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Innovative Materials for Seismic and Energy Retrofitting of the Existing EU Buildings

Dionysios Bournas

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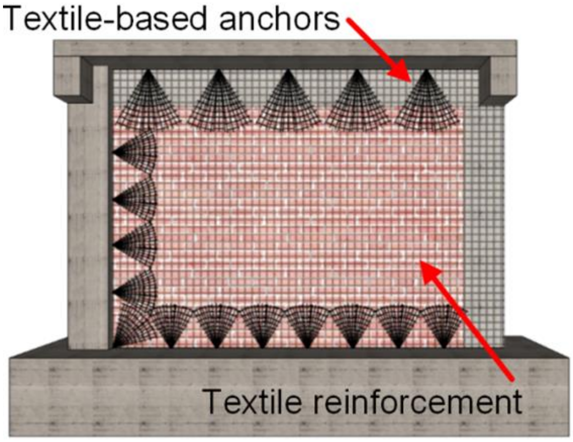

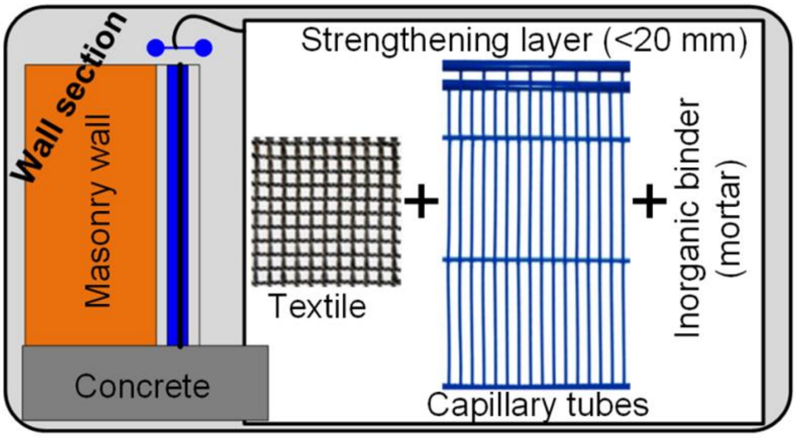

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Abstract

The seismic and energy retrofitting of existing European buildings with innovative materials is addressed in this report. The need for retrofitting of old buildings emanates from their substandard design in terms of both earthquake resistance and thermal insulation. This is revealed during strong earthquakes that result in collapses and damages of old buildings and consequently in economic losses, severe injuries and loss of human lives. Moreover, the poor energy performance of old building envelopes increases their energy consumption. The objective of this report is to explore innovative solutions for seismic and energy retrofitting of existing buildings. Towards such an objective, this report conducts a state-of-the-art review on advanced materials and solutions for enhancing the safety, energy and resource efficiency of the deficient EU residential buildings. Following the consideration of the conventional and state-of-the-art building materials and solutions, the report goes beyond the state-of-the-art by introducing. At the end the main challenges that need to be addressed in building retrofitting projects are listed (cost, sustainability, durability), and recommendations for future research activities towards sustainable buildings retrofitting are proposed. Finally, the socio-economic and environmental impact expected from such research projects is preliminary assessed.

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Abstract

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1 Introduction

1.1 General

Collapses or serious damages of existing old buildings during strong earthquakes have resulted in significant economic losses, severe injuries and loss of human lives (i.e. Athens, Greece 1999; L' Aquila, 2009; Emilia 2012, Central Italy 2016). Moreover, the low energy performance of old buildings, which is mainly attributed to the low thermal insulation of their envelopes, increases significantly their energy consumption. Therefore there is a tremendous (socio-economic and environmental) need to enhance the safety, energy efficiency and durability of the existing building stock in a cost-effective way.

Replacing the low energy performance and seismic vulnerable buildings in the near future with new is not a viable option as it would be prohibitively expensive. For this reason a shift from new construction towards renovation and modernisation has been witnessed in the European construction sector, between 2004 and 2013, with practically 50% of the total construction output being renovation and structural rehabilitation. (i.e. €305bn turnover on rehabilitation and maintenance works in EU-27 for 2012, see *www.fiec.eu*). Currently energy and structural retrofitting are treated separately, and therefore meeting both needs is prohibitively expensive.

The **overall objective** of this report is to explore innovative solutions for **seismic and energy retrofitting** of existing **buildings**. To work towards such an objective a **state-of-the-art review on advanced materials and solutions** for enhancing the safety, energy and resource efficiency of existing buildings is conducted. To achieve impact and cost effectiveness, a novel approach is developed in this report, proposing for the first time a hybrid **structural-plus-energy retrofitting solution** based on innovative lightweight materials for building envelopes, aiming to simultaneously increase their seismic resistance and energy efficiency.

Chapter 1 introduces the need for seismic and energy retrofitting of existing buildings, highlighting the impact of the building sector on the EU economy, energy and environment and also summarises the relevant to the construction sector EU policies. **Chapter 2** reviews the EU building stock with the aim of capturing the deficiencies in the existing buildings envelopes designed without provisions for seismic safety and energy efficiency. A state-of-the-art review on retrofitting materials and solutions is presented in **Chapter 3**, addressing conventional, state-of-the-art and future materials and solutions for seismic and energy retrofitting. Then **Chapter 4**, after naming the main challenges (cost, sustainability, durability) that need to be addressed in building retrofitting projects, it identifies the research needs and finally recommends areas and projects that the SSB Unit could expand its future activities. The socio-economic and environmental impact expected from such research projects is preliminary assessed in **Chapter 5**. Finally, the main findings of this work are summarised in **Chapter 6**.

1.2 Impact of the Building sector on the EU Economy, Energy Consumption and Environment

The 2014 statistics from the European Construction Industry Federation (FIEC)[1] report that construction is the largest European single activity accounting for 9.2 % of the EU-28 GDP worth just above EUR 1.2 trillion, when considering the extended value chain (i.e. the manufacture of construction products, architecture and engineering). It is the biggest European industrial employer accounting for 28.7% of industrial employment (6.5% of total employment), directly involving nearly 15 million people within more than 3 million enterprises, 95% of which being SMEs with less than 20 people. FIEC estimates

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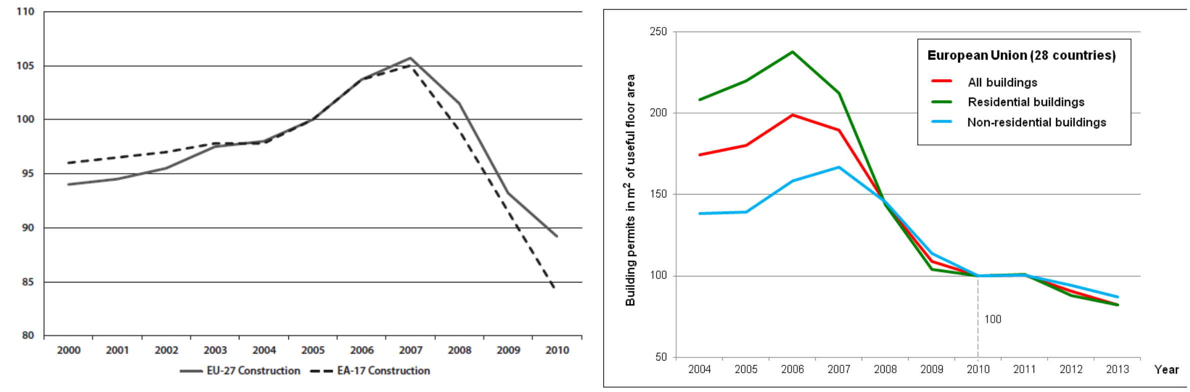
[1] http://www.fiec.eu/en/the-construction-industry/in-figures.aspx

that 42.3 million workers in the EU depend, directly or indirectly, on the construction sector. The **building sector contributes about 80% in the construction sector** (the rest 20% is civil engineering works), and therefore plays a unique role in the EU economy.

At the same time, the building stock is the largest single consumer of energy in Europe as it accounts for around 40% of the total energy usage, making buildings responsible for 38% of the EU's total CO_2 emissions. Large parts of this energy usage and CO_2 emissions are directly related to the heating and cooling of buildings [1]. More particular, the building stock accounted for 68% of total gas consumption in the EU in 2012, which represented 35% of all gas imports. The building stock's exposure to gas supply disruptions varies among Member States, depending on the proportion of gas consumed in buildings and the origin of gas imports. In this framework, the building industry could be one of the key enablers for achieving both the 2050 decarbonisation goal of the European economy and a stable and abundant energy supply for Europe [2].

1.3 The critical role of refurbishment of existing buildings

Before the financial and economic crisis, the construction of new residential buildings was growing more, and more steadily, than that of non-residential buildings. Since 2006-2007, the financial and economic crisis has significantly impacted on the activities in the building sector. Eurostat reports that the sector continues to experience a significant reduction in the construction outputs (Fig. 1.1). The construction of new buildings has been also hit by the oversupply of buildings in some Member States (i.e. Spain). As a result, the maintenance of existing buildings is progressively becoming the major activity for the sector. It worth's mentioning that the specialized construction activities that included **renovation work and energy retrofits accounted for 66 % of total building output** (Table 1.1) in EU-28 [3]. Considering also that half of the existing building stock in 2012 is expected to be operational by 2050 (BPIE)[2], it becomes apparent that tackling refurbishment of existing buildings is a top European priority for addressing both their needs in terms of safety and energy efficiency.



(a) (b)

Figure 1.1 (a) EU-27 & EA-17 Construction output (production index[3], 2000-2010,annual data, 2005=100, Source: Eurostat; (b) Building permit indices (m^2 of useful floor area) Source [3]; dSource: Eurostat, building permits-annual data http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=sts_cobp_a&lang=end

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[2] The institute was founded in 2010, by the ClimateWorks, the European Climate Foundation and the European Council for an Energy Efficient Economy (ECEEE), providing analyses targeted at the Energy Performance of Buildings Directive (EPBD).

Table 1.1 Value added of the building sector (EU/2011)[3].

	Value added (€ billions)
Total non-financial business economy	**6,077**
Total construction	**501**
Construction of buildings	144
Specialised construction activities	283
Total buildings	**427**

Key point: Specialised construction activities that include renovation work and energy retrofits add almost twice as much value as the construction of buildings [3]. Source: Eurostat, (NACE Rev. 2) http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=sbs_na_sca_r2&lang=en

1.4 The Policy context

The impact of the construction sector on the economy, energy consumption, and the environment, as well as the need to retrofit existing buildings to ensure sustainability in all these sectors is reflected in many recent EU policies. This section presents a brief summary of the existing EU policy framework aiming to identify environmental and resource efficiency policies that are of significance to the built environment and the construction sector. The EU has developed a series of policy frameworks that establish relevant macro-objectives for the economy as a whole, cities and urban areas, individual building performance, construction products and specific industrial activities in the supply chain. These take a number of different forms:

- *Programmes, strategies and blueprints for action: These encompass the 7th Environment Action Programme, EU climate change policy, urban policy, resource efficiency, circular economy, and the management of natural resources;*
- *Directives and Regulations requiring action: These encompass energy performance and supply, construction products and manufacturing, construction and demolition waste and the management of natural resources.*

The policy frameworks identified, the form they take and their macro-objectives are in turn briefly reviewed for their relevance in Table 1.2. The detailed review of those EU policies, some additional ones, as well as the corresponding policies from Member States are presented in a forthcoming JRC report [4].

