alternative, as they offer ease and speed of installation, less labor work, minimum geometric changes, very high strength to weight ratio and minimum occupancy disruption (e.g. Triantafillou 2001). On the other side, they exhibit very poor behavior when exposed to high temperatures, in which case they need protection, and demand high quality work to be performed by experienced personnel).

2.1.2 Fiber types

The most commonly used fiber type in seismic upgrading applications is carbon (CFRP), due to its high elastic modulus and excellent durability; however, it is the most expensive material as well. Another, less costly option is to use glass or basalt or even polymeric fibers. All of them have considerably lower moduli of elasticity (roughly 3, 2.5 and 200 times lower than carbon for glass, basalt and polyethylene, respectively), lower strength, and some of them (glass and basalt) need to be protected against alkali corrosion with some kind of coating. For the case of masonry strengthening, low modulus fibers are very interesting solutions, probably the most reasonable to implement in real structures. Typical stress-strain curves for various types of fibers are given in Figure 9.

Figure 9. Typical σ-ε curves for various types of fibers



Source: Lecture notes, T. Triantafillou.

2.1.3 Strengthening methods and material types

2.1.3.1 Reinforced concrete retrofitting

2.1.3.1.1 General

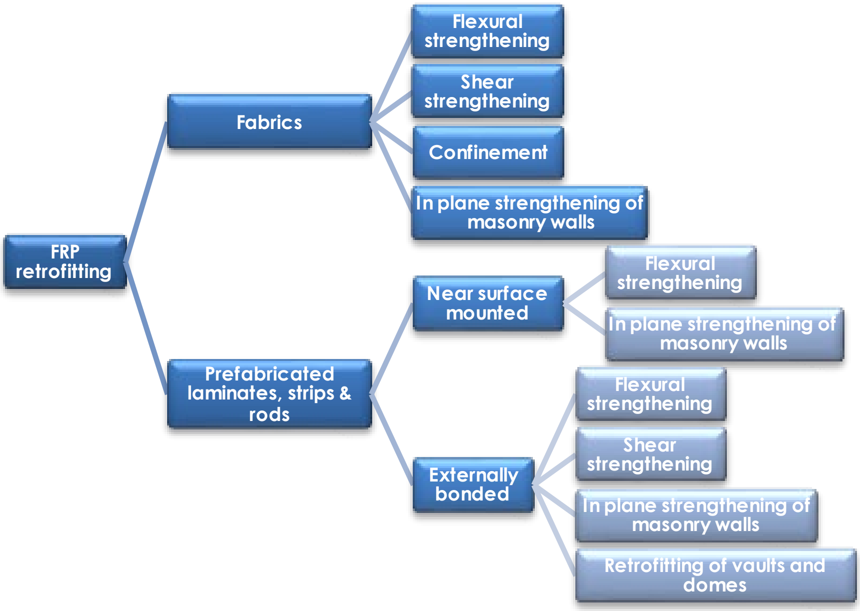
FRP are normally used in the field of member strengthening as externally bonded reinforcement (EBR) and can be applied (typically) in two distinct ways. The first and most frequent is to use FRP in the form of fabrics (Figure 10a) and attach them to the concrete substrate using epoxy resins. This way, they can be used as shear reinforcement in beams and columns with insufficient stirrups in order to ensure a ductile flexural response. Moreover, when wrapped around columns they provide confinement to the inner concrete and that way significantly increase the section's ductility. Alternatively, and rather rarely in seismic retrofitting, FRP can be used in the form of prefabricated laminates, strips or bars (Figure 10b) to act as external longitudinal or transverse reinforcement in existing elements and thus increase their flexural or shear capacity. Strengthening solutions with FRP are summarized in Figure 11.

Figure 10. (a) Wrapping of RC columns and (b) Flexural and shear strengthening with FRP laminates

(a) (b)

Source: Lecture notes, T. Triantafillou.

Figure 11. FRP strengthening roadmap



2.1.3.1.2 Seismic retrofitting with FRP

When it comes to seismic retrofitting, FRP have been proved to be most effective when they are used in the form of sheets as shear reinforcement or as a means to provide extra confinement. A review on seismic retrofitting of RC with FRP is given in Triantafillou (2001) and a more detailed treatment on the subject is presented in Pantazopoulou et al. (2016) and in *fib* (2019).

2.1.4 Masonry retrofitting

Fiber reinforced polymers can be used successfully for the structural upgrading of URM structures, as experimental studies have shown that they can dramatically increase both the flexural and shear resistance of masonry walls and curved elements, such as arches, vaults and domes. Moreover, FRP jackets may be used to enhance the capacity of masonry columns through confinement. In addition to increasing strength, FRP have been successful in increasing the deformation capacity of masonry substantially. If the above are combined with their excellent durability properties, minimal weight and low disturbance during their application, one can easily understand why these materials are getting more popular over time. Typical FRP applications on masonry buildings are given in Figure 12.

Figure 12. FRP retrofitting of masonry: (a) In-plane shear strengthening with diagonal and possibly vertical/horizontal strips; (b) near-surface mounted FRP strips;

2.1.5 Steel members retrofitting

2.1.5.1 General

The main advantage of FRP over steel in such applications is the high strength and stiffness to weight ratio, leading to ease and speed of transportation and installation, the immunity to corrosion, and the ability of the material to follow curved and irregular surfaces; this is difficult to achieve using steel plates. Another advantage is that its material properties in different directions can be tailored for a particular application. As a result, FRP jackets with fibers oriented only or predominantly in the circumferential direction can be used to confine steel tubes/shells or concrete-filled steel tubes to delay or eliminate local buckling problems, thereby enhancing the strength and/or seismic resistance of such structures (e.g. Teng et al. 2012).

2.1.5.2 Flexural strengthening

Similar to an RC beam, a steel beam (or a steel-concrete composite beam) can be strengthened by bonding an FRP (generally CFRP) plate to its tension face (i.e. the soffit if a beam in positive bending is assumed), e.g. Linghoff et al. (2009). The bonded FRP plate can enhance not only the ultimate load but also the stiffness of the beam (especially when a high modulus CFRP is used); the latter means that the strains in the beam are reduced under the same load and the first yielding of the beam is delayed. A number of failure modes are possible for such FRP-plated steel beams, including in-plane bending failure, lateral buckling, plate-end debonding, intermediate debonding due to local cracking or yielding, and local buckling of the flange or the web. It should be noted that even if a beam for which local buckling modes are not critical before FRP strengthening, they can become critical when the strengthening involves only the bonding of FRP to the tension flange only.

2.1.5.3 Connection retrofitting

Surveys carried out in the aftermath of strong earthquakes, e.g., the 1994 Northridge (California) and the 1995 Hyogoken-Nanbu (Japan) quakes, showed that extensive brittle fracture developed at connections, particularly welded flange - bolted web beam-to-column (Youssef et al. 1995). Moreover, surveys carried out during past earthquakes showed that braced frames, particularly concentric braced frames, exhibit extensive damage (e.g. fracture at bolt holes, weld fracture, local buckling etc) at bracing connections if they are not properly designed (Tremblay et al. 1996).

Improved beam-to-column connection details shift the beam plastic hinge away from the face column. Such details may be grouped in two categories as a function of the rehabilitation measure adopted: weakening of the beam section at a certain distance from the column flange and strengthening of the beam section at the column face. Strategies to repair beam-to-column connections in existing buildings, as reported in FEMA 351 (2000). Information on bracing connections may be found in Di Sarno and Elnashai (2002).

2.2 TRM-based systems

2.2.1 General

Despite their great success and popularity, FRP still suffer by a number of disadvantages, which make their application difficult or even impossible in some cases. Probably the most important one is their vulnerability to high temperatures, which results in their complete disintegration in case of fire, if no fire-protection measures have been employed. The high cost of the epoxy resins also increases considerably the overall cost of the intervention method, especially when large material quantities are necessary. Apart from that, the inability to apply these materials on wet surfaces or at low temperatures combined with the fact that experienced personnel is required, makes their employment in practice even more difficult. In addition, the incompatibility of epoxy resins and some substrate materials, as well as restrictions related to intervention strategies for historic masonry buildings (e.g. requirements for reversibility), may possibly inhibit the success of FRP application on RC or masonry.

A possible solution to address the above-mentioned issues is to use the same fibrous materials (carbon, glass, basalt etc.) in the form of textiles embedded in cementitious mortars, instead of fabrics impregnated in epoxy resins. These textiles are essentially fabric meshes made of long woven, knitted, or even unwoven fiber rovings in at least two (typically orthogonal) directions. The density (quantity and spacing) of rovings in each direction can be controlled independently, thus affecting the mechanical characteristics of the textile and the degree of penetration of the mortar matrix through the mesh. The end material is called Textile Reinforced Mortar (TRM).

TRM have demonstrated superior performance than FRP as strengthening materials at high temperatures (e.g. Tetta and Bournas 2016, Raoof and Bournas 2017a,b, Cerniauskas et al. 2020), whereas the TRM mechanical behaviour has also been found satisfactory after exposure to fire (Triantafillou et al. 2017, Kapsalis et al. 2019). Figure 13 illustrates the application of TRM in RC and masonry buildings, respectively.

Figure 13. Applications of TRM jacketing on (a) RC column and (b) masonry wall


(a)


(b)

2.2.2 Strengthening of RC members

The use of textiles as tensile reinforcement for the fabrication of new RC elements is not new, however their employment in the field of seismic retrofitting of existing elements has been examined only during the last 15 years. As with FRP, TRM applications regarding the seismic retrofitting of existing RC members target two main areas: providing confinement to the inner concrete section and increasing the member's capacity in shear.

Triantafillou et al. (2006) investigated concrete TRM confinement on unreinforced concrete, reporting that TRM jackets can provide a substantial gain in the compressive strength as well as deformation capacity of concrete cylinders, with that gain being higher as the number of the confining layers increases. Those findings were confirmed by Bournas et al. (2007, 2009) who studied the effectiveness of TRM jackets as a means of confining RC columns with limited capacity and also compared them to FRP jackets. A significant increase was again observed both in terms of strength and ultimate deformation. Moreover, when compared to FRP jackets of equal stiffness, TRM jackets were found to be slightly less effective (by about 10%) in terms of increasing strength and deformation capacity.

As far as shear strengthening is concerned, several studies demonstrated that TRM jacketing is highly effective in enhancing the shear capacity of RC members (e.g. Triantafillou and Papanicolaou 2006; Tetta et al. 2015, 2016; Tzoura and Triantafillou 2016). A simple design method for the for the calculation of the contribution of TRM jacketing to the total shear resistance of RC beams is presented by Tetta et al. (2018). A detailed treatment of TRM and their use in seismic retrofitting can be found in Koutas et al. (2019).

2.2.3 Strengthening of masonry members

A critical aspect of TRM-retrofitted masonry is the bond between TRM overlays and masonry substrates. Bond failure may appear macroscopically as loss of cohesion due to either shear failure of the substrate or the inorganic matrix, or sliding of the fibre reinforcement inside the inorganic matrix. Another possible failure mechanism, albeit not due to debonding, is the rupture of the textile. Studies on TRM-masonry bond have been recently performed (e.g. D'Ambrisi et al. 2013, Askouni and Papanicolaou 2017).