Table 1.2 Summaries of Policies Relevant to the Built Environment and the Construction Sector

Name of the Policy Document	**Policy Relevance to the Built Environment and the Construction Sector**
Programmes, strategies and blueprints for action	
The 7th Environment Action Programme of the European Union (**EAP**) [5]	• Re-enforces the 2020 objective of creating a '*low carbon and resource-efficient economy*'. • Sets out objectives to reduce the overall impact of resource use and enhancing the sustainability of cities. • Addresses adverse impacts on the climate, forests, air quality, waste and land degradation.
EU Strategy on adaptation to climate change (2013) [6]	• Need for the '*climate proofing*' of cities as well as physical infrastructure and assets. • Major threats to buildings and constructions are identified as[4]: Extreme precipitation; Extreme summer heat events; Exposure to heavy snow fall; Rising sea levels increasing the risk of flooding. • Overheating of built environment has implications for building materials and for the comfort and wellbeing of occupiers.
Thematic Strategy for the Urban Environment (2006)	• Better urban planning to support EU legislation, including the co-ordination of land use planning with sustainable urban transport; • A priority focus on transport and buildings, including setting and enforcing standards on sustainable construction and supporting the retrofitting of existing buildings;
The Raw Materials Initiative (2011)	• Resource efficiency and supply of 'secondary raw materials' through recycling • Production using recycled materials is often much less energy intensive than manufacturing goods from virgin materials. Recycling can thus reduce production costs and GHG emissions and has a great potential to improve Europe's resource efficiency.
The Roadmap to a Resource Efficient Europe (2011) [7]	• Highlights the significant impact of construction on natural resources • Outlines how Europe's economy can be transformed into a sustainable one by 2050 by increasing resource productivity and decouple economic growth from resource use and its environmental impact. • Highlights how more efficient construction and use of buildings in the EU would influence approximately 42% of final energy consumption, 35% of greenhouse gas emissions, more than 50% of all extracted materials and up to 30% of water. • It proposes that existing policies for promoting energy efficiency and renewable energy use in buildings should be complemented with policies for wider resource efficiency. Such policies would address a range of environmental impacts along the life-cycle of buildings.
An EU action plan for the Circular Economy (2015)	• Measures to address the whole (construction/building) materials cycle, from production and consumption through to waste management and the use of recycled (secondary) raw materials, with the aim of contributing to 'closing the loop' of product lifecycles through greater recycling and re-use. • Seeks to make links to other EU priorities, including creating jobs and growth, industrial innovation and tackling climate change. • The package also makes specific reference to the development of a common framework of indicators for buildings in application of COM

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[4] Commission Staff Working Document, Adapting infrastructure to climate change, SWD(2013) 137, Brussels, 16.4.2013

	(2014)445 [8]. • Construction and demolition are identified as a priority area. The significant volume of waste, the wide variance in re-use and recycling rates across the EU and the role of the construction sector in influencing the performance of buildings throughout their life are highlighted. • Design improvements to buildings to increase their **durability** and **recyclability**.
Directives and Regulations requiring action	
Energy Performance of Buildings Directive (2010) [9]	• The construction and refurbishment of buildings in order to reduce energy use and CO_2 emissions is a central environmental policy objective for Europe. • The recast *Energy Performance of Buildings Directive 2010/31/EU (EPBD)* sets out requirements for buildings that contribute towards ambitious EU targets for energy efficiency by 2020. Member States to transpose into national legislation: o Minimum, cost optimal energy performance requirements for new buildings, for major renovation of buildings and for the replacement or retrofit of building elements (i.e. heating and cooling systems, roofs, walls); o The inclusion of energy performance certificates in all advertisements for the sale or rental of buildings; o All new buildings must be '*nearly zero energy*' by 31 December 2020 and all public buildings by 31 December 2018. • It refers to '*high efficiency*' systems that use the electricity from the grid more efficiently to provide heating or cooling (i.e. heat pumps) or which use fuels more efficiently to generate electricity, heating and cooling (i.e. Combined Heat and Power supplying district heating and cooling). • The new Communication on the Energy Union [10] highlights the efficiency gains from district heating and cooling, noting that it will be addressed by a future Commission Strategy.
The Energy Efficiency Directive (2012) [1]	• Package of energy efficiency measures that Member States must implement in order to meet the EU's 2020 target for energy efficiency. • Key focus on raising the energy efficiency of new and existing buildings. • EU countries must establish national plans for **renovating** their **existing building stock** which currently accounts for approximately **38% of the EU's CO2 emissions**. These plans shall include the '*identification of <u>cost-effective approaches to renovations</u> relevant to the building type and climatic zone*' and '*policies and <u>measures to stimulate cost-effective deep renovations of buildings</u>, including staged deep renovations*'. • A **specific renovation rate of 3%** of the total floor area of central **government buildings** to the minimum EPBD levels is set as a target. The Directive also incorporates the definitions of '*high efficiency*' cogeneration from the repealed Cogeneration Directive.
The Renewable Energy Directive (2009)	• *Member States shall introduce in their building regulations and codes appropriate measures in order to increase the share of all kinds of energy from renewable sources in the building sector*'. • Member States shall also ensure that new public buildings and existing buildings subject to major renovation '*fulfil an exemplary role*'.
The Construction Products Regulation (2011)	• Reliable information on the performance of construction products by providing a '*common technical language*' based on uniform assessment methods of the performance of construction products. This is to be implemented by: o Manufacturers when declaring the performance of their products,

[11]	○ The authorities of Member States when specifying requirements for them. ○ Users (architects, engineers, constructors etc.) when choosing the products most suitable for their intended use in construction works. • Basic requirements for construction works' which include specific reference to emissions to the environment (requirement 3) and the sustainable use of natural resources (requirement 7). Basic requirement 7 states that: *'the construction works must be designed, built and demolished in such a way that the use of natural resources is sustainable and in particular ensure the following:* ○ *reuse or recyclability of the construction works, their materials and parts after demolition;* ○ *durability of the construction works;* ○ *use of environmentally compatible raw and secondary materials in the construction works.'*
The Industrial Emissions Directive (2010) [12]	• Applies to a range of production processes for materials and products that form a significant component of EU building material flows, i.e. cement works, the processing of metals, the manufacturing of glass, ceramics and polymers. Permitting shall take into account integrated performance standards, emissions limit values.
The Waste Framework Directive (2008) [13]	• Construction and demolition waste (CDW) accounts for between 25% and 30% of the waste generated in the EU • CDW has been identified as a priority waste stream by the European Union because there is a high potential for recycling and re-use of this waste type, based on the potential value and the use of well-developed technologies and strategies. • *Member States shall take the necessary measures designed to achieve that by 2020 a minimum of 70% (by weight) of non-hazardous construction and demolition waste (excluding naturally occurring material defined in category 17 05 04 in the List of Wastes) shall be prepared for re-use, recycled or undergo other material recovery.* • The Waste Framework Directive has the high level aim of moving towards a *'European recycling society with a high level of resource efficiency*'. Based on a recent assessment of CDW, the potential for increasing the level of recycling and re-use is significant, with performance at Member State level varying between under 10% and over 90%. The average recycling rate was calculated as part of the same assessment to be 46% across the EU.

2 Review of existing deficient buildings envelopes

2.1 Split of the EU building stock

The total amount of residential and commercial buildings was estimated in 2013 to be 233 million in the EU-27 [14]. In terms of floor area, **residential buildings make up to 75% of building stock** followed by retail (7%), offices (6%), education (4%), hotels and restaurants (3%) and healthcare (2%), sports facilities (1%) and other uses (2%). It is estimated that 12% of the building stock is public and 88% are private buildings. The residential buildings which account for the largest share tend also to have longer life and slower replacement rate, resulting in progressively older building stock with high maintenance needs for achieving modern buildings performance both in terms of safety (i.e. Eurocodes) and energy performance (i.e. EPBD).

Figure 2.1 illustrates the age of the residential building stock, with the big majority of the stock being pre-1990 [15]. With an estimated annual replacement rate 1-2% and a renovation rate of between 0.5% and 1.2% for the EU building stock, **the performance of the existing buildings** is therefore significantly **more important** within the short to medium term than new buildings.

This explains why the market has seen an increased focus on better use of existing building assets, reflected in a wider trend in EU office markets – both public and private - for major renovations instead of new-build projects. Inclusion of existing buildings within the scope is also important because of the stock of materials and structures contained within those buildings. Estimates from Germany, for example, suggest that the country's built environment forms a repository of approximately 50 billion tonnes [16].

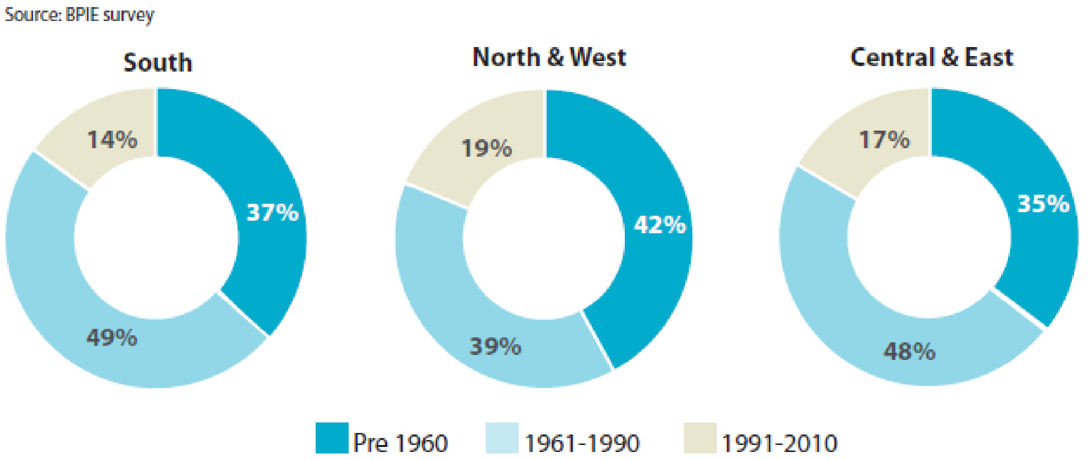


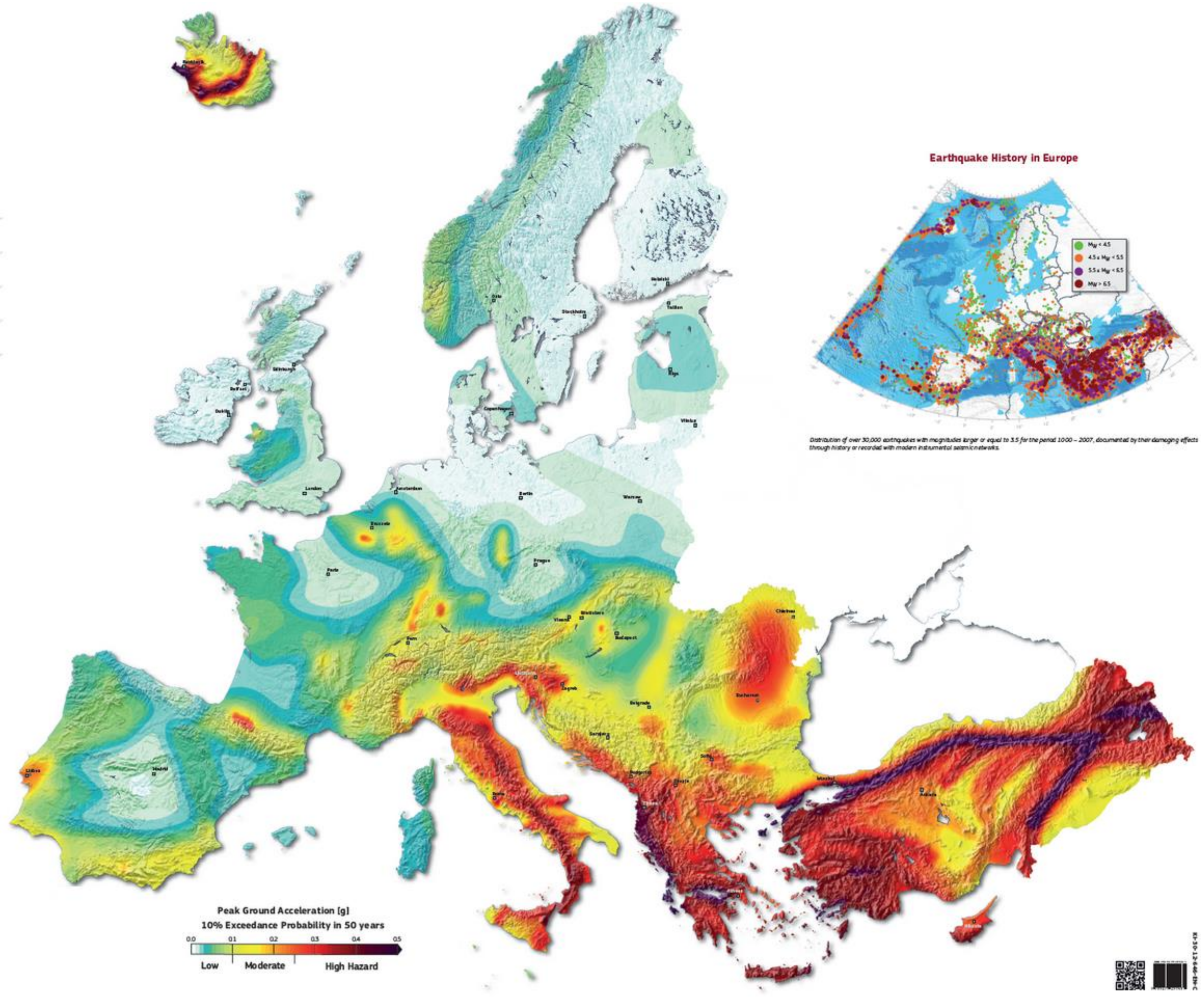
Figure 2.1 Age categorisation of housing stock in Europe; Source [15]

This report focuses on existing reinforced concrete (RC) and masonry buildings which account for the big majority of buildings in most of the Member States. As it is further explained in the following sections, the application of modern codes for seismic and energy design of buildings followed a parallel road for European countries, as it started in the 80s or 90s among different Member States. Therefore, the vulnerabilities of RC and masonry building envelopes are considered both in terms of seismic safety and energy performance, with the aim of suggesting retrofitting solutions based on advanced construction materials.

2.2 Seismic activity in Europe and seismic deficiencies of RC Building Envelopes

2.2.1 Seismic activity in Europe

Figure 2.2 presents the European-Mediterranean Seismic Hazard Map, edited in 2013 by Giardini et al. for the EU-FP7 SHARE Project. This map depicts Peak Ground Acceleration (PGA) with a 10% chance of exceedance in 50 years for a firm soil condition. The map colours correspond to the actual level of the hazard: the cooler colours represent lower hazard while the warmer colours are associated with higher hazard (Giardini et al., [17]).



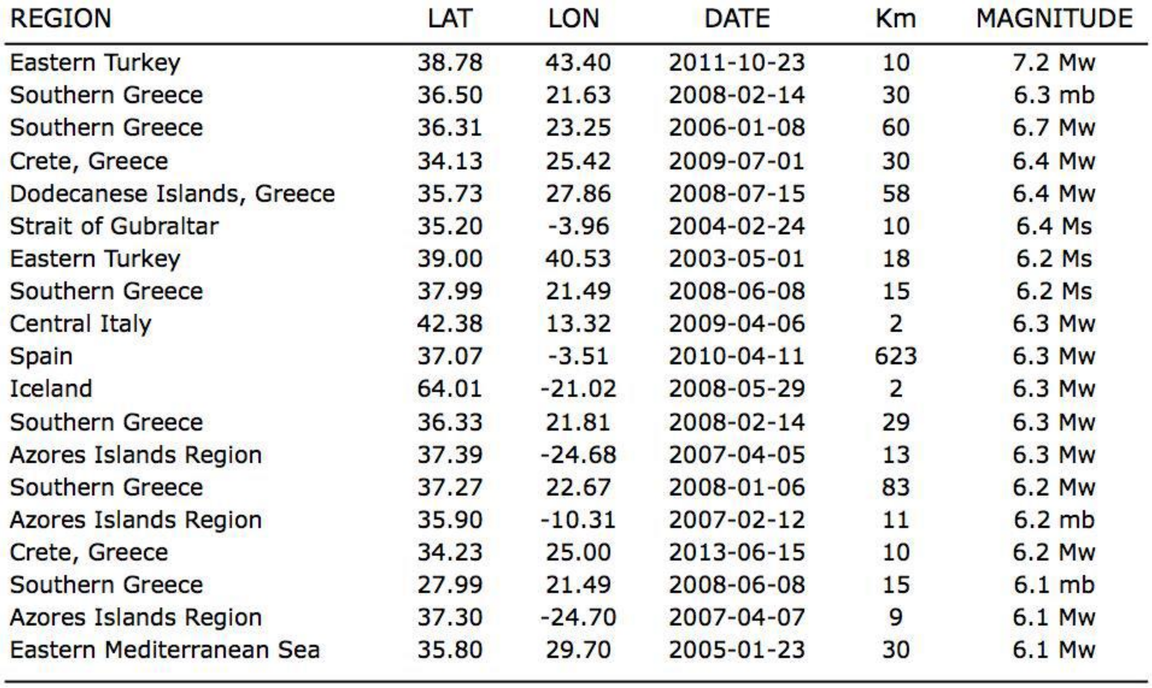
Distribution of over 30,000 earthquakes with magnitudes larger or equal to 3.5 for the period 1000 – 2007, documented by their damaging effects through history or recorded with modern instrumental seismic networks.

Figure 2.2 European-Mediterranean Seismic Hazard Map; Source [17].

The map shows that the highest earthquake hazard is concentrated in Iceland and in the south-eastern areas of Europe. In particular the most hazardous countries are Greece, Italy, Turkey, Romania and the Balkan region, with PGA values exceeding the 0.4g. On the other hand, Spain, Portugal, France, Germany and Belgium are European countries with low/moderate hazard, although some of them (i.e. Portugal) have experienced devastating earthquakes through their distant and recent past.

The European seismic activity is recorded on a real time basis in the whole European-Mediterranean region. Seismological data are collected from different institutes, notably the EMSC (www.emsc-csem.org). The strongest earthquakes in the Euro-Med region in the last decade are reported in Table 2.1. It could be seen that they are all located in the highest European hazard zones (Turkey, Greece, Italy, Spain, Iceland) [18].

Table 2.1 The strongest earthquakes in the Euro-Med zone for the period 2003-2013 (data source: www.seismicportal.eu) [18].



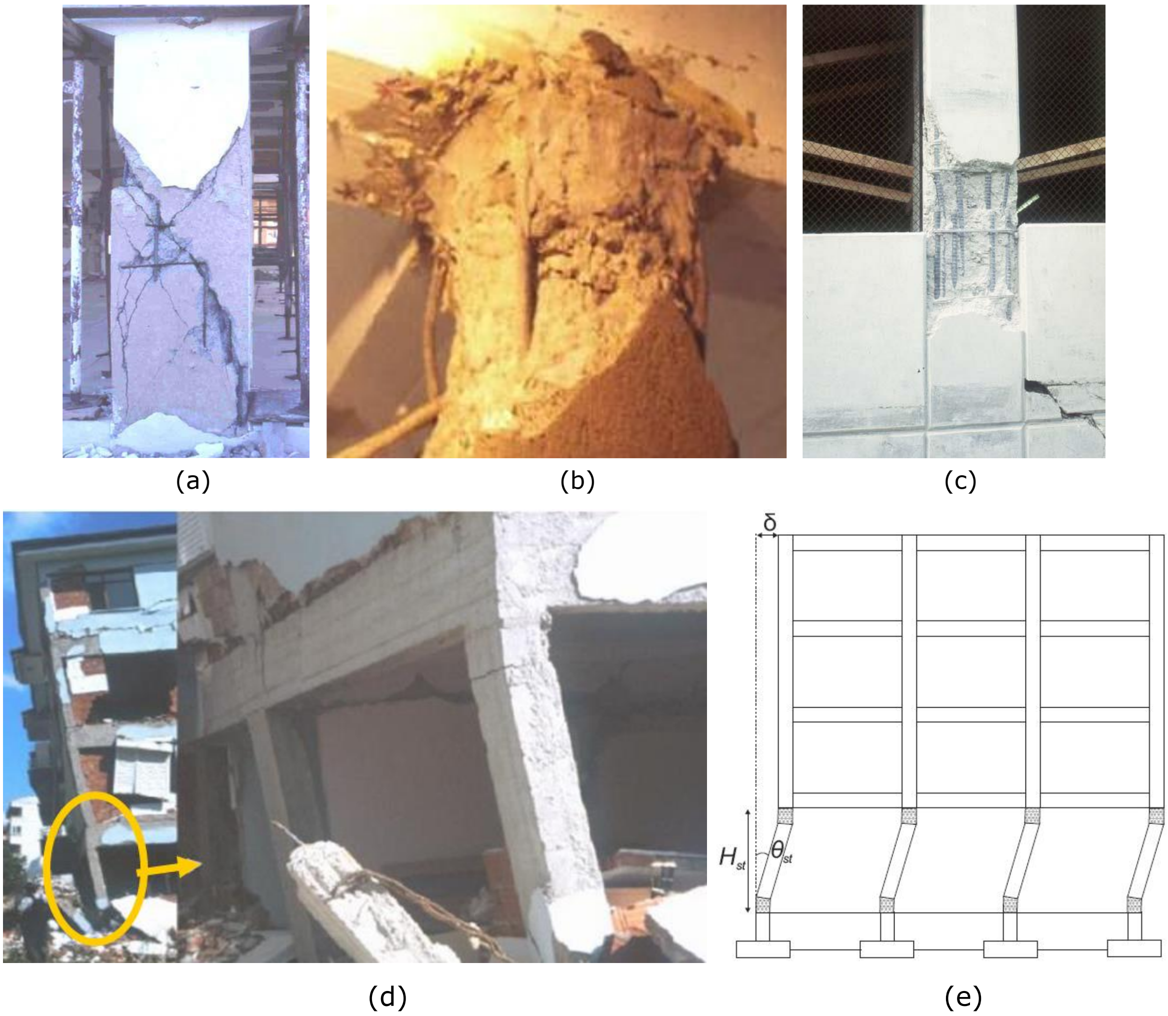
REGION	LAT	LON	DATE	Km	MAGNITUDE
Eastern Turkey	38.78	43.40	2011-10-23	10	7.2 Mw
Southern Greece	36.50	21.63	2008-02-14	30	6.3 mb
Southern Greece	36.31	23.25	2006-01-08	60	6.7 Mw
Crete, Greece	34.13	25.42	2009-07-01	30	6.4 Mw
Dodecanese Islands, Greece	35.73	27.86	2008-07-15	58	6.4 Mw
Strait of Gubraltar	35.20	-3.96	2004-02-24	10	6.4 Ms
Eastern Turkey	39.00	40.53	2003-05-01	18	6.2 Ms
Southern Greece	37.99	21.49	2008-06-08	15	6.2 Ms
Central Italy	42.38	13.32	2009-04-06	2	6.3 Mw
Spain	37.07	-3.51	2010-04-11	623	6.3 Mw
Iceland	64.01	-21.02	2008-05-29	2	6.3 Mw
Southern Greece	36.33	21.81	2008-02-14	29	6.3 Mw
Azores Islands Region	37.39	-24.68	2007-04-05	13	6.3 Mw
Southern Greece	37.27	22.67	2008-01-06	83	6.2 Mw
Azores Islands Region	35.90	-10.31	2007-02-12	11	6.2 mb
Crete, Greece	34.23	25.00	2013-06-15	10	6.2 Mw
Southern Greece	27.99	21.49	2008-06-08	15	6.1 mb
Azores Islands Region	37.30	-24.70	2007-04-07	9	6.1 Mw
Eastern Mediterranean Sea	35.80	29.70	2005-01-23	30	6.1 Mw