Strengthening of URM walls subjected to out-of-plane or in-plane loading (e.g. Papanicolaou et al. 2007, 2008, Kariou et al. 2018) have proved that TRM overlays are extremely effective in increasing the strength and the deformation capacity of URM walls and masonry arches (e.g. Kariou et al. 2019), while TRM jacketing was also recently proved very effective for the confinement of masonry columns (Koutas and Bournas 2020). Design methods are presented e.g. in Triantafillou (2016) and Kouris and Triantafillou (2019), whereas an overall review of the state-of-the-art on the topic is given in Kouris and Triantafillou (2018).

3 Global measures

When a drastic increase in the lateral load capacity of a structure is needed, local retrofitting measures alone are either inadequate or usually require extended interventions which make the total retrofitting cost prohibitive. In such cases, global measures should be selected, aiming at either increasing the structure's lateral strength or decreasing the seismic demand.

The former is typically achieved by designing and adding new structural elements to the existing building, thus significantly increasing its lateral stiffness and resistance. In this category fall various retrofitting techniques, like the addition of metallic bracing systems, concrete shear walls and the infilling of existing frames with reinforced masonry. The new structural elements are designed to undertake the majority of the seismically induced loads by controlling their stiffness. Therefore, the existing ones are relieved and practically contribute only as vertical load bearing elements.

The alternative of decreasing the earthquake induced forces to a given structure in the first place, is normally achieved through the employment of base isolation systems or energy dissipating devices (dampers). Due to their relatively high cost, such approaches are normally used for the rehabilitation of critical and essential facilities, with expensive and valuable equipment, or structures where performance well above normal performance levels is required.

A state-of-the-art review of global retrofitting schemes is provided in the subsequent sections, which are applicable to RC, masonry and steel buildings. Again, both traditional and innovative techniques will be analyzed, but more emphasis will be placed on the latter.

3.1 Capacity increase

3.1.1 Addition of bracing systems for RC and steel buildings

Adding a bracing system within selected frames of RC and steel buildings appears to be an effective way for enhancing their stiffness and strength characteristics. The added elements can be designed to fully take up the lateral loads, however, great care must be paid to their connections as well as to the increased axial loads, which will be induced to the columns. Moreover, given that in such intervention the works are normally done on the outside frames of the structure, the loss in living space area and the occupancy disruption are minimal.

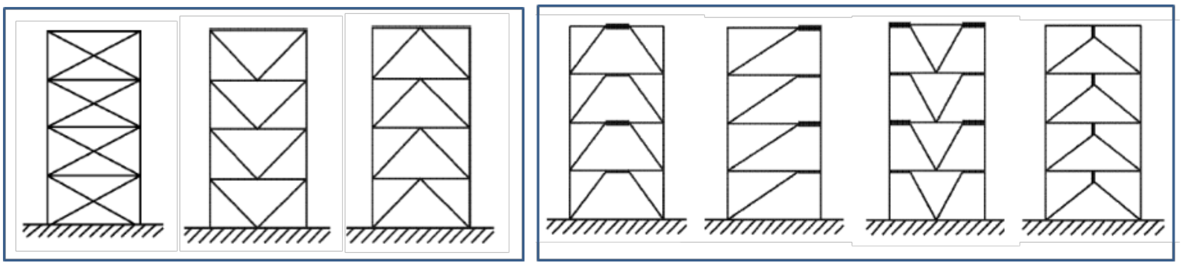
A number of different bracing types exist and can be employed to RC and steel buildings. The most usual is that of concentric bracing (Figure 14a), in which the horizontal seismic forces are resisted by axially loaded members. Alternatively, eccentric braces (Figure 14b) resist the horizontal forces by a combination of axially loaded members and shear links, which are used as energy dissipating mechanisms. Different bracing types can be applied to RC and steel structures: V and inverted V-bracings should be used with caution because of the likelihood of damage in the beam mid-span for steel structures.

Concentrically braced frames (CBF) should be designed according to EC8 (1998). However, it is recommended (Goel 1992) to provide at least 50% of the tensile capacity in compression, for the sake of satisfactory hysteretic behavior. Eccentrically braced frames (EBF) exhibit excellent performance under earthquake loads because of the high ductility and energy dissipation capacity. In EBF the braces intersect the beam at an eccentricity e, hence the link beam, i.e. the length of the beam defined by e, behaves in shear and/or bending. The link acts as a fuse by yielding and dissipating energy and prevents buckling of the braces. While retaining the advantages of CBF in terms of drift control, EBF represent an excellent configuration for failure mode control; yet they offer a higher degree of flexibility in locating openings. The lateral stiffness of EBF may be calibrated by varying the length of the link beam; reductions of interstorey drifts more than 50% may be achieved with short links. Design rules for detailing the link beams should conform to EC8 (1998).

Eccentric braces, when designed correctly, do not exhibit buckling failure types. However, they do that in the expense of the frame's lateral stiffness, which in some cases might be necessary. A possible solution to that is to use concentric buckling-restrained braces (BRB). BRB are considered among the state-of-the-art retrofit options, because they have fully balanced hysteretic behavior for both tension and compression even after large inelastic deformations (e.g. Uriz and Mahin 2008).

Bouwkamp et al. (2001) investigated experimentally the efficiency of eccentric, inverted Y braces as a means to retrofit RC buildings without seismic design. They used a set of steel beams, diagonal elements and a ductile shear link to replace a masonry infill in one bay of the structure. The bracing system was designed to have the same shear resistance, but considerably higher ductility. The authors reported that the retrofitted structure exhibited satisfactory post-peak behavior and higher drift capacity. Furthermore, the shear link was reported to have dissipated 45% of the total energy dissipated in the structure.

Figure 14. (a) Concentric and (b) eccentric bracing systems

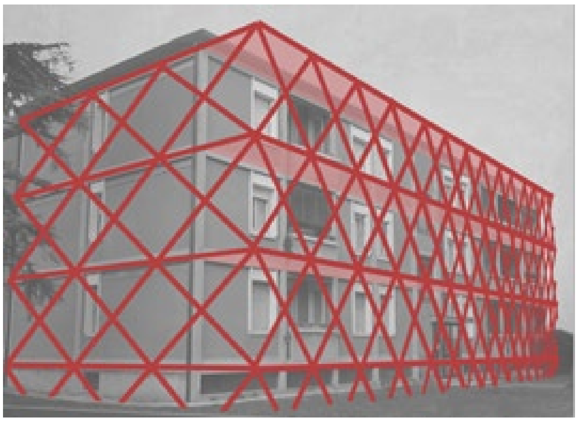


To address the problem of buckling, which is inherent in braces, buckling-restrained braces have been developed and constitute another viable option. Last, but not least, post-tensioned rods or prestressed cables is a relatively new retrofitting scheme which can also be employed to solve buckling-related problems.

3.1.1.1 Diagrid exoskeletons

A recently proposed retrofitting scheme for RC frames involves the application of diagonal grids ("diagrids") from the outside of existing RC buildings, in the form of a 3D lattice structure, called exoskeleton (Figure 15). Diagrid diagonal members are designed to intersect at floors, where they are connected to steel horizontal ring beams, which have the double function to stabilize the diagrid exoskeleton and to collect and transfer the seismic forces from the building floor diaphragms to the diagrid and to a new foundation system. Diagrid exoskeletons may be combined with thermal insulation, to offer integrated solutions for combined seismic and energy retrofitting (e.g. Labo et al. 2016, 2017, Marini el al. 2017).

Figure 15. Concept of the diagrid exoskeleton



Source: Courtesy A. Marini, Univ. Bergamo.

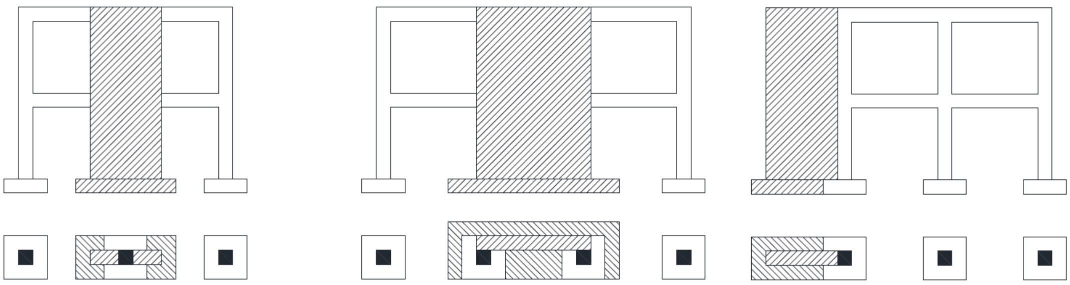
3.1.2 Addition of RC shear walls

Adding shear walls is an alternative to using braces as lateral load resisting mechanisms for RC and steel buildings. The new elements are designed to resist the majority of seismic loads so that the existing elements only play a secondary role. Shear walls are very effective in reducing interstorey drifts, mitigating irregularities, and preventing soft-storey failure mechanisms. However, their application may be time consuming with high labor costs and significant obstructions to the buildings' occupancy.

3.1.2.1 New shear walls in RC frames

New shear walls can be constructed around an existing column, on the external side of a selected frame or externally of the building as buttresses (see Figure 16). It is very important that the new elements are properly connected to the structure as well as adequately supported to the ground with new, strong foundations.

Figure 16. New RC shear walls (a) placed around a column, (b) external to the frame, (c) as buttress



Bush et al. (1991) performed experiments on two-storey RC frames with weak columns, in which RC shear walls were built around the existing columns (Figure 16a). The authors reported that the lateral strength and stiffness was significantly increased and that a beam-sway mechanism was achieved. They also observed monolithic response, yet they proposed a conservative procedure for the design of the anchors.

Kaltakci et al. (2008) conducted cyclic loading experiments on two-storey RC frames, strengthened with external, buttress-like shear walls (Figure 16c). They observed a significant increase in the strength and stiffness of the retrofitted specimens, compared to the as-built one. It is claimed that the proposed retrofitting scheme causes very little occupancy disturbance, as most of the strengthening works are performed externally to the structure.

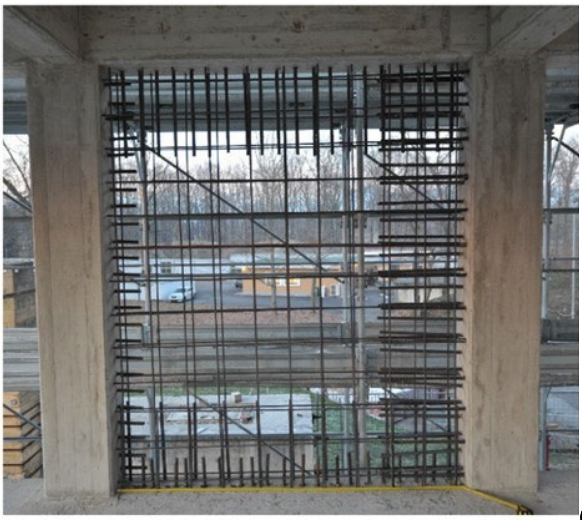
More recently, Kaplan et al. (2011) tested a two-storey RC building strengthened with an RC shear wall which was constructed on the exterior side of its middle bay (Figure 16b). They reported a 200% increase in the structure's lateral strength and a seven times higher stiffness. Failure occurred along with shear sliding at the base of the wall after the rupture of its longitudinal reinforcing bars.

For a more detailed treatment of seismic retrofitting with shear walls the reader may refer to the JRC report presented by Tsonis et al. (2014).

3.1.2.2 RC infilling of bays

Shear wall RC elements can also be constructed within existing RC frames, thus creating an infill with high lateral strength and stiffness. In the framework of SERFIN project, Poljanšek et al. (2014) conducted pseudo-dynamic experiments on a large-scale, testing a 4-storey, 3-bay RC building, at ELSA lab of the JRC. The mid-bay was infilled at its whole length with an RC wall having the same width (250 mm) as the surrounding columns and beams (Figure 17). Dowels and starter bars were used for connecting the new element to the existing RC frame (Fig. 17). Their distribution was variable along the height of the structure and CFRP U-jackets were constructed at the ground level, at the column bases. The authors reported that the strengthened building was able to sustain a 0.25g earthquake without any significant damage. Moreover, the connection of the wall behaved satisfactorily. It was concluded that the RC infilling technique is an effective technique for seismic strengthening of substandard and/or flexible RC frames.

Figure 17. Serfin Project: (a) RC infill wall dowels and web reinforcement; (b) Prototype testing


(a)

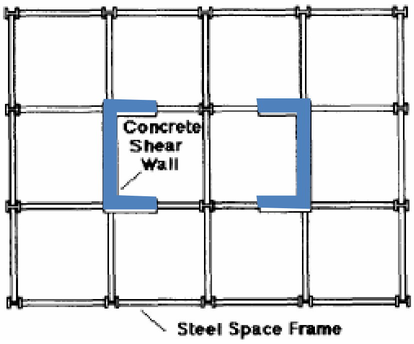
(b)

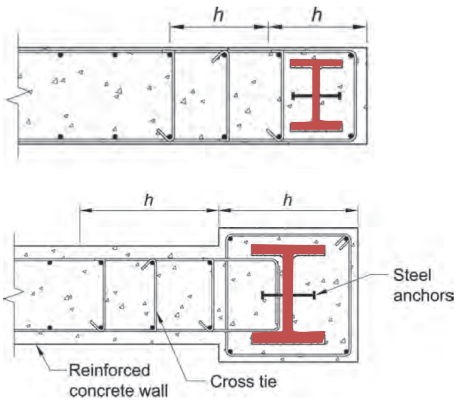
Source: Poljanšek et al. (2014).

3.1.2.3 Reinforced concrete shear walls in steel frames

Steel frames may be retrofitted by constructing RC shear walls, thus efficient dual systems are obtained (Figure 18a). In such hybrid systems the RC core provides strength and stiffness for resisting earthquake loads, while the steel frame provides ductility (e.g. Roeder 1998). The enhanced stiffness, particularly for structures designed originally only for gravity and wind loads, allows floor drifts to be controlled. However, the added mass is significant, hence, higher seismic forces are attracted, and significant upgrading of the foundations is required. For instance, it may be required to modify shallow foundations of existing frames into deep foundations on piles; the walls present high overturning moments when loaded horizontally.

Figure 18. (a) Dual system with steel frame and RC shear walls. (b) RC wall with fully encased steel columns





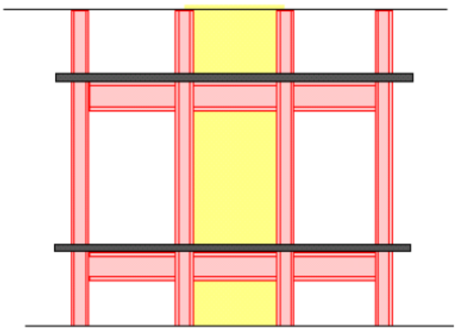
(a) (b)

Typically, RC walls are connected to fully encased structural steel members, as shown in Figure 18b for columns. Adequate steel reinforcement and connectors are required at the connection of the wall with the steel members. For instance, cross ties should be placed in the wall for a length equal to the section width. This requirement avoids undesirable splitting along vertical planes inside the wall near the columns. Moreover, shear studs provide a uniform transfer of forces between the RC wall and the boundary members. The strength, stiffness and the dissipative capacities of dual systems are comparable to those of pure RC walls. The in-plane strength of the columns is enhanced by the composite action with the wall. These boundary members are also effective to delay the flexural hinges in slender walls. Detailing should comply with the requirements for the design of new buildings (EC8 1998).

3.1.2.4 Steel plate shear walls in steel buildings

The selection of novel Steel Plate Shear Walls (SPSW) as the primary lateral force resisting system in steel buildings has increased in recent years as design engineers discover the benefits of this option. The response of SPSW under horizontal loads is similar to a vertical plate girder (Figure 19) in which the columns act as flanges, the steel plate is the girder web and the floor beams act as transverse stiffeners. They provide additional stiffness, strength and enhance the energy dissipation capacity of frames to which they are connected. The low weight of steel panels reduces the inertial loads on the retrofitted structure and gives rise to lower additional loads to existing columns and foundations if compared with traditional concrete or masonry shear walls.

Figure 19. Steel plate shear walls



3.1.2.5 Slitted shear walls

Slitted shear walls consist of a steel plate shear wall with vertical slits. In this system, the steel plate segments between the slits behave as a series of flexural links, which undergo large flexural deformations relative to their shear deformation, providing a ductile response without significant out-of-plane stiffening of the wall (Hitaka and Matsui 2003, Jacobsen et al. 2010). The stiffness and strength of the slitted shear walls can be controlled more or less independently of one another by changing the slit design (i.e., slit length, number of slit tiers, and distance between slits). The introduction of slits in the shear wall limits the out-of-plane deformation, therefore there is little need for out-of-plane stiffening. The slitted shear wall does not have to occupy the full beam span and may be integrated into the walls of residential buildings, where tall doors or window openings may be the only locations where earthquake-resisting elements can be installed.

3.1.3 Addition of infills

3.1.3.1 Masonry infills

Judging from past earthquake experience, it has been recognized that masonry infills have in most cases been beneficial as they provide extra lateral force capacity and also reduce the interstorey drifts, thanks to their high stiffness. However, infills have also occasionally been the reason for the partial or total collapse of existing structures.

For example, in case they are omitted at the ground storey of a structure, then a soft storey mechanism might form during a strong earthquake, leading to extreme rotation demands to the columns and eventually total collapse. The floor-wise positioning of infills is also a major factor affecting the seismic response of a building. If they are not evenly distributed, torsional effects might be introduced, leading to increased demands to specific RC elements and possibly, their failure. Moreover, when frames are partially infilled heightwise, captive columns form. These columns have increased shear demands, much above the ones designed against, and eventually exhibit brittle shear failure. Last, but not least, out-of-plane collapse of

URM infills can occur as it has been evidenced repeatedly in the past, with the falling debris posing a serious threat to human life. This mode of failure is more common for URM infills with low quality connection to the surrounding frame and is more likely to occur to infills with pre-existing in-plane damage.

For what concerns steel structures, it is well accepted also that masonry infills have a beneficial effect on their strength, stiffness and ductility (e.g. Saneinejad and Hobbs 1995). For instance, Moghaddam et al. (1988) reported an increase in stiffness of 15-40 times over that of bare steel frames and an increase in strength of 2.75-9 times.

Taking into account these beneficial effects, practitioners have used masonry infills as retrofitting elements. Recently, researchers developed innovative concepts based on infill walls, as described next.

3.1.3.2 FRP-jacketing of masonry infills in RC frames

FRP-jacketing of masonry infills to RC frames was found to enhance strength and ductility. FRP-jacketed infills can achieve similar strength and stiffness gains, when compared to RC infilling, however they exhibit faster post-peak degradation (Erdem et al. 2006). In other studies, FRP-strengthened infills achieved superior seismic performance than the unretrofitted masonry-infilled frames exhibiting significantly higher strength and stiffness (e.g. Yuksel et al. 2005, 2010, Almusallam and Al-Salloum 2007).

3.1.3.3 TRM-jacketing of masonry infills in RC and masonry buildings

The effectiveness of TRM jacketing in seismic retrofitting RC frames has been recently investigated experimentally and analytically.

Initially Koutas et al. (2015a) investigated experimentally the use of TRM as reinforcement for masonry infills in RC frame structures. Two three-storey, 2:3 scale RC frames were built and then infilled with perforated clay bricks. One specimen was tested as-built, while the other was reinforced using TRM overlays over the infills and CFRP wrapping at the columns' critical regions. The connection of the TRM to the surrounding frame was realized using textile spike anchors or extra TRM patches. The retrofitted specimens exhibited 56% higher lateral strength, 52% higher deformation capacity and 22% higher energy dissipation capacity, compared to the as-built ones. Numerical simulations were also performed by Koutas et al. (2015b), who also proposed an analytical model to simulate the aforementioned retrofitting scheme; the model was found in excellent agreement with test results. The model was found in excellent agreement with test results, whereas Pohoryles and Bournas (2020) applied the same modelling approach, namely a macro-model with an additional tensile tie to account for the TRM, but calibrated against all available experiments.

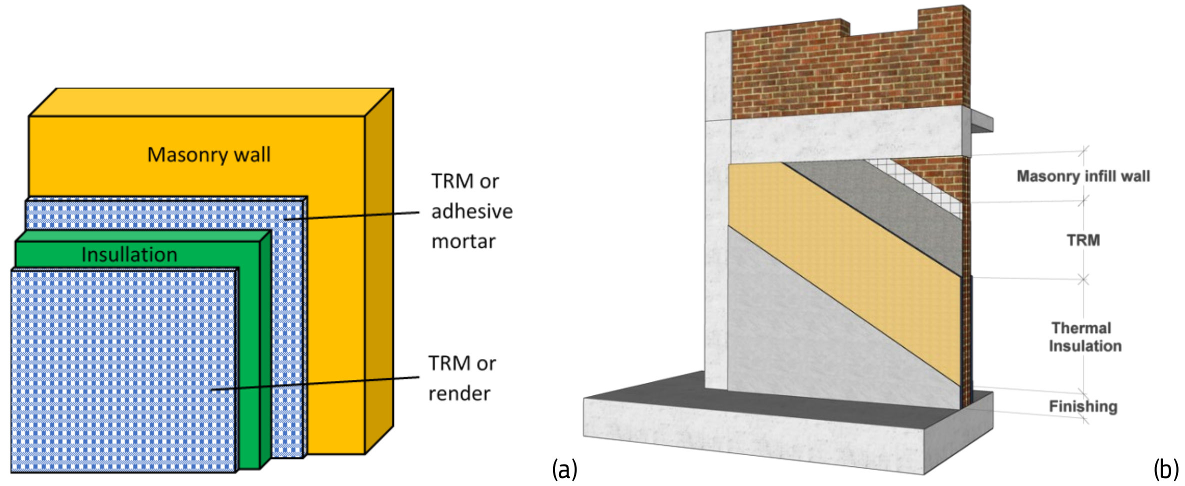
Koutas and Bournas (2019) performed experiments on half-scale, single-storey RC frames with masonry infills reinforced with TRM overlays, to assess the infills' out-of-plane behavior. The parameters under investigation included the connection configuration between the masonry infill wall and the surrounding RC frame members, and the thickness of the wall. The authors reported that the out-of-plane performance was dramatically improved in all cases of retrofitted walls, as the maximum load resisted increased 3.79-5.45 times for single-wythe walls and 2.45 times for the double-wythe walls. Moreover, the peak load was not governed by the flexural capacity of the wall, but by that of its connections to the surrounding frame. Lastly, the connection of the TRM reinforcement to the frame was found to be important with respect to providing a post-peak residual strength to the wall.