2.2.2 Structural member deficiencies and collapse mechanisms

The progress made in earthquake engineering over the last few decades has a tremendous impact on the seismic safety of modern RC buildings designed according to new standards (i.e. Eurocode 8). However, as analysed in the section 2.1, the vast majority of the existing buildings do not meet the safety requirements of Eurocodes. This is in fact very unpleasantly proved by every recent earthquake that repeatedly highlights the vulnerability of these older RC structures, which have on occasion proved to be fatal to human life.

Old, substandard RC structures exist, not only due to poor workmanship and poor material quality but also due to ageing and misuse. Their biggest handicap is that they were built at times when general understanding about the importance of reinforcement detailing was still at its infancy. In the period referred to, the design philosophy was based on allowable stress design (mainly considering gravity loads, without adequate provision for seismic detailing), and therefore there was no control of the mode of failure and the corresponding deformation capacity of the individual members. As summarised by Thermou and Pantazopoulou [19], if a general attribute may be sought to describe old existing RC buildings, it would be: light reinforcing details, frequently unfavourable distribution of stiffness and mass and complete lack of any capacity design considerations. As a rule, in former European codes seismic coefficients were assigned low values. Since then, these have been reset to 3–4 fold their original values [19].

For what concerns the structural members, earthquakes have exposed the vulnerability of RC columns to seismic loading. Poorly detailed columns are the most critical structural elements, which may fail due to shear (Fig. 2.3a), compressive crushing of concrete and reinforcing bar buckling (Fig. 2.3b), bond at lap splices (Fig. 2.3c), and flexure (Fig. 2.3d). Actually, the latter case which indicates *weak-beam-strong columns* situations and is very typical for building designed without seismic considerations, could trigger a soft storey mechanism and lead to collapse. The development of such a global collapse mechanism, which is particularly critical in *pilotis-type* RC frames, is illustrated in Fig. 2.2e. Local retrofit measures based on advanced structural materials are suggested (see sections 3.1.3 and 3.1.4) to increase RC columns strength and/or deformation capacity.


(a) (b) (c)

(d) (e)

Figure 2.3 Typical failure of RC columns after earthquakes: (a) Shear failure; (b) Bar buckling; (c) loss of bond at short lap-splices; (d-e) flexural failure in a "*weak column-strong beam*" situations.

A very illustrative example on the vulnerability of two RC buildings subjected to a strong earthquake was presented by Thermou and Pantazopoulou [16]. Figures 2.4a and b depict pictures from two residential, two-storey RC houses in Vartholomio, Western Peloponesse that were subjected to the 6.5 magnitude in the Richter scale of the 6/8/2008 Pyrgos (Greece) earthquake. Both were built in the early 1980s, with similar materials and methods; the one that collapsed (Fig. 2.4a) featured a soft first storey, whereas the other, with masonry infills in the first storey, sustained a serious damage without collapse (Fig. 2.4b). Due to their small size the base shear attracted by the two structures was not excessive; the collapsed structure failed at a low displacement, equal to 25% of the yield value, i.e. whereas still in the elastic range. Thus, it was not lack of flexural inelastic deformation capacity, but lack of stiffness and shear strength that led it to collapse. In buildings with the pathogenicity described, the reduction of seismic displacements through control of the lateral stiffness is vital for the survival of the building during strong ground motion. To increase sufficiently the lateral stiffness a global retrofit measure including most possibly the addition of shear walls is required (see section 3.1.2).


(a) (b)

Figure 2.4 (a) and (b) Residential houses in Vartholomio; Source [19].

2.2.3 Non-structural elements (in and out-of-plane failures)

Numerous surveys carried out in the aftermath of recent earthquakes in Europe (i.e. L'Aquila 2008; Kefalonia 2014) showed that the vast majority of the existing RC multi-storey buildings did not collapse. However, non-structural damage was extensive as shown in Fig. 2.5. In many cases, masonry infill failed with out-of-plane (Fig. 2.5a and b) mechanisms because of the weak connections between the interior and exterior walls (i.e. Verderame et al., [20]); sometimes the connections were absent and the brick walls possessed high slenderness. The in-plane failure of masonry infills (Fig. 2.5c and d).


(a) (b)

(c) (d)

Figure 2.5 Example of damage to masonry infills in RC multi-storey buildings: (a)-(b): L'Aquila 2008, M_s 6.3; Source [21]; (c)-(d) Kefalonia 2014, M_s 5.9; Source [22].

The effect of masonry infills over the entire response curve of existing reinforced concrete (RC) structures subjected to earthquake loading is significant, both before separation of the infill from the surrounding frame occurs—as encountered during frequent earthquakes—and during large cycles of imposed deformations near collapse [23]. As reported in the literature, the most common beneficial contribution of the infills is the increase in both the global lateral stiffness and shear strength of infilled frames and their contribution to the global energy dissipation capacity (i.e., Mehrabi et al. [24]; Fardis and Panagiotakos [25]). Nevertheless, the presence of infills induces or aggravates potential adverse effects, with the most critical one being the potential brittle shear failure of columns due to the additional shear demand in the column end-region where the so-called diagonal strut of the infilling is in contact with the frame members. In addition, regarding multi-storey infilled RC buildings, there is a concern about the tendency for concentration of interstory drift demand and damage within the first story, ultimately leading to the development of a soft-story mechanism (Fardis [26]).

Strengthening of frame structures usually aims at increasing the resistance and deformation capacity of the frame itself, for the structure to comply with the code-prescribed levels of performance. An alternative route to improve the performance of existing structures and avoid the excessive economic consequences of infill failure is the effort of **converting infilling to a more reliable source of resistance** over the whole spectrum of structural response, **through a guaranteed and quantifiable contribution** to the **building's strength/stiffness** ([22] – more information in section 3.1.4).

2.3 Low energy performance of existing envelopes

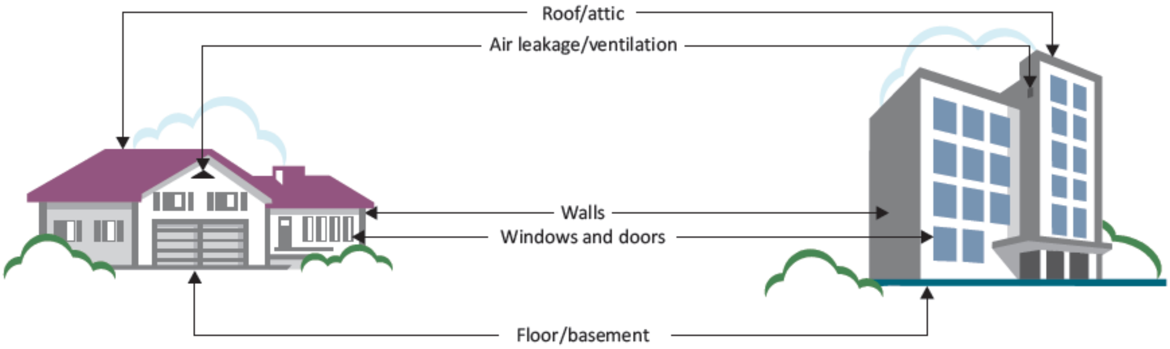
2.3.1 Age of the building versus energy performance

Similarly to the lack of old buildings design according to the Eurocodes standards, the majority of the residential housing in the EU was built before the application of energy performance requirements. The first energy codes for buildings were introduced in response to the oil crisis in the 1970s, when **66 % of the current EU building stock had already been built** (IEA-UNDP [27]). In a recent JRC report [3] it is recognised that the age profile of a building is a critical factor in estimating the depth of energy renovation needed, as the baseline for calculating energy savings potential depends on the current energy performance of the building. Age profile is also important from an industrial perspective, as the technological solutions to be implemented will differ according to when a building was built. There is a need to develop and market energy renovation 'kits' tailored to construction periods, climatic zones and building types. Three different construction periods can be considered:

- **Before 1945:** This period includes all dwellings built before the post-World War II building wave. These were built with materials and techniques reflecting local conditions. Their design often incorporated energy-sufficiency measures (i.e. bioclimatic design), so they waste less energy;
- **1945 to 1980:** Homes built in this period are the least efficient. They were built with the first industrial techniques and prior to the introduction of energy-efficiency requirements in most Member States. Some Member States brought in building energy codes after the oil crisis, but the requirements were not very stringent and most countries did not check for compliance [27]; and
- **After 1980:** In this period, all Member States introduced building energy codes as the main policy instrument to reduce the energy consumption of new buildings. From 2002, the EPBD required Member States to apply energy code provisions to existing buildings that undergo major renovation. The EPBD recast harmonised methodologies for calculating buildings' energy performance across Member States and introduced the calculation of energy requirements on the basis of a methodology for determining optimum cost-efficiency [28].

2.3.2 Review of building envelop components

The building envelope – also known as the building shell, fabric or enclosure – is the boundary between the conditioned interior of a building and the outdoors. The energy performance of **building envelope components**, including **external walls**, **floors**, **roofs**, **ceilings**, **windows** and **doors**, is critical in determining how much energy is required for heating and cooling (Fig. 2.6). Energy loss through the building envelope is highly variable and depends on numerous factors, such as building age and type, climate, construction technique, orientation, geographical location and occupant behaviour.



Note: unless otherwise stated, all material in figures and tables derives from IEA data and analysis.

Figure 2.6 Building Envelope components; Source [29].

Over the years, code requirements on building envelopes have improved significantly, and continue to increase in performance. Table 2.1 shows for example how building envelope standards in the UK have changed over time. With each revision, the building envelope standards were upgraded substantially, emphasizing the growing need for energy conservation [30]. This calls for a need for the continuous development of new materials with high thermal insulation in order to achieve as low thermal transmittance values as possible. Thermal transmittance also known as U-value, is the rate of transfer of heat through a structure (which can be a single material or a composite), divided by the difference in temperature across that structure. Its units of measurement are watts per square metre per Kelvin (W/m²K). The better-insulated a structure is, the lower the U-value will be. Workmanship and installation standards can strongly affect the thermal transmittance. If insulation is fitted poorly, with gaps and cold bridges, then the thermal transmittance can be considerably higher than desired. Thermal transmittance takes into account heat loss due to conduction, convection and radiation.

Table 2.1 Code standard U-values (in W/m^2 K) for UK buildings; Source: John et al. [31].

Envelope element	1995 Standard *U*-values (W/m^2 K)	2000 Standard *U*-values (W/m^2 K)	Percentage reduction in *U*-value (%)
Walls	0.45	0.35	22
Roofs	0.25	0.16	36
Floors	0.45	0.25	44
Windows	3.3	2.2	33

2.3.2.1 Walls

The **external walls** comprise the **major fraction of a building envelope** and are expected to provide thermal and acoustic comfort within a building, without compromising its aesthetics. The thermal resistance (R-value) of the wall is crucial as it influences the building energy consumption heavily, especially, in high rise buildings where the ratio between wall and total envelope area is high. The market available centre-of-cavity R-values and clear wall R-values consider the effect of thermal insulation. Conventionally, based on the materials used in construction, walls can be classified as wood-based walls, metal-based walls and masonry-based walls. There are other types of advanced building wall designs that are applied to improve the energy efficiency and comfort levels in buildings.

Framing structures for example allow for cavities to be filled with insulation, but the structural members remain as thermal bridges, with significantly higher heat transfer properties. High thermal mass structures were often built without any insulation but conserve some energy because of their thermal mass. Older framed structures often do not have insulation in cavities (Fig. 2.5d). Insulation strategies need to take into account these different characteristics, which can make integrated solutions very complex if they involve a variety of insulation materials. Although the big majority of RC building use single (Fig. 2.5d) or double with or without insulation (Fig. 2.5a) masonry-based walls, more advanced wall technologies (passive solar walls, lightweight concrete walls; cavity walls; precast concrete sandwich panels; walls with latent heat storage) have been developed for new buildings (i.e. Fig. 2.7). Chapter 3 provides detailed information on materials and methods for the energy retrofitting of external walls of existing buildings.

(a) (b)

Figure 2.7 Typical Cavity walls in new buildings: (a) Detail of the insulation material; (b) Mechanical connection of the wall faces.

2.3.2.2 Fenestration (windows and doors)

Windows and doors have several functions, including giving access to the building, providing outlook and letting in daylight. In specifying window performance for a specific region, it is necessary to consider both heating and cooling loads to maximise performance and achieve the lowest total annual energy impact, or best energy balance. In some climates, a positive energy balance – or energy gain – can be achieved using advanced static glazings combined with well-insulated window systems and architectural shading optimised for seasonal impacts (i.e. a triple-glazed window system with two layers of low-e glass, high solar heat gain, low-conductive frame, exterior shading, in a moderate European climate, [32]).

Although most cold-climate OECD member countries are making a significant effort to promote high - performance windows, triple-glazed windows, have not achieved full market share in any country. Triple glazing with clear glass was more prevalent in Northern European countries but then diminished because manufacturers were able to achieve comparable performance using modern, double-glazed, low-e coated windows. This trend is changing, however, with the promotion of the Passivhaus programme and recent more stringent building codes. Austria, Germany and Switzerland have the highest market share for triple glazing usually with two low-e surfaces, at 54% of total window sales. New construction and the residential sector have the highest market penetration. Overall, the majority of windows sold in the European Union are still double-glazed [33].

Unfortunately, windows are still being sold in many regions of the world that are only single-glazed, with clear glass and poorly insulated frames. These have U-values of approximately 4.5-5.6 W/m^2K. The majority of OECD member countries in cold climates have moved to double-glazed windows with low-e coatings, low-conductive frames, and inert gas for the residential sub-sector, with U-values of approximately 1.8 W/m^2K. As shown in Fig. 2.8, highly insulated windows such as the ones discussed above for the European Union, have U-values around 1.1 W/m^2K [29].

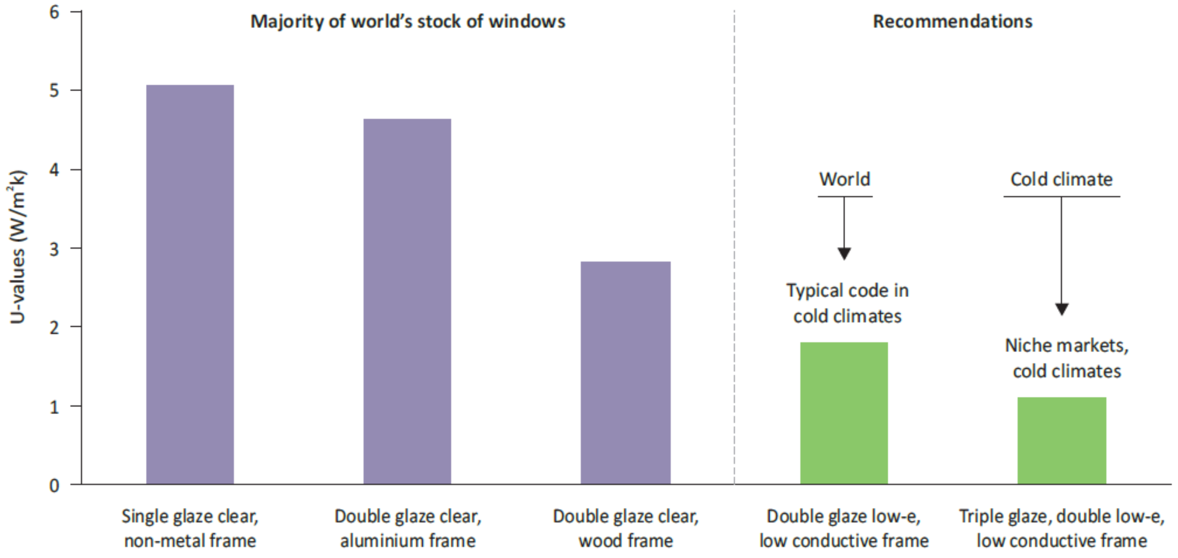


Figure 2.8 Most common types of windows in service and being sold today[5]; Source [29].

Therefore, there is a clear need to improve the energy performance in the majority of Europe's installed windows. This could be achieved (in light or deep renovation projects) by setting more stringent performance criteria for both new and existing buildings. The potential of **triple glazing windows** in penetrating the European market for energy of retrofitting of existing buildings is high, especially **in light energy renovation** projects.

2.3.2.3 Roofs

Roofs are a critical part of the building envelopes that are highly susceptible to solar radiation and other environmental changes, thereby, influencing the indoor comfort conditions for the occupants.

Roofs account for large amounts of heat gain/loss, especially, in buildings with large roof area such as sports complexes, auditoriums, exhibition halls etc. This heat gain/loss is less pronounced in residential buildings, where the exterior walls comprise the major part of the envelope. In accordance with the UK building regulations, the upper limits of U-value for flat roofs in 1965, 1976 and 1985 were 1.42W/m^{2}K, 0.6W/m^{2}K and 0.35W/m^{2}K, respectively. Currently, 0.25W/m^{2}K or less is required for all new buildings in the UK [34]. Similar trends are observed in the building standards of other Member States (i.e. Germany, France). This reduction in the U-value over the years emphasizes the significance of thermal performance of roofs in the effort to increase the overall thermal performance of buildings [30].

Roofs can be classified into different categories based on the type of construction. The most commonly used roofing structures in Europe along with recent developments include RC roofs, lightweight roofs, ventilated and micro-ventilated roofs, solar-reflective/cool roofs, green roofs and photovoltaic roofs. The last two categories together with the thermal roof insulation systems that constitute also retrofitting solutions are presented in the next section. A detailed review on all types of roofs was presented by Sadineni at al. [30].

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[5] Note: U-values presented in this roadmap represent whole-window performance unless noted in accordance with International Organization for Standardization (ISO) 15099, thus an ISO 10077 standard of 1.0 W/m2K is roughly equal to 1.1 W/m2K per ISO 15099).

2.3.2.3.1 Retrofitting of Roofs

Roof thermal insulation could be an economic and quite efficient energy retrofitting solution for low storey buildings, especially in buildings with large floor area. On the contrary, their efficiency is dramatically reduced in multi-storey buildings where the energy savings are negligible for more than three floors below the roof. In the latter case, the exterior wall and windows dominate the global energy performance of the building.

RC roofs are used in many houses in southern Europe due to its good resistance to loads and climatic conditions but also thanks to the availability and cost effectiveness of concrete ingredients. During warm summers however, they tend to exhibit unfavourable thermal characteristics such as higher soffit temperature and longer heat retaining capacity that affect the indoor air comfort conditions and increase energy costs. The indoor temperatures might exceed 35^{o}C due to high roof temperatures of about 50^{o}C or above. Higher soffit temperatures make them emit long wavelength infrared radiation towards the occupants. Even worse is that it might continue into the night due to the heat capacity of the slab. The insulation of concrete roofs with an antisolar coating was very efficient for very warm climatic conditions (i.e. Pakistan [35]). By lowering the roof temperature using this system, it was observed that the roof heat gain in summer was reduced by 45 kWh/day for a roof area of 208m^2. Also, the overall heat transfer coefficient of the roof is reduced from 3.3W/m^2 K to 0.54W/m^2 K. Therefore, simple and low cost RC roof insulation could be achieved using antisolar coatings [30].