The combined in- and out-of-plane behavior of TRM-reinforced masonry infills in RC frames was investigated experimentally by Sagar et al. (2019). Bidirectional loading of the infills was achieved by successive application of slow cyclic in-plane loading and shake table-generated motion for out-of-plane loading. The authors reported that the strengthened infills withstood safely drifts of 2.2%, without compromising their out-of-plane stability. Gkournelos et al. (2020) showed that in-plane loaded TRM-strengthened walls outperformed significantly their non-retrofitted counterparts, whereas out-of-plane loaded walls with combined TRM/thermal insulation performed much better or at least as good as their TRM-only retrofitted counterparts, for the case with or without prior in-plane damage, respectively.

Recently a combined seismic and energy retrofitting approach for the building envelopes was explored. Initially, combined seismic and energy retrofitting with advanced materials was investigated experimentally for the case of masonry (Figure 20a) subjected to both out-of-plane and in-plane loading (Triantafillou et al. (2017, 2018). A similar system for the concurrent seismic and energy retrofitting for the case of RC buildings (Figure 20b) was proposed by Bournas (2018) and was experimentally investigated by Baek et al. (2022). These studies introduced the combination of TRM with standard or even highly fire-resistant thermal insulation materials

The same concept, namely that of combining TRM jacketing with thermal insulation material was further explored in analytical studies (Gkournelos et al. 2019, Pohoryles et al. 2020, Pohoryles and Bournas 2021). It was demonstrated that, for countries with high seismicity, the payback time of the renovation costs are reduced when energy is applied simultaneously with seismic retrofitting of the building envelope via the combination of TRM and thermal insulation, thanks to large savings related to the labor costs. A detailed review on integrated seismic and energy retrofitting was recently presented by Pohoryles et al. (2022)

Figure 20. Schematic illustration of integrated seismic and energy retrofitting system for (a) masonry [Source: Triantafillou et al. 2017] and (b) RC building [Source Pohoryles et al. 2020] envelopes.

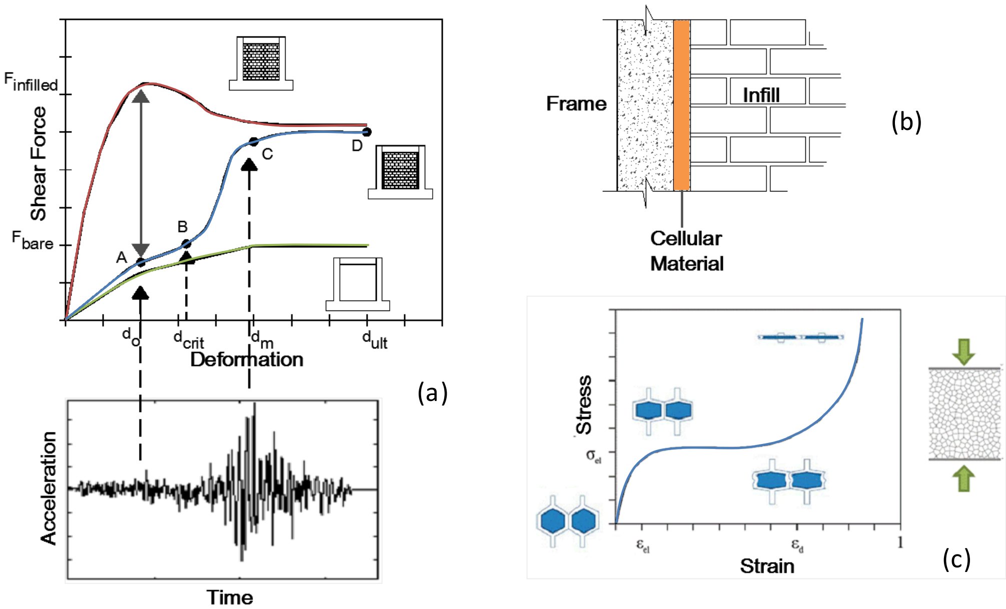


3.1.3.4 Isolated masonry infills in RC and steel buildings

With the aim of enhancing the seismic behaviour of masonry-infilled RC and steel frames, very recently, Tsantilis and Triantafillou (2018) proposed an innovative technique, namely by isolating the infill panels through the use of a highly deformable cellular material (foam) at the interface between masonry infills and the surrounding frame. As illustrated in Figure 21, infilled steel/RC frames behave similarly to bare frames, that is with negligible interaction with the surrounding members, for low to moderate seismic excitations. However for strong earthquakes and large interstorey drifts, the cellular materials become fully compressed, and the infill is activated as a diagonal compression strut, thereby providing extra strength and stiffness to the frame-infill system.

Through a systematic experimental investigation involving small-scale infilled steel frames, the following conclusions were drawn: Critical parameters in the design of isolation joints made of cellular materials are the position of the joints and their thickness. Fully isolated infills, that is with joints all around their perimeter, get activated as diagonal compression struts at lateral (interstorey) displacements approximately equal to two times the joint thickness. On the other hand, infills with side isolation only, provided by vertical joints, get activated much earlier, at lateral displacements approximately equal to the joint thickness. Based on these preliminary rules of thumb, the designer may select the joint thickness needed to activate frame-infill interaction at a desired drift.

Figure 21. Schematic illustration of the proposed concept: (a) response of RC frame with isolation using cellular materials; (b) placement of cellular material at the frame-infill interface; and (c) behavior of cellular materials in uniaxial compression



Source: Tsantilis and Triantafillou (2018).

3.1.3.5 High-performance fiber-reinforced concrete infill panels

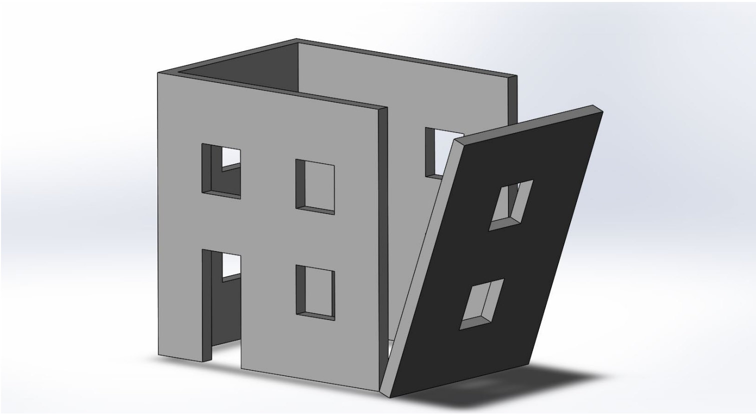
Recent breakthroughs in fiber-reinforced concrete technology have demonstrated that high-performance fiber-reinforced concrete (HPFRC) materials have the advantage of little to no spalling and a ductile tensile pseudostrain hardening behavior that allows for elements typically failing in shear to instead have a more ductile flexural failure, through multiple cracking and spreading of yielding of the reinforcing bars (e.g. Olsen and Billington 2011). Lignos et al. (2014) evaluated experimentally an innovative seismic retrofit system for existing steel moment-resisting frames, which were designed in accordance with old seismic provisions. The proposed retrofit system developed by Hanson and Billington (2009), consists of a set of two vertical infill panels, two steel channel bolted connections, and two steel plates with slotted holes. Each panel utilizes a single layer of welded wire fabric (WWF) to provide shear resistance and bolster flexural strength. The bottom channel connection is bolted to threaded studs that are welded to the top flange of the steel beam of the bottom storey. In order to weld the studs, holes would be cored into the existing slab of a building exposing the top flange of the steel beam. New threaded studs would be welded through the cored hole and grouted in place. Each set of two vertical infill panels is grouted into the two-channel bolted connection. The two HPFRC infill panels are connected at midheight of a storey with two steel plates, which have slotted holes to allow the vertical movement of the two panels with respect to each other. The slotted holes also guarantee that the inflection point of the bending diagram of the HPFRC infill panel system is always at midheight of a storey; therefore, damage is evenly distributed to both infill panels during an earthquake. The bolted connection details allow for damaged panels to be removed and replaced quickly after an earthquake, provided that the residual storey drift ratios of the building are not large.

This system was tested experimentally through hybrid simulation by Lignos et al. (2014), who concluded the following: (a) Through microcracking, the proposed infill panel system dissipates energy during service-level earthquakes and protects the main lateral resisting system from minor yielding; (b) During a design-level or a maximum considered earthquake, the proposed retrofit system reduces seismic demands in terms of storey and residual drift ratios compared with the unretrofitted bare frame by approximately 40%. (c) No out-of-plane deformations of the infill panel system were observed during both testing phases, indicating that no axial load is built up in the infill panels during an earthquake regardless of the level of lateral deformations. The HPFRC infill panels reach zero bending strength after 3% rad. (d) The proposed infill panel system was proven to work effectively as a retrofit system without having to be replaced in between two design level earthquakes. The second ground motion represented a major aftershock typically following a design-level earthquake. (e) No indication of severe structural damage was observed for both the design-level and maximum considered earthquake in any of the structural components (beams and columns) of the test frame, including the numerical portion of the hybrid model. The lack of major structural damage is attributed to the energy dissipation through multiple cracking and reinforcement yielding in the HPFRC panels during the earthquake.

3.2 Integrity enhancement of masonry structures

One of the major weaknesses usually encountered in existing masonry buildings is the lack of structural integrity. This may result in partial collapse of parts of such buildings, because of their inadequate connection to the neighboring elements. An example of such a collapse is the out-of-plane, overturning failure of a whole wall, as shown schematically in Figure 22.

Figure 22. Out-of-plane collapse of wall with inadequate connection



The best way to tackle this major issue is to tie the walls of a masonry structure together in order to enforce a box-type behavior. If such a response is achieved, a number of advantages are immediately available:

- Overturning failures, like the one depicted in Figure 22, are prevented.
- Lateral loads are transferred more effectively to those walls which are parallel to the loading direction. This results in their in-plane stressing, which is much more predictable.
- Effective tying of the walls activates higher levels of arching action for the walls subjected to out-of-plane loading. As a result, higher levels of out-of-plane capacity are also achievable.

Based on the logic explained above, a number of techniques exist which target the structural integrity enhancement of masonry structures, including TRM jacketing presented in sub-section 3.1.3.3. One way this can be achieved is by constructing confining RC beam elements at storey heights and, possibly, column elements at corners and intermediate places within the body of a wall. Creating stiff floor diaphragms with proper connections to the surrounding walls is also a very effective way towards achieving a box behavior. As far as special, historic structures are concerned, many of them contain domes and vaults which in many cases are not properly integrated with their supporting elements. Their stabilization is therefore of upmost importance.