The development of **green roofs** (partly covered with a layer of vegetation) is a widespread and environmental friendly technique for energy retrofitting of building roofs. There are two types of green roofs: intensive and extensive, the former has a deeper substrate layer and allows to cultivate deep rooting plants such as shrubs and trees; whereas the latter with thinner substrate layer allows to grow low level planting such as lawn or sedum [30]. The extensive type is most common in energy retrofitting of buildings as it can be applied without modifications to the existing roof structure and also requires minimum maintenance. It worth's noting that the typical additional load associated with an extensive green roof is about 120–150 kg/m^2 [36], which from the structural point of view is within the acceptable range of most buildings.

The moisture content in growing media of the green roof influences its insulating properties. The wetter the medium, the poorer its insulating behaviour compared to the dry growing media. The equivalent albedo of green roofs is about 0.7–0.85 as against an albedo of 0.1–0.2 for bitumen/tar/gravel roof [37]. Therefore, green roofs reflect solar radiation more efficiently than most conventional roofs. The performance of green roofs on office buildings in Athens is simulated and validated in [38]. It is observed through simulations that for a turf-type extensive green roof system installed on a non-insulated roof yielded 10.5% annual savings compared to only 0.6% annual savings when installed on an insulated roof [38]. The building energy savings and the retrofit potential of green roofs in UK have been evaluated [30].

3 Innovative materials and solutions in buildings retrofitting: State-of-the-art review

3.1 Seismic retrofitting

3.1.1 Retrofit measures and criteria

Seismic retrofit measures and criteria for existing RC buildings were recently presented in a JRC report by Tsionis et al. [39]. It is reported that deficiencies of existing buildings are revealed through structural assessment, which is followed by the selection of the most appropriate measure or combination of measures to improve the performance of the building. Guidance documents such as the fib Bulletin on Seismic Assessment and Retrofit of Reinforced Concrete Buildings (fib 2003) and the FEMA Techniques for the Seismic Rehabilitation of Existing Buildings (FEMA 2009) provide advice on the cases where each measure is most effective. In general terms, local measures are more appropriate when some elements possess insufficient capacity, whereas global measures are suitable in case of large deformation demands, including the possibility of pounding and irregularities [39].

Based on the two main objectives in seismic retrofitting (reduce demand or to increase capacity), and three main response properties under consideration (strength, stiffness and deformation capacity), Tsionis et al. [39] proposed a comprehensive summary of the most common retrofit measures together with the properties they affect (Table 3.1). It was shown that some measures impact more than one property of the structure, one of which may lead to an unfavourable effect. For example, an increase in stiffness aiming to reduce the deformation demand will lead to higher force demands that could exceed the as-built capacity of some elements. The interaction between properties at both local and global level might be critical in the process of designing the retrofit. Relevant documents (CEN 2005 [40], FOEN 2008[41]) explicitly call for the designer to consider this issue.

Table 3.1 Effect of local and global retrofit measures on building properties [39].

		Strength	**Stiffness**	**Ductility**	**Irregularity**	**Force demand**	**Deformation demand**
Local measures	Concrete jacket	✓	✓	✓		×	✓
	Steel jacket	✓		✓			
	FRP jacket	✓		✓			
	Post-tensioning	✓		✓			
	Strength reduction	×					
Global measures	New frames, shear walls, braces	✓	✓		✓	×	✓
	Mass removal				✓	✓	×
	Partial demolition				✓	✓	
	Isolation				✓	✓	✓
	Dampers		✓			×	✓
	Expansion joints				✓		
	Connect independent sections				✓		

The following sections presents a state-of-the-art review on seismic retrofitting techniques using conventional and advanced structural materials.

3.1.2 Conventional techniques and materials

Steel or RC jacketing are the most common conventional strengthening techniques which are applied to increase the strength and ductility of RC members. RC jacketing (Fig. 3.1) of columns is widely used in seismic rehabilitation of old buildings as it can increase considerably the strength of columns when weak columns-strong beam situations are met (i.e. Fig. 2.3d and e). When though there is lack of lateral stiffness in the building, RC jacketing is not much effective, as an intervention to significantly reduce the displacements is needed. To increase sufficiently the lateral stiffness a global retrofit measure including most possibly the addition of shear walls, as shown in Fig. 3.2, is required [39].

Figure 3.1 Application of RC jacketing for seismic retrofitting of insufficient RC columns.

Overall, the application of conventional strengthening techniques, such as steel, RC jacketing or RC walls placed around columns (Figs. 3.1 and 3.2), require intensive labour and skilful detailing (high cost), considerable quantities of materials (higher embodied CO_2 emissions, more energy in manufacturing), and significantly disrupt the occupancy of the building (or traffic in railways, bridges, roads) under renovation. To overcome the disadvantages of conventional strengthening techniques, researchers have introduced the use of fibre-reinforced polymer (FRP) materials.

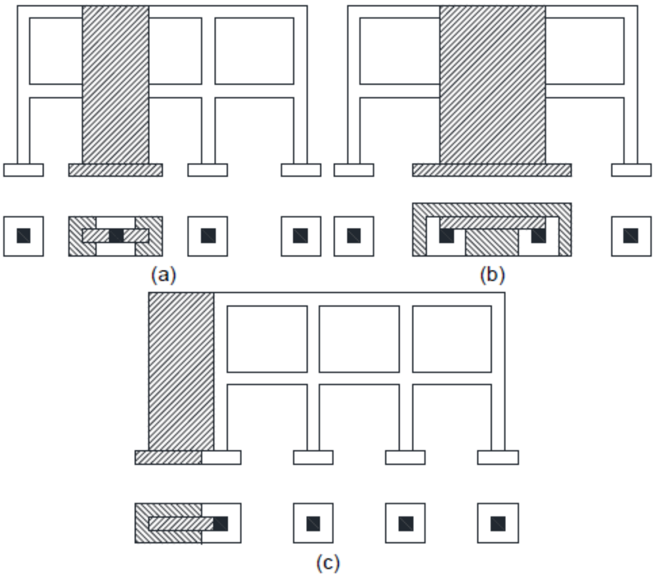
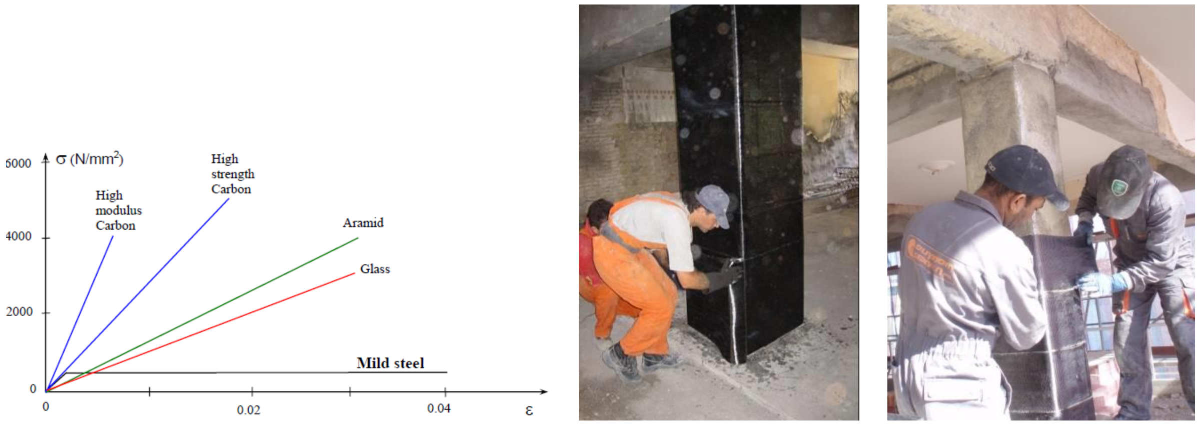


Figure 3.2 View and cross-section above the foundation of RC frames strengthened with new RC walls placed around a column (a), external to the frame (b), or as buttress (c); Source [39].

3.1.3 Fibre-Reinforced Polymers (FRP)

Recent developments related to new materials, methods and techniques for structural strengthening and seismic retrofitting the existing civil engineering infrastructure have been enormous over the last three decades. One of today's state-of-the-art techniques is the use of fibre reinforced polymer (FRP) materials. FRPs for strengthening of structures are available in the form of: (a) thin unidirectional strips (with a thickness in the order of 1mm), (b) flexible sheets or fabrics, made of high strength fibres (i.e. Fig. 3.3a) in one or at least two directions, respectively, which are usually impregnated with resin. Central to the understanding of composites bonded to concrete is the fact that tensile stresses in these materials are carried out only by the fibres, in the respective directions.

The use of FRP has gained increasing popularity in the civil engineering community, due to the favourable properties possessed by these materials, namely: extremely high strength to weight ratio, corrosion resistance, ease and speed of application, minimal change in the geometry. As explained in Table 3.1, FRP jacketing can be used to increase the strength and deformation capacity of RC members. In particular, FRP jacketing is very effective in addressing all failure mechanisms of columns illustrated in Fig.2.2 (namely shear, bar buckling and concrete crushing, short lap-splices), except flexure. When the flexural strength (moment capacity) of the columns is lower than its adjoining beams, a soft storey mechanism could be triggered (i.e Fig. 2.3d-e).



(a) (b)

Figure 3.3 (a) Typical uniaxial stress-strain diagrams for different fibres; (b) and (c) Strengthening and seismic retrofitting of RC columns; Source [42]

Effective strengthening of columns in flexure (often needed, for instance, to satisfy capacity design requirements, that is, the elimination of weakness in strong-beam/weak-column situations or when existing reinforcing bars have been affected by corrosion) calls for the continuation of longitudinal reinforcement. This reinforcement should extend beyond the end cross sections, where moments are typically maximum. Therefore, placement of externally bonded FRP jacket, as shown Fig. 3.4, is not effective. On the other hand, as explained above, RC jacketing (Fig. 3.1) requires intensive labour, increases the dimensions and weight of columns and result in substantial obstruction of occupancy.

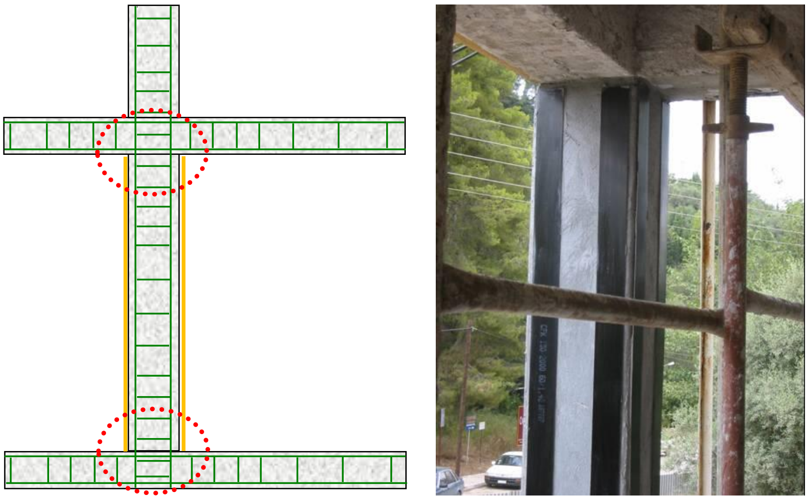


Figure 3.4 Ineffective flexural strengthening of RC columns by means of non-anchored externally bonded FRP reinforcement; Source [42].

To overcome difficulties associated with conventional strengthening techniques and FRP jacketing, recent research efforts have focused on the use of near-surface mounted (NSM) FRP or stainless steel reinforcement (i.e. [43], [44]) or through a combination of externally bonded (EBR) FRP sheets (or laminates) and anchors (i.e. [45],[46]) for the flexural strengthening of columns. This form of externally applied longitudinal reinforcement is prevented from local buckling in highly compressed areas through the use of confining jackets made of composite materials (i.e. TRM/FRP) [47]. These concepts are illustrated in Fig. 3.5.

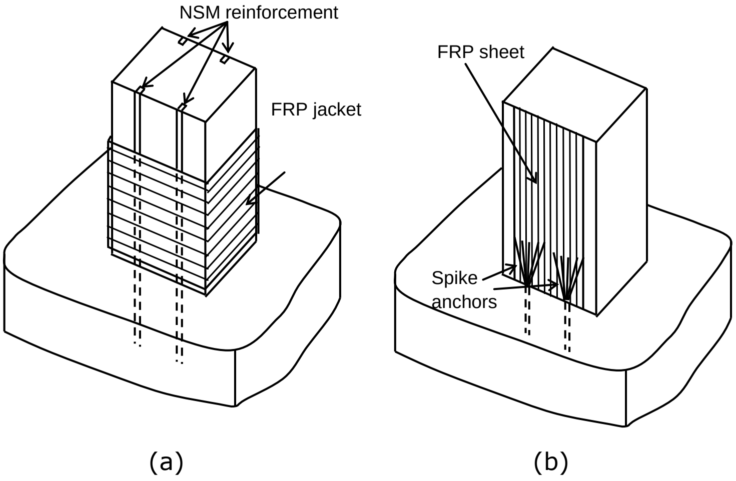


Figure 3.5 Flexural strengthening of RC column with: (a) NSM reinforcement combined with composite material jacketing; (b) externally bonded FRP sheets combined with spike anchors; Source [47].

Despite their well-established advantages (high strength, corrosion resistance, ease and speed of application), the FRP strengthening technique entails drawbacks: poor behaviour at high temperatures, high costs, inapplicability on wet surfaces or low temperatures, health and safety issues for manual workers, incompatibility with substrate materials, mainly attributed to the organic resins used to bind and impregnate the fibres.

3.1.4 Advanced textile-based materials in inorganic matrices

3.1.4.1 State-of-the-art

To address the problems of steel/concrete jacketing or FRPs, a novel structural material, **Textile-Reinforced Mortar (TRM)** has been recently proposed for structural retrofitting (i.e. [48], [49]). TRM is materials made of textiles that are fabric meshes made of long woven, knitted or even unwoven fibre rovings in at least two directions (Fig. 3.6), impregnated with inorganic binders, such as cement-based mortars. TRM is a low cost, friendly for manual workers, fire resistant, and compatible to concrete and masonry substrates material which can be applied on wet surfaces or at low temperatures. For all these reasons, using TRM will progressively become more attractive for the strengthening of existing concrete and masonry structures than the widely used FRP.

Over the last decade it has been reported in the literature that TRM is a very promising alternative to the FRP retrofitting solution. Significant research effort has been put in the last decade to enrich the state-of-the-art, exploiting TRM in several cases of retrofitting reinforced concrete (RC) structures; namely flexural strengthening (i.e. [50]), shear strengthening of RC elements (i.e. [51, 52]), seismic retrofitting of RC columns (i.e. [47,53]), seismic retrofitting of infilled RC frames [22]. TRM has also been successfully used for retrofitting masonry structures (i.e. out-of-plane strengthening [54] and shear strengthening of masonry walls [55]).

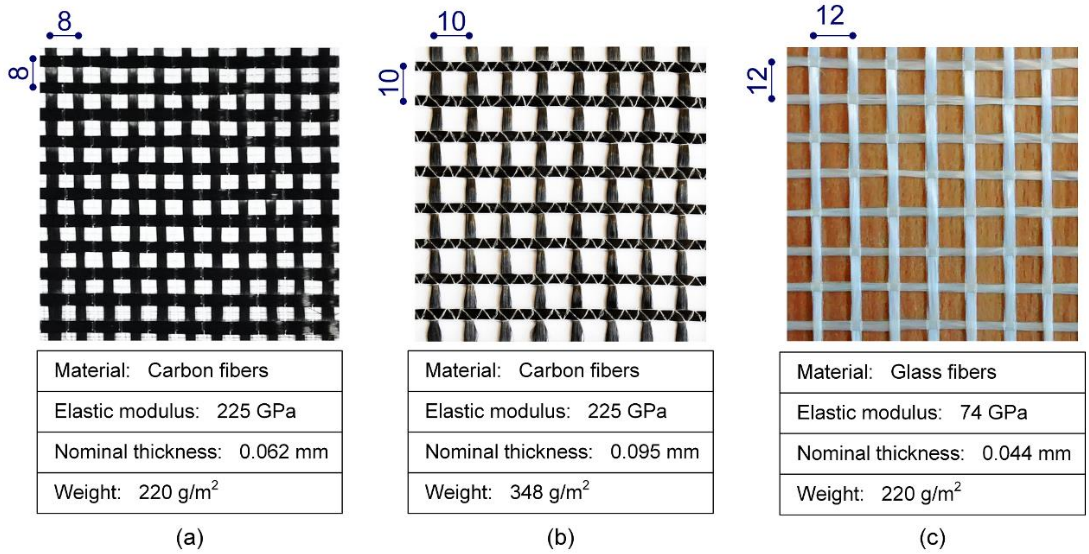


Figure 3.6 Textiles fabrics: (a) light carbon-fibre textile; (b) heavy carbon-fibre textile; (c) glass fibre textile; Source [50].

3.1.4.2 Applications

The following figures illustrate various cases of TRM applications as strengthening material including seismic retrofitting of RC columns (Fig. 3.7), shear strengthening of RC beams (Fig. 3.8) and seismic retrofitting of infilled RC frames (Fig. 3.9).

Figure 3.7 Seismic retrofitting procedure of RC column base via TRM jacketing to increase its deformation capacity: (a) Application of first mortar layer; (b)-(c) application of the textile into the mortar to complete TRM jacketing; Source [49].

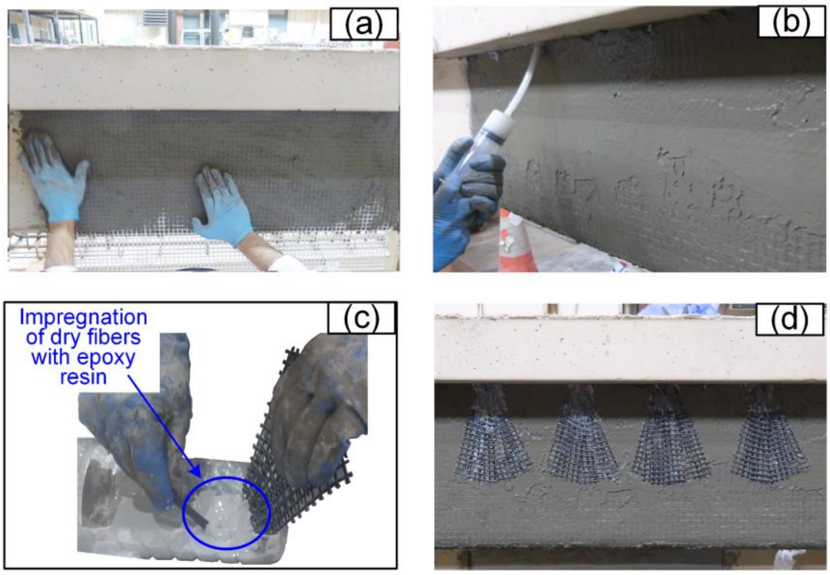


Figure 3.8 Shear strengthening of T-beams with TRM and textile-based anchors: (a) Impregnation of the textile fibers with mortar; (b) injection of epoxy resin into the slab holes; (c) impregnation of dry fibers at the central part of anchor with epoxy resin; (d) textile-based anchors applied over the TRM layer; Source [50].

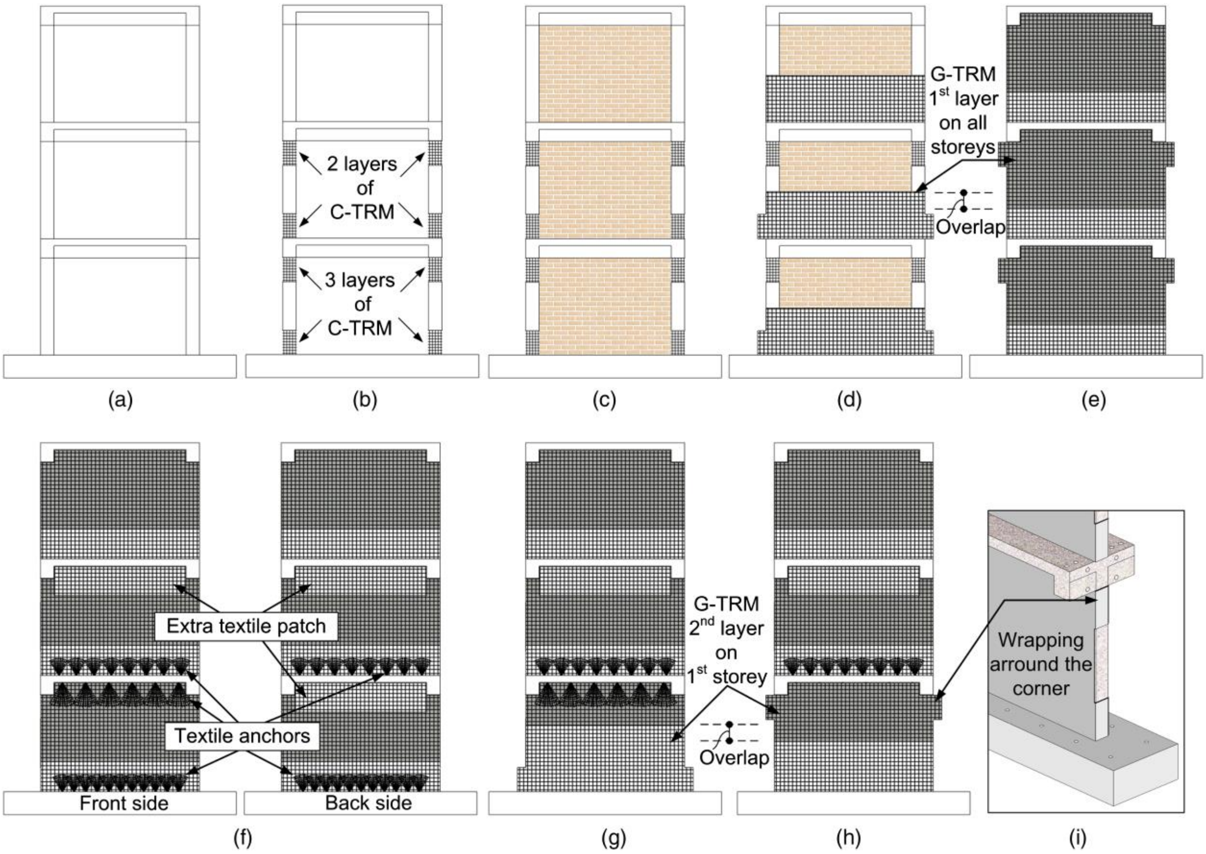


Figure 3.9 Seismic Strengthening of Masonry-Infilled RC Frames with TRM; Application steps: (a) bare frame; (b) shear strengthening of first and second story columns at shear-critical regions; (c) infilling with masonry; (d) application of first TRM layer on the face of masonry infills, bottom part of the textile; (e) application of

first TRM layer on the face of masonry infills, top part of the textile; (f) application of textile anchors and extra textile patches on the front and back side of the specimen, respectively; (g) application of second TRM layer on the faces of first story masonry infill, bottom part of the textile; (h) application of second TRM layer on the faces of first story masonry infill, top part of the textile; (i) wrapping of the overhanging textile around the column; Source [22].