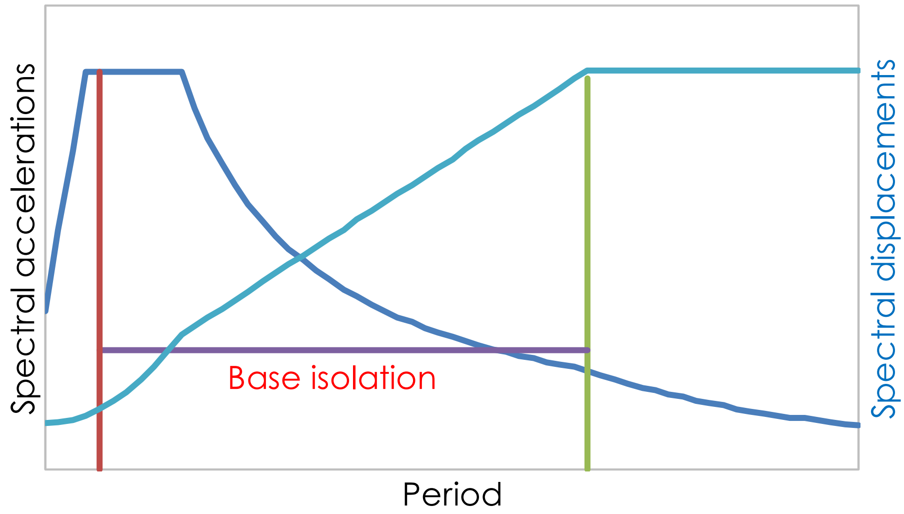
3.3 Demand reduction

Although seismic upgrading techniques that enhance the lateral load and stiffness capacity of a building are typically applied for mitigating the seismic risk, their applicability might be problematic, as for instance, they generally increase the lateral stiffness and are introducing higher seismic forces to the building, which might ultimately lead to soil failure, triggering a global overturning failure mechanism. In addition, the capacity-increase-related techniques do not reduce the floor accelerations experienced by the structures during an earthquake such accelerations can be critical and lead to the failure of various non-structural elements. Finally, when sensitive equipment is to be installed inside buildings (e.g. hospitals), limiting floor oscillations becomes critical, and therefore an alternative route to increasing structural capacity is the reduction of demand. This may be achieved by using base isolation and/or devices for energy dissipation (e.g. seismic dampers), as discussed in the following sections.

3.3.1 Base isolation

The target of base isolation is to decouple the building (superstructure) from the understructure foundation soil, so that the building is actually subjected to minimal vibrations during a strong ground motion. Base isolation is provided by using various isolator systems, e.g. lead-rubber bearings, friction-pendulum bearings, elastomeric bearings, which increase the buildings's natural period of vibration and hence leading to lower spectral accelerations and significantly lower base shear demands, but at the same to large-period structures with larger spectral displacements. This concept is illustrated in Figure 23. For this reason, the employed isolator systems also have damping-increasing characteristics and/or are combined with supplementary dampers.

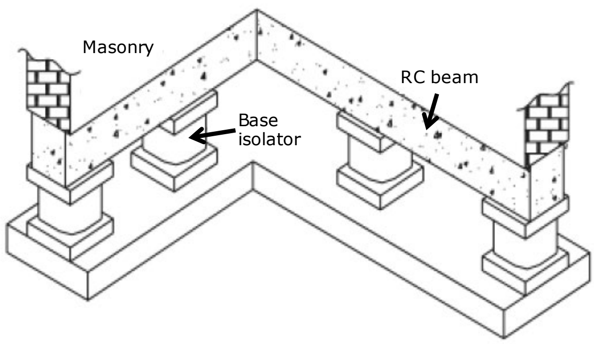
Figure 23. Base isolation concept



Although base isolation is clearly an efficient technique for reducing buildings' seismic vulnerability, its applicability in the case of existing buildings is rather challenging. Inserting for instance the isolation system just below the building's ground level, requires that the vertical elements to be completely cut off sequentially, so that bearings of any type can be installed. In addition, both above and below the isolation plane, strong diaphragms have to be formed to ensure the uniform excitation of the superstructure. The design of such a retrofitting scheme should ensure that the building will remain elastic during a major event, without the need of any additional strengthening measures or with only minor ones. This solution effectively protects a building against earthquakes and reduces the floor accelerations to a minimum at all levels, thus minimizing non-structural damage and protecting any sensitive equipment. At the same time, minimal or none at all aesthetic alterations need to be done to the existing structure, something that is of high importance for heritage buildings.

When incorporating seismic isolators in masonry structures underpinning is needed to provide temporary supports along the masonry walls to prevent collapse. A common technique in this case involves progressive openings in the wall to place the isolators and at the same time to build an RC beam mounted over the seismic isolators and over the masonry wall. Then, the temporary supports are removed, transferring the vertical load of the structure to the foundation through the beam and the isolators (Figure 24).

Figure 24. Isolators between concrete beams and foundation



Research done by Tomaževič et al. (2009) has shown that base isolation alone is not sufficient for improving the seismic behavior of old masonry buildings without wall ties. Despite of all the merits though, the realization of such a retrofitting scheme often demands considerably higher amounts of funds, which might not justify its actual implementation.

In cases that even the slightest intervention to the existing building is prohibited either for cultural or operational reasons, a technique similar to the one described above cannot be employed. To address this matter, Clemente and De Stefano (2011) proposed a seismic isolation procedure which consists of creating an isolated platform under the foundations, without touching the building at all. A set of horizontal pipes are inserted below the foundations and the isolation devices are placed at the horizontal diametric plane. A trench is then formed around the building, thus completing its isolation from the surrounding soil. At the end of the intervention, both the structure, as well as the ground directly below it are seismically isolated, without having affected at all any architectural characteristic of the former. The authors reported that this isolation scheme is perfectly applicable for historical buildings.

3.3.2 Seismic dampers and passive energy dissipation systems

Seismic dampers are mechanical devices added to the structure with the role of dissipating the energy induced by the earthquake to the structure. Seismic waves propagate through the soil and from substructure reach the superstructure carrying a certain amount of input energy. A portion of the energy input in the structure is being absorbed by superstructure itself while the rest is absorbed by damping devices (active or passive). The passive damping systems are mostly used as energy dissipating systems applied to masonry structures. Dampers can be categorized by three different criteria: displacement-activated (metallic dampers, friction dampers, self-centering dampers, viscoelastic dampers); velocity-activated (viscous dampers, viscoelastic dampers); and motion-activated (tuned-mass dampers).

3.3.2.1 Metallic yield dampers

Metallic dampers are displacement activated dampers that are commonly called hysteretic dampers. The increase of the structure stiffness generates higher base shear loads in the superstructure, so often some additional interventions on the main structure are needed in order to optimize the efficiency of hysteretic dampers. Metallic dampers consist of bracing elements and a yielding metallic element that is fixed to the chevron brace elements and a horizontal element of a structure. A yielding metallic device dissipates energy through a deformation caused by the relative displacement between the structure above and below the bracing system the device. One of the first metallic damper systems applied in buildings is the Added Damping and Stiffness (ADAS) system, which was tested extensively by Bergman and Goel (1987) and Whittaker et al. (1991).

The ADAS system has been used for the seismic retrofitting of steel and steel-concrete composite structures e.g. by Aiken et al. (1993) and Soong and Spencer (2002). ADAS dampers should be designed in such a way that at their yielding, axial loads in the braces are lower than the buckling values. The design is therefore uneconomical, because the tensile capacity of diagonals is not fully exploited. Moreover, these systems need regular inspection and should also be replaced after large earthquakes that may cause their fracture. The performance of ADAS dampers depends upon the elastic stiffness of the structure to which it is applied. Maximum effectiveness is achieved if the device has high stiffness and high yield strength.

Due to the fact that application of the ADAS system requires complex and long demolition interventions when applied to masonry buildings, Benedetti et al. (2014) have studied the use of ADAS system installed on added external concrete walls. This way the dynamic properties of the structure are changed, but the demolition of existing masonry elements is minimized. Apart from the ADAS system, a series of alternative metallic damping systems were developed throughout the years: TADAS (Tsai et al. 1993), Honeycomb Damper System (HDS), etc.

Oinam and Sahoo (2019) recently performed an experimental and analytical investigation on the use of metallic dampers as a means to improve the seismic performance of soft-storey RC frames. The damper consists of a shear plate and two end flexure plates placed along and normal to the direction of lateral force, respectively. This device may be placed e.g. at the midspan of an RC beam and supported by steel Λ-braces. The authors reported that the proposed retrofitting scheme was effective in improving the lateral strength, stiffness, energy dissipation and the drift capacity of RC frames.

3.3.2.2 Viscous and viscoelastic dampers

Viscous and viscoelastic dampers are widely used in the aerospace industry, in tall buildings for damping the wind vibrations, and during the last two decades they have also found their application in seismic retrofitting.

Viscous dampers are velocity activated systems that dissipate energy without any change of stiffness in the structure.

Viscoelastic dampers (VED) more specifically consist of thin steel plates combined with viscoelastic material laminates (e.g. Xu et al. 2010). These materials are able to withstand the high shear strains, which develop during strong earthquakes and that way dissipate large amounts of the seismic energy. Such devices are normally installed at the connection points of metallic braces, therefore they can be employed along with a bracing system of a broader seismic retrofitting scheme (e.g. see in Section 3.1.1). A recent devolopment of VED is the so-called rotary rubber braced damper (RRBD), which uses pads sandwiched between steel plates with the capacity to rotate (Mehrabi et al. 2017).

Even though they have been proved to be a very effective energy dissipating system, they have rarely been used for masonry structures strengthening. Branco et al. (2011) have shown that the use of viscous dampers can be a viable option for the seismic retrofitting of masonry structures due to the fact that these systems are efficient, easy to apply, and reversible. As a general comment, it should be stated here that the application of seismic dampers in the retrofitting of URM is very rare.

3.3.2.3 Friction dampers

Friction dampers (e.g. Aiken and Kelly 1990) rely on the friction developed between specially treated steel plates, which are clamped in contact using high strength bolts. Relative slip occurs at a predefined load, which is selected so that it is not exceeded under the wind loading cases. The hysteresis loops of these dampers are rectangular, thus resulting in large amounts of energy dissipation and protecting the structural elements. This type of dampers is also installed within bracing systems.

Various materials are used for the sliding surface, such as brake pad material on steel, steel on steel, steel on brass in slip bolted connections, graphite impregnated bronze on stainless steel and other metal alloys. Generally, friction devices provide good performance and their response is independent from loading amplitude, frequency and number of cycles. Therefore, they combine high energy-dissipation potential and relatively low cost; yet they are easy to install and maintain.

Valente (2013) investigated through numerical analyses the use of friction dampers as a means to improve the seismic performance of existing precast RC buildings. The dampers are selectively positioned at beam-column joints in order to provide a moment connection, capable of large energy dissipation. The author reported a significant increase in the dissipating capacity of buildings. Moreover, plastic deformations were concentrated within the friction dampers, protecting that way columns from severe damage.

3.3.2.4 Viscous-fluid dampers

Viscous-fluid dampers are similar to shock absorbers in a car. They consist of a piston within a damper chamber filled with a compound of silicon oil (e.g. Constantinou et al. 1993), eventually pressurized (Tsopelas and Constantinou 1994, Pekcan et al. 1995). As the piston moves within the cylinder the oil is forced to flow through small holes in the piston, thus causing friction. Viscous dampers have low resistance to deformation when loads are applied slowly, but resistance increases with the deformation rate. When installed in buildings, usually in bracings, friction transforms seismic input energy into heat. The brace reduces the deformation in the damper due to storey drift. In fact, the former behaves like a spring, so the system is a spring-dashpot system in series (Maxwell model); therefore, the spring deformability reduces the relative displacement of the damper. However, this effect is a function of connection flexibility: the higher the connection flexibility, the lower the damping force. The damper-structure interaction depends significantly on whether the structure undergoes inelastic deformations.

Different types of passive damping mechanisms are the tuned mass dampers (TMD), which were initially used to mitigate wind-induced excitations, but they have also been used in the field of earthquake engineering. TMD are tuned to a specific frequency which is chosen to coincide with the structure's fundamental frequency, so they can be most effective in reducing the dynamic response quantities. An alternative to TMD are tuned liquid dampers, which work using the same principle and also have lower cost (Soong and Dargush 1999).

3.3.2.5 Shape memory alloy dampers

SMA dampers are made of shape memory alloys, which are special metal alloys with superelastic properties, i.e. they can undergo large strains (in the order of 10%) with no residual deformation after unloading. This mechanism is based upon reversible solid-to-solid transformation (austenite to martensite), which can be either thermal or stress induced. SMA devices consist of bars and wires; the former are designed to resist bending and/or shear and/or torsion, and the latter are used for pure axial loads. SMA dampers have been studied e.g. by Housner et al. (1997), Dolce et al. (2000), Soong and Spencer (2002), and Morais et al. (2017). They rely on re-centering and the high energy dissipation capacity of Ni-Ti alloys; however, the higher the re-centering, the lower the dissipation.

3.3.2.6 Self-centrering systems

Ricles et al. (2001), Christopoulos et al. (2002) and Collins and Filiatrault (2003) proposed the design of self-centering systems for the seismic retrofitting of steel structures. These innovative structural systems: incorporate the nonlinear characteristics of yielding structures and, thereby, limit the induced seismic forces and provide additional damping characteristics; encompass self-centering properties allowing the structural system to return to its original position after an earthquake; and reduce or eliminate cumulative damage to the main structural elements.

The use of passive damping devices for seismic retrofitting is aimed at protecting frame components, i.e. beams, columns and connections, in the event of moderate-to-severe earthquakes. Reduced storey drifts are guaranteed by the supplemental damping provided by the devices. Moreover, dampers are effective to mitigate the vibrations due to ordinary environmental actions, e.g., wind and small earthquakes. Hysteretic (yield) dampers, friction dampers and viscoelastic dampers are advised, because their design rules are mature, and their enhanced seismic performances have been validated in several successful applications worldwide.

The development of dampers employing new metallic materials is one of the future directions for passive control using hysteretic devices (Ikeda et al. 2019). Stainless steel is one such new metallic material. The advantages of stainless steel are the high tensile strength, high breaking elongation, good aesthetics, and good recyclability. Test results confirmed that stainless steel specimens have stable hysteretic loops, higher strength and higher strain hardening in comparison with common steel. A new Fe-Mn-Si based alloy, which is a type of shape memory alloy with excellent fatigue performance, is another example.

4 Discussion and conclusions

Due to the poor structural performance of structures during past earthquakes, the field of seismic upgrading of existing buildings has received great attention both in the academic world and in engineering practice. The present review study outlined the seismic upgrading methods that have been developed for application in RC, masonry and steel buildings, emphasizing on novel approaches. Both local and global techniques were discussed and assessed in terms of their strengths and weaknesses.

When a building has an acceptable level of lateral strength and stiffness, the application of local retrofitting measures is selected. Typically, retrofitting solutions involve jacketing of RC beams and columns aiming at increasing their flexural, shear strength, and members' deformation capacity. FRP have been used successfully in many experimental campaigns as well as real-world applications for the seismic upgrading of RC, masonry and steel buildings. To address the poor behavior of FRP at high temperatures, TRM offer a very promising alternative to FRP for RC and masonry buildings, as strengthening materials. Although TRM may have slightly reduced effectiveness, they are more cost-effective, easy to easy to install and have superior fire resistance and behaviour at high temperatures.

Global Structural upgrading techniques, both increasing the capacity and decreasing the demand, were also analysed. Concerning the former, addition of bracing systems, infill walls and shear walls (of different types) were examined; all these yield a significant increase in a building's lateral strength and stiffness. Buckling-restrained braces, replaceable infill panels made of high-performance materials, and isolated infill walls are promising solutions, worth of further detailed investigation. The addition of RC shear walls, either as new elements or by infilling of existing frames, can also be beneficial for the seismic strengthening of RC and steel buildings. Still, different failure modes need to be considered, depending on the initial deficiencies of the as-built structure. Moreover, masonry infills consist a very economical way of increasing a structure's lateral strength and stiffness. When strengthened using FRP, TRM or reinforced mortar overlays, they form a reliable lateral load resisting mechanism. Finally, integrated seismic and energy upgrading can be provided in some of the global seismic retrofitting measures reviewed (e.g. by combining TRM, exoskeleton systems, RC/masonry infilling with thermal insulation). To enhance the integrity of masonry structures, a number of retrofitting techniques have been developed with the aim of consolidating the entire structure, improving the stress redistribution capabilities and forcing a box-type behavior.

Last but not least, seismic load reduction techniques were discussed as well, including base isolation and passive energy dissipation systems, which can be employed to effectively reduce the seismically induced vibrations on RC, masonry and steel buildings. This family of methods might not always be structurally or economically feasible, however it has the advantage of minimally altering the aesthetics of the structure to be retrofitted. This feature might make such retrofitting methods particularly attractive for the protection of monument-type masonry buildings, where the preservation of the original architectural view is a requirement; or in cases of retrofitting important structures or when vibration control is of outmost importance, such methods can yield extremely good results.

Selecting the appropriate retrofitting solution for a given structure is a multiparametric problem without a one-fits-all solution. The specific details of the examined structure, the desired level of performance upgrade, the availability of materials, specialized personnel etc., and of course, the overall intervention cost need to be accounted for. Moreover, the design of such retrofitting measures usually calls for advanced simulations. Therefore, it is important that engineers have a robust regulatory framework to follow, so that their designs can be reliable.

With the exception of EN 1998-3, today we lack a regulatory framework for the design of the seismic retrofitting of existing buildings with novel technologies. EN 1998-3 covers (only partially) FRPs for the enhancement of the shear capacity of RC columns and walls, for the enhancement of the available ductility at beam or column ends through added confinement, and for the prevention of lap splice failures through increased lap confinement. It is hoped that the upcoming version of the Eurocodes will play some role with respect to that matter. To the best of the authors' knowledge, the upcoming version of EN 1998-3 will include revised models for FRP retrofitting of RC members. Moreover EN 1998-3 will make also reference to vertical and horizontal steel bars, FRP or other composite strips as a means of strengthening masonry walls, as well as to the possibility of adding bracings, dissipative passive or active devices, without providing specific design guidance. However other novel techniques, as discussed in this report, do not seem to be covered, despite the fact that research has already advanced substantially, and certainly more than for the case of traditional techniques. This is a gap that needs to be filled.

The authors believe that research gaps with regards to seismic upgrading of RC, masonry and steel buildings with novel techniques are generally minor. An emerging field, which will progressively be gaining the attention of the scientific community, is the *integration* of today's novel seismic upgrading techniques with interventions for energy upgrading including advanced materials, and possibly with low cost – yet reliable – systems for smart monitoring.

References

Aiken I.D., Kelly J.M. (1990), "Earthquake simulator testing and analytical studies of two energy-absorbing systems for multistory structures", *Report No. UCB/EERC-90/03,* University of California at Berkeley, California, USA.

Aiken I., Nims D., Whittaker A., Kelly J.M. (1993), "Testing of passive energy dissipation systems", *Earthquake Spectra*, 9(2), 335-370.

Akin A., Sezer R. (2016), "A study on strengthening of reinforced concrete frames using precast concrete panels", *KSCE Journal of Civil Engineering*, 20(6), 2439-2446.

Alam M.S., Nehdi M., Amanat K.M. (2009), "Modelling and analysis of retrofitted and unretrofitted masonry-infilled RC frames under in-plane lateral loading", *Structure and Infrastructure Engineering*, 5(2), 71-90.

Almusallam T.H., Al-Salloum Y.A. (2007), "Behavior of FRP strengthened infill walls under in-plane seismic loading", *Journal of Composites for Construction*, 11(3), 308-318.

Askouni P.D., Papanicolaou, C.G. (2017) "Experimental investigation of bond between glass textile reinforced mortar overlays and masonry: the effect of bond length", *Materials and Structures*, **50**(2), doi.org/10.1617/s11527-017-1033-7.

Baek, E., Pohoryles, D.A., Kallioras, S., Bournas, D.A., Choi, H., and Kim, T. (2022), "Innovative Seismic and Energy Retrofitting of Wall Envelopes Using Prefabricated Textile-Reinforced Concrete Panels with an Embedded Capillary Tube System". Eng. Struct., 265, p. 114453, https://doi:10.1016/j.engstruct.2022.114453.s

Bergman D.M., Goel S.C. (1987) "Evaluation of cyclic testing of steel plate device for added damping and stiffness", Report No. UMCE 87-10, *The University of Michigan*, Ann Arbor, MI.

Bournas D.A. (2018), "Concurrent seismic and energy retrofitting of RC and masonry building envelopes using inorganic textile-based composites with insulation materials: A new concept", *Composites Part B: Engineering*, 148, 166–179.

Bournas D.A., Lontou P.V., Papanicolaou C.G., Triantafillou T.C. (2007), "Textile-reinforced mortar (TRM) versus FRP confinement in reinforced concrete columns", *ACI Structural Journal*, 104(6), 740-748.

Bournas D.A., Triantafillou T.C, Zygouris, K., Stavropoulos, F. (2009). "Textile-reinforced mortar versus FRP jacketing in seismic retrofitting of RC columns with continuous or lap-spliced deformed bars", Journal of Composites for Construction, 13(5), 360-371.

Bournas D.A., Triantafillou T.C. (2009), "Flexural strengthening of reinforced concrete columns with near-surface-mounted FRP or stainless steel", *ACI Structural Journal*, 106(4), 495-505.

Bournas D.A., Triantafillou T.C. (2013), "Biaxial bending of reinforced concrete columns strengthened with externally applied reinforcement in combination with confinement", *ACI Structural Journal*, 110(2), 193-204.

Bouwkamp J., Gomez S., Pinto A.V., Varum H., Molina J. (2001), "Cyclic tests on RC frame retrofitted with K-bracing and shear-link dissipater", EUR Report 20136 EN, ELSA, Joint Research Centre, Ispra, Italy.

Branco M., Guerreiro L.M. (2011) "Seismic rehabilitation of historical masonry buildings*", Engineering Structures*, **33**(5), 1626-1634.

Bush T.D., Wyllie L.A., Jirsa J.O. (1991), "Observations on two seismic strengthening schemes for concrete frames", *Earthquake Spectra*, 7(4), 511-527.

Cerniauskas G, Tetta Z, Bournas DA, Bisby LA. (2020) "Concrete confinement with TRM versus FRP jackets at elevated temperatures", Mater Struct 2020;53:58. https://doi.org/10.1617/s11527-020-01492-x.

Cho C.G., Han B.C., Lim S.C., Morii N., Kim J.W. (2018) "Strengthening of reinforced concrete columns by high-performance fibre-reinforced cementitious composite (HPFRC) sprayed mortar with strengthening bars", *Composite Structures*, 202, 1078–1086.

Cho C.G., Kim Y.Y., Feo L., Hui, D.V. (2012), "Cyclic responses of reinforced concrete composite columns strengthened in the plastic hinge region by HPFRC mortar", *Composite Structures*, 94, 2246-2253.

Christopoulos C., Filiatrault A., Folz B., Uang C.M. (2002), "Post-tensioned energy dissipating connections for moment-resisting steel frames", *Journal of Structural Engineering*, 128(9), 1111- 1120.

Clemente P., De Stefano A. (2011), "Application of seismic isolation In the retrofit of historical buildings", *Earthquake Resistant Engineering Structures VIII*, 120, 41-52.

Collins J.H., Filiatrault A. (2003), "Application of post-tensioned energy dissipating (PTED) connections in steel moment-resisting frames", Report No. SSRP-2003/05, Department of Structural Engineering, University of California, San Diego.

Commission Staff Working Document (SWD) European framework for action on cultural heritage, 2018, 491 final.

Communication (COM) from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions – The European Green Deal, 2019, 640 final.

Communication (COM) from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions – A Renovation Wave for Europe -greening our buildings, creating jobs, improving lives, 2020, 550 final.

Constantinou M.C., Symans M.D., Tsopelas P., Taylor D.P. (1993), "Fluid viscous dampers in applications of seismic energy dissipation and seismic isolation", In: *Proceedings ATC 17-1* on *Seismic Isolation, Passive and Active Control*, 2, 581-592.

D'Ambrisi A., Feo L., Focacci F. (2013) "Experimental and analytical investigation on bond between Carbon-FRCM materials and masonry" *Composites Part B: Engineering*, **46**, 15-20.

Di Bucci, D., M. Dolce, D.A. Bournas, D. Combescure, D. De Gregorio, L. Galbusera, M. Leone, et al., Science for Disaster Risk Management 2020: Acting Today, Protecting Tomorrow. EUR 30183 EN, Edited by A. Casajus Valles, M. Marin Ferrer, K. Poljanšek, and I. Clark, Publications Office of the European Union, Luxembourg, 2021, ISBN 978-92-76-18182-8, doi:10.2760/571085, JRC114026.

Decision (EU) 2017/864 of the European Parliament and of the Council of 17 May 2017 on a European Year of Cultural Heritage (2018), Official Journal of the European Union, L131, 2017, pp. 1–9.

Directive (EU) 2018/844 of the European Parliament and of the Council of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency, *Official Journal of the European Union*, L156, 2018, pp. 75–91.

Di Sarno L., Elnashai A.S. (2002), "Seismic retrofitting of steel and composite building structures", Technical Report, Mid-America Earthquake Center, University of Illinois at Urbana-Champaign.

Dolce M., Cardone D., Marnetto R. (2000), "Implementation and testing of passive control devices based on shape memory alloys", *Earthquake Engineering and Structural Dynamics*, 29(7), 945-968.

Economidou, M., B. Atanasiu, D. Staniaszek, J. Maio, I. Nolte, O. Rapf, J. Laustsen, P. Ruyssevelt, D. Strong, and S. Zinetti. (2011), Europe's Buildings under the Microscope. A Country-by-Country Review of the Energy Performance of Buildings.

EN 1998 (2004), "Design of structures for earthquake resistance – Part 1: General rules, seismic actions and rules for buildings", European Committee for Standardization.

EN 1998-3 (2005), "Design of structures for earthquake resistance – Part 3: Assessment and retrofitting of buildings".

European Parliament (2016), "Boosting building renovation: What potential and value for Europe?", Directorate General for Internal Policies.

Erdem I., Akyuz U., Ersoy U., Ozcebe G. (2006), "An experimental study on two different strengthening techniques for RC frames", *Engineering Structures*, 28, 1843-1851.

Federal Emergency Management Agency (2000), "Recommended seismic evaluation and upgrade criteria for existing welded steel moment-frame buildings", *Report No. FEMA 351*, Washington, DC, USA.

fib (2003), "Seismic assessment and retrofit of reinforced concrete buildings", Bulletin 24, Fédération Internationale du Béton, Lausanne.

fib (2019), "Externally applied reinforcement for concrete structures", Bulletin 90, Fédération Internationale du Béton, Lausanne.

Gkournelos P.D., Bournas D.A., Triantafillou T.C. (2019), "Combined seismic and energy upgrading of existing reinforced concrete buildings using TRM jacketing and thermal insulation", *Earthquakes and Structures*, 16(5), 625-639.

Gkournelos PD, Triantafillou TC, Bournas DA, (2020), "Structural and Energy Retrofitting of Masonry Walls: The Effect of In-plane Damage on the Out-of-plane Response", Journal of Composites for Construction, https://doi.org/10.1061/(ASCE)CC.1943-5614.0001066.

Gkournelos PD, Triantafillou TC, Bournas DA, (2021), "Seismic upgrading of existing reinforced concrete buildings: A state-of-the-art review", Engineering Structures, 240,112273. https://doi.org/10.1016/j.engstruct.2021.112273

Gkournelos P.D., Triantafillou, T.C. and Bournas, D.A. (2022) "Seismic Upgrading of Existing Masonry Structures: A State-of-the-Art Review", Soil Dynamics and Earthquake Engineering, Vol. 161, October 2022, p. 107428, https://doi:10.1016/j.soildyn.2022.107428.d

Goel S.C. (1992), "Cyclic post-buckling behaviour of steel bracing members", Stability and ductility of steel structures under cyclic loading, Y. Fukumoto and G.C. Lee Eds., CRC Press, 75-104.

Hitaka T., Matsui C. (2003), "Experimental study on steel shear wall with slits", *Journal of Structural Engineering*, 129(5), 586 – 595.

Housner G.W., Bergman L.A., Caughey T.K., Chassiakos A.G., Claus R.O., Masri S.F., Skelton R.E., Soong T.T., Spencer B.F. Jr., Yao T.P. (1997), "Structural control: past, present and future", Journal of Engineering Mechanics, 123(9), 897-971.

Ikeda Y., Yamamoto M., Furuhashi T., Kurino H. (2019), "Recent research and development of structural control in Japan", *Japan Architectural Review*, 2(3), 219-225.

Jacobsen A., Hitaka T., Nakashima M. (2010). "Online test of building frame with slit-wall dampers capable of condition assessment", *Journal of Constructional Steel Research*, 66(11), 1320–1329.

Kaltakci M.Y., Arslan M.H., Yilmaz U.S., Arslan H.D. (2008), "A new approach on the strengthening of primary school buildings in Turkey: An application of external shear wall", *Building and Environment*, 43(6), 983-990.

Kaplan H., Yilmaz S. (2012), "Seismic strengthening of reinforced concrete buildings", In: A. Moustafa (ed.) *Earthquake-resistant structures - Design, assessment and rehabilitation*, InTech.

Kapsalis P., El Kadi M., Vervloet J., De Munck M., Wastiels J., Triantafillou, T.C., Tysmans, T. (2019), "Thermomechanical behavior of textile reinforced cementitious composites subjected to fire", Applied Sciences 9, 747.

Kariou, F. A., S. P. Triantafyllou, D. A. Bournas, and L. N. Koutas. (2018). "Out-of-plane response of masonry walls strengthened using textile-mortar system" Constr. Build. Mater. 165: 769–781. https://doi.org/10.1016/j.conbuildmat.2018.01.026.

F.A. Kariou, S.P. Triantafyllou, D.A. Bournas (2019). "TRM strengthening of masonry arches: An experimental investigation on the effect of strengthening layout and textile fibre material" Compos Part B: Eng 173, 106765. https://doi.org/10.1016/j.compositesb.2019.04.026

Kouris L.A.S., Triantafillou T.C. (2018) "State-of-the-art on strengthening of masonry structures with textile reinforced mortar (TRM)", *Construction and Building Materials*, 188, 1221-1233.

Kouris L.A.S., Triantafillou T.C. (2019) "Design methods for strengthening masonry buildings using textile-reinforced mortar", *Journal of Composites for Construction*, 23(1): 04018070, doi 10.1061/(ASCE)CC.1943-5614.0000906.

Koutas L.N., Bournas D.A. (2019), "Out-of-Plane Strengthening of Masonry-Infilled RC Frames with Textile-Reinforced Mortar Jackets", *Journal of Composites for Construction*, 23(1), 04018079.

Koutas L., Bousias S.N., Triantafillou T.C. (2015a), "Seismic strengthening of masonry-infilled RC frames with TRM: Experimental study", *Journal of Composites for Construction*, 19(2), 04014048.

Koutas L.N., Triantafillou T.C., Bousias S.N. (2015b), "Analytical modelling of masonry-infilled RC frames with textile-reinforced mortar", *Journal of Composites for Construction*, 19(5), 04014082.

Koutas LN, Tetta Z, Bournas DA, Triantafillou TC. (2019) "Strengthening of Concrete Structures with Textile Reinforced Mortars: State-of-the-Art Review", Journal of Composites for Construction, 23, 03118001. https://doi.org/10.1061/(ASCE)CC.1943-5614.0000882.

Koutas LN, Bournas DA (2020) "Confinement of masonry columns with textile-reinforced mortar jackets" Constr Build Mater 258:120343. https://doi.org/10.1016/j.conbuildmat.2020.120343

Labò S., Passoni C., Marini A., Belleri A., Camata G., Riva R., Spacone E. (2016), "Diagrid solutions for a sustainable seismic, energy, and architectural upgrade of European RC buildings", *Proceedings of the XII International Conference on Structural Repair and rehabilitation,* Porto, Portugal.

Labò S., Passoni C., Marini A., Belleri A., Camata G., Riva P., Spacone E. (2017), "Prefabricated responsive diagrids for holistic renovation of existing mid-rise RC buildings", COMPDYN 2017, 6th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering, Papadrakakis M. and Fragiadakis M. (eds.), Rhodes Island, Greece.

Linghoff D., Haghani R., Al-Emrani M. (2009), "Carbon-fibre composites for strengthening steel structures", *Thin-Walled Structures*, 47(10), 1048–1058.

Marini A., Passoni C., Belleri A., Feroldi F., Preti M., Metelli G., Riva P., Giurani E., Plizzari G. (2017), "Combining seismic retrofit with energy refurbishment for the sustainable renovation of RC buildings: A proof of concept", *European Journal of Environmental and Civil Engineering*, doi:10.1080/19648189.2017.1363665.

Mehrabi M.H., Suhatril M., Ibrahim Z., Ghodsi S.S., Khatibi H. (2017), "Modeling of a viscoelastic damper and its application in structural control", *PLoS ONE*, 12(6), e0176480.

Moghaddam H., Dowling P.J., Ambraseys N.N. (1988), "Shaking table study of brick masonry infilled frames subjected to seismic excitation", *Proceedings of the 9th World Conference on Earthquake Engineering*, Tokyo/Kyoto, Japan, 8, 913-918.

Morais J., Gil de Morais P., Santos C., Campos Costa A., Candeias P. (2017), "Shape memory alloy based dampers for earthquake response mitigation", *Procedia Structural Integrity*, 5, 705-712.

Oinam R.M., Sahoo D.R. (2019), "Using metallic dampers to improve seismic performance of soft-story RC frames: Experimental and numerical study", *Journal of Performance of Constructed Facilities*, 33(1), 04018108.

Pantazopoulou S., Tastani S., Thermou G., Triantafillou T., Monti G., Bournas D., Guadagnini M. (2016) "Background to the European seismic design provisions for retrofitting RC elements using FRP materials", *Structural Concrete (Journal of the fib)*, 17(2), 194-219.

Papanicolaou C.G., Triantafillou T.C., Karlos K., Papathanasiou M. (2007), "Textile-reinforced mortar (TRM) versus FRP as strengthening material of URM walls: In-plane cyclic loading", *Materials and Structures*, **40**(10), 1081-1097.

Papanicolaou C.G., Triantafillou T.C., Papathanasiou M., Karlos K. (2008), "Textile reinforced mortar (TRM) versus FRP as strengthening material of URM walls: Out-of-plane cyclic loading", *Materials and Structures*, **41**(1), 143-157.

Pekcan G., Mander J.B., Chen S.S. (1995), "The seismic response of a 1:3 scale model RC structure with elastomeric spring dampers", *Earthquake Spectra*, 11(2), 249-267.

Poljanšek, M., Taucer, F., Chrysostomou, C., Kyriakides, N., Onoufriou, T., Roussis, P., Kotronis, P., Panagiotakos, T., Kosmopoulos, A., Molina, J.R. (2014) "Seismic retrofitting of RC frames with RC infilling (SERFIN Project)", Research Report No. 227887, Joint Research Centre, Ispra, Italy.

Pohoryles DA, Bournas DA, (2020) "Seismic retrofit of infilled RC frames with textile reinforced mortars: State-of-the-art review and analytical modelling", Composites Part B: Engineering, 183, 107702, doi:10.1016/j.compositesb.2019.107702.

Pohoryles DA, Maduta C, Bournas DA, Kouris LA. (2020) "Energy performance of existing residential buildings in Europe: A novel approach combining energy with seismic retrofitting", Energy and Buildings, 223, 110024. https://doi.org/10.1016/j.enbuild.2020.110024.

Pohoryles, D. A. and Bournas, D. A., iRESIST+ Innovative seismic and energy retrofitting of the existing building stock, EUR 30583 EN, Publications Office of the European Union, Luxembourg, 2021, ISBN 978-92-76-29687-4, doi:10.2760/768985, JRC123638.

Pohoryles, D.A., Bournas, D.A., Da Porto, F., Caprino, A., Santarsiero, G. and Triantafillou, T. (2022) "Integrated Seismic and Energy Retrofitting of Existing Buildings: A State-of-the-Art Review", Journal of Building Engineering, Vol 61, 105274. https://doi.org/10.1016/j.jobe.2022.105274

Raoof S.M., Bournas D.A. (2017a), "Bond between TRM versus FRP composites and concrete at high temperatures", *Composites Part B: Engineering*, 127, 150–165, doi:10.1016/j.compositesb.2017.05.064.

Raoof S.M., Bournas D.A. (2017b), "TRM versus FRP in flexural strengthening of RC beams: Behaviour at high temperatures", *Composites Part B: Engineering*, 154, 424–437, doi:10.1016/j.conbuildmat.2017.07.195.

Ricles J.M., Sause R., Garlock M.M., Zhao C. (2001), "Posttensioned seismic-resistant connections for steel frames", *Journal of Structural Engineering*, 127(2), 113–122.

Roeder C.W. (1998), "Overview of hybrid and composite systems for seismic design in the United States", *Engineering Structures*, 20(4-6), 355-363.

Sagar S.L., Singhal V., Durgesh C.R. (2019), "In-plane and out-of-plane behavior of masonry-infilled RC frames strengthened with fabric-reinforced cementitious matrix", *Journal of Composites for Construction*, 23(1), 04018073.

Saneinejad A., Hobbs B. (1995), "Inelastic design of infilled frames", *Journal of Structural Engineering*, 121(4), 634-650.

Soong T.T., Spencer B.F. Jr. (2002), "Supplemental energy dissipation: state-of-the-art and state-of-practice", *Engineering Structures*, 24(3), 243-259.

Teng J.G., Yu T., Fernando D. (2012), "Strengthening of steel structures with fiber-reinforced polymer composites", *Journal of Constructional Steel Research*, 78, 131-143.

Tetta Z.C., Koutas, L.N., Bournas, D.A. (2015), "Textile-reinforced mortar (TRM) versus fibre-reinforced polymers (FRP) in shear strengthening of concrete beams", *Composites Part B: Engineering*, 77, 338-348.

Tetta Z.C., Koutas L.N., Bournas D.A. (2016), "Shear strengthening of full-scale RC T-beams using textile-reinforced mortar and textile-based anchors", *Composites Part B: Engineering*, 95, 225-239.

Tetta Z.C., Bournas D.A. (2016), "TRM versus FRP jacketing in shear strengthening of concrete members subjected to high temperatures", *Composites Part B: Engineering* 106, 190-205.

Tetta Z.C., Triantafillou T.C., Bournas D. A. (2018). "On the design of shear-strengthened RC members through the Use of textile reinforced mortar overlays", *Composites Part B*, 147, 178-196.

Tomaževič M., Klemenc I., Weiss P. (2009), "Seismic upgrading of old masonry buildings by seismic isolation and CFRP laminates: a shaking-table study of reduced scale models", *Bulletin of Earthquake Engineering*, **7** (1), 293-321.

Tremblay R., Bruneau M., Nakashima M., Prion H.G.L., Filiatrault A., De Vall R. (1996), "Seismic design of steel buildings: lessons from the 1995 Hyogoken Nanbu Earthquake, *Canadian Journal of Civil Engineering*, 23(3), 757-770.

Triantafillou T.C. (2001), "Seismic retrofitting of structures using FRPs", *Progress in Structural Engineering and Materials*, 3(1), 57-65.

Triantafillou T.C. (2016) editor, *Textile fibre composites in Civil Engineering*, Woodhead Publishing.

Triantafillou T.C., Papanicolaou C.G, Zissimopoulos P., Laourdekis T. (2006), "Concrete confinement with textile-reinforced mortar jackets", *ACI Structural Journal*, 103(1), 28-37.

Triantafillou T.C., Papanicolaou C.G (2006), "Shear strengthening of reinforced concrete members with textile reinforced mortar (TRM) jackets", *Materials and Structures*, 39(1), 93-103.

Triantafillou T.C., Karlos K., Kefalou K., Argyropoulou E. (2017). "An innovative structural and energy retrofitting system for URM walls using textile reinforced mortars combined with thermal insulation: Mechanical and fire behaviour", *Construction and Building Materials* 133, 1–13.

Triantafillou T.C., Karlos K., Kapsalis P., Georgiou L. (2018), "Innovative structural and energy retrofitting system for masonry walls using textile reinforced mortars combined with thermal insulation: In-plane mechanical behaviour", *Journal of Composites for Construction*, 22(5), doi:10.1061/(ASCE)CC.1943-5614.0000869.

Tsantilis A.V., Triantafillou T.C. (2018), "Innovative seismic isolation of masonry infills using cellular materials at the interface with the surrounding RC frames", *Engineering Structures*, 155, 279-297.

Tsopelas P., Constantinou M.C. (1994), "Experimental and analytical study of a system consisting of sliding bearings and fluid restoring forces/damping devices", *Technical Report NCEER-94-0014*, National Center for Earthquake Engineering Research, Buffalo, New York, USA.

Tsionis G., Apostolska R., Taucer F. (2014), *Seismic strengthening of RC buildings*, JRC Science and Policy Reports, doi:10.2788/138156.

Turk M., Ersoy U., Ozcebe G. (2003), "Retrofitting of reinforced concrete frames with reinforced concrete infills walls", *fib Symposium on Concrete Structures in Seismic Regions*, Athens, Greece.

Tzoura E.A., Triantafillou T.C. (2016), "Shear strengthening of reinforced concrete T-beams under cyclic loading with TRM or FRP jackets", *Materials and Structures, RILEM*, 49(1), 17-28.

Uriz P., Mahin S. (2008), "Toward earthquake-resistant design of concentrically braced steel-frame structures", Report 2008/08, Pacific Earthquake Engineering Research Center (PEER), University of California Berkeley, Berkeley, CA.

Valente M. (2013), "Improving the seismic performance of precast buildings using dissipative devices", *Procedia Engineering*, 54, 795-804.

Whittaker A.S., Bertero V.V., Thompson C.L., Alonso L.J. (1991) "Seismic testing of steel plate energy dissipation devices", *Earthquake Spectra*, **7** (4), 563-604.

Xu Z.D., Wang D.X., Shi C.F. (2010), "Model, tests and application design for viscoelastic dampers", *Journal of Vibration and Control*, 17(9), 1359-1370.

Yuksel E., Ilki A., Erol G., Demir C., Karadogan H.F. (2005), "Seismic retrofit of infilled reinforced concrete frames with CFRP composites", In book: *Advances in Earthquake Engineering for Urban Risk Reduction*.

Youssef, N.F.G., Bonowitz, D. Gross, J.L. (1995), "A survey of steel moment-resisting frame buildings affected by the 1994 Northridge earthquake", *Report No. NISTR 56254*, National Institute for Science and Technology, Gaithersburg, Maryland, USA.

List of abbreviations and definitions

ADAS	Added Damping and Stiffness
AFRP	Aramid Fiber Reinforced Polymer
BFRP	Basalt Fiber Reinforced Polymer
BRB	Buckling-Restraint Brace
CFRP	Carbon Fiber Reinforced Polymer
EBF	Eccentrically Braced Frame
EBR	Externally Bonded Reinforcement
ECC	Engineering Cementitious Composite
EU	European Union
FRCM	Fabric Reinforced Cementitious Matrix
FRP	Fiber Reinforced Polymer
GFRP	Glass Fiber Reinforced Polymer
HPRFC	High Performance Fiber Reinforced Concrete
HPFRCC	High Performance Fiber Reinforced Cementitious Composite
MR-MD	Magnetorheological Mass Driver
NSM	Near Surface Mounted
PET	Polyethylene Terephthalate
PGA	Peak Ground Acceleration
PSD	Pseudo-Dynamic Test
RC	Reinforced Concrete
TMD	Tuned Mass Damper
TRC	Textile Reinforced Concrete
TRM	Textile Reinforced Mortar
UHPFRC	Ultra High Performance Fiber Reinforced Concrete
URM	Unreinforced Masonry

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