3.1.4.3 Experimental Results

The results of TRM strengthened concrete specimens indicate the high effectiveness of this composite material. Figure 3.10 displays the load-displacement response curves two full-scale columns tested in simulated seismic loading, one as built (C) and the other confined with a TRM jacket (M4). The unretrofitted column (Fig. 3.10a) attained a drift ratio at failure of approximately 3.5% and failed prematurely due to bar buckling at the base of the column (such a failure mode is also observed in real earthquakes- see Fig. 2.3b). The behaviour of the TRM retrofitted column (Fig. 3.10b) M4, was far better than its unretrofitted counterpart; its deformation capacity increased by a factor of more than 2, corresponding to a drift ratio at failure of approximately 7.5%, whereas peak resistance was practically the same as in the unretrofitted column, and the post peak response was quite stable, displaying a very gradual strength degradation. Therefore, TRM jacketing is an effective local strengthening technique to increase the deformation capacity of substandard detailed RC columns.

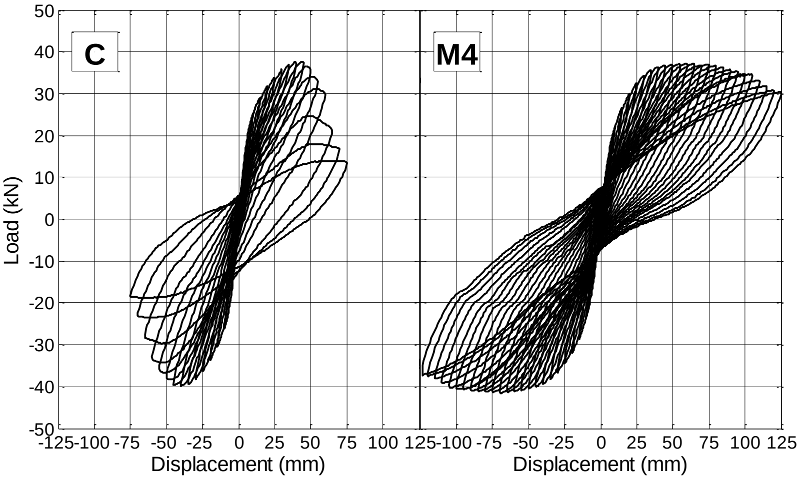


Figure 3.10 Load-displacement curves for: (a) unretrofitted column (C); and (c) TRM-retrofitted column (M4); Source [49].

When the objective of seismic retrofitting is to increase the flexural strength of RC columns to meet the "*strong columns-weak beams*" requirement, NSM with FRP/TRM jacketing was found to be most effective. Figure 3.11 presents the response of the control and S_R_J which was flexurally strengthened with 4 (12 mm) NSM stainless steels bars and TRM confined (i.e. Fig. 3.5a). Specimen S_R_J, displayed an improved behaviour, comprising stable hysteresis loops until large drift ratios, in the order of 8% and attained a flexural resistance, which was nearly double that of the control specimen.

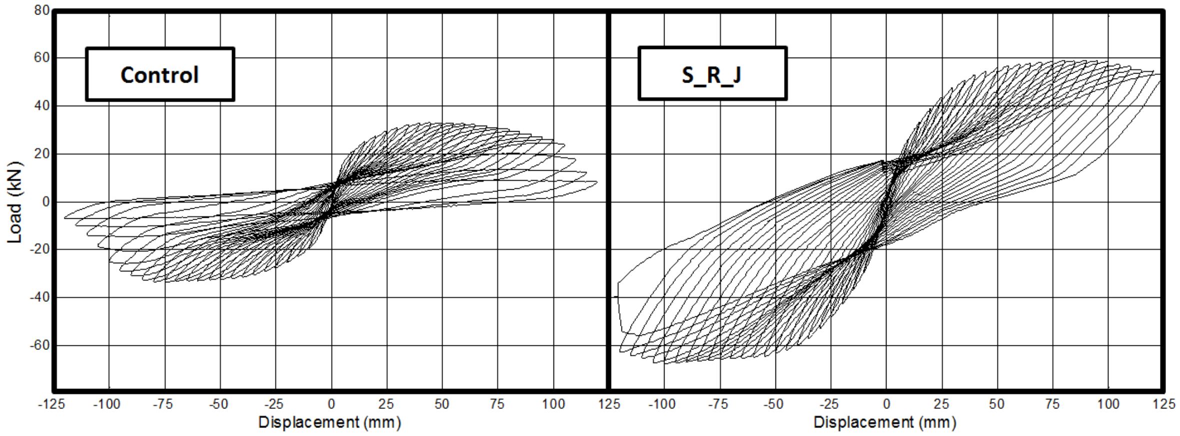


Figure 3.11 Load-displacement curves for: (a) unretrofitted column (Control); and (c) NSM and TRM strengthened column; Source [43].

The seismic retrofitting of masonry-infilled RC frames with TRM, as for example presented in Fig. 3.9, is suggested as a global retrofit measure to address both the damage in non-structural masonry (see Figs 2.5), but also for increasing the strength and stiffness of the structure. Figure 3.12 summarize the tests performed by Koutas et al. [23] on an unretrofitted and a retrofitted large-scale frame. This retrofitting scheme resulted in an enhanced global response of the infilled frame both in terms of lateral strength and deformation capacity; an approximately 56% increase in the lateral strength was observed, accompanied with a 52% higher deformation capacity at the top of the structure at ultimate strength state.

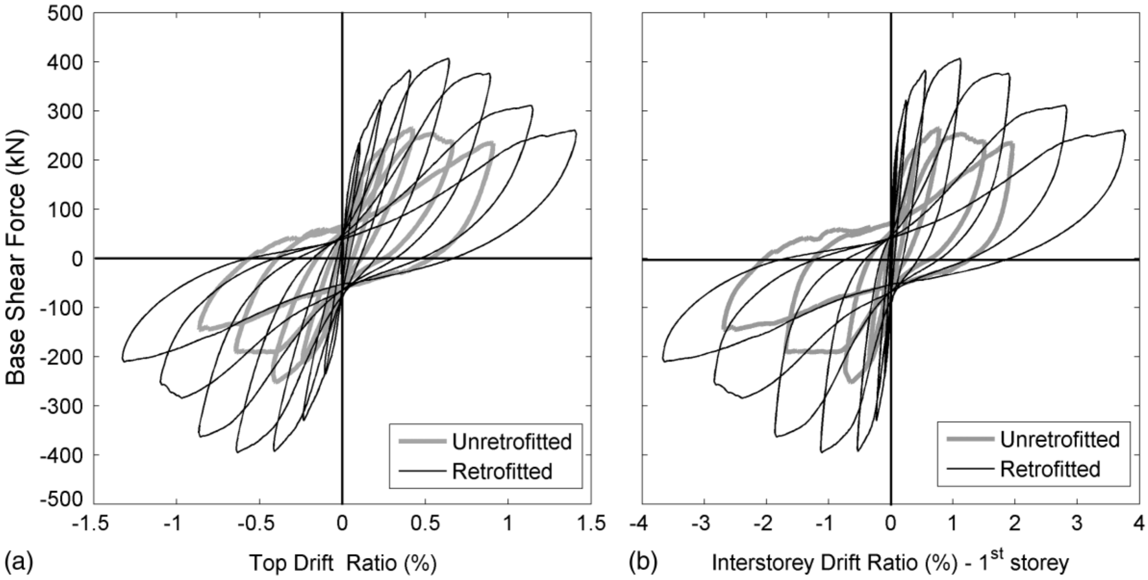


Figure 3.12 Comparative response curves for the two specimens in terms of base shear versus (a) top drift ratio; (b) first story drift ratio; Source [23].

Selected case studies of actual applications of TRM in the construction field can be found in [56]. The case study presented here is related to the strengthening and seismic retrofitting of a building school in Greece. TRM was selected to strengthen a school building in Karystos, Greece (Triantafillou, [57]). This involved both flexural strengthening of RC slabs (Figure 3.13a) with heavily corroded reinforcement and shear strengthening of unreinforced stone masonry walls (Figure 3.13b). Strengthening was carried out using carbon fiber meshes combined with cementitious mortar.

Figure 3.13 Strengthening of (a) concrete slabs and (b) stone masonry walls in a mixed concrete–masonry school building. Kind permission of Triantafillou (2007); Source [57].

3.2 Energy retrofitting of envelopes

3.2.1 Thermal insulation

Thermal insulation is a material or combination of materials, that, when properly applied, retard the rate of heat flow by conduction, convection, and radiation. It retards heat flow into or out of a building due to its high thermal resistance. The proper use of thermal insulation in buildings reduces not only the energy usage but also downsizes the heating, ventilation and air-conditioning (HVAC) system during design. A simple and effective way to improve the energy efficiency of a building is by **improving the thermal insulation of the envelope**.

The thickness of insulation in building has increased since the early 1970s, almost doubling in northern Europe [58]. The best performance of **thermal insulation** is achieved by placing it **closest to the surface of heat entry**; i.e. in space heating load dominant regions, insulation should be placed close to the inner surface of the building envelope while in cooling load dominant regions it should be closer to the outer surface [28].

The selection of thermal insulation thickness is strongly connected with the thermal conductivity and thermal inertia of the selected insulation material. The increase in temperature and moisture content of the thermal insulation increases its thermal conductivity, thereby degrading its performance. In fact, studies have shown that water in the form of vapor or liquid has a detrimental effect on the material characteristics of slag-rock wool fibers and fiberglass [59]. Environmental and health impacts and flammability are also important factors in selecting an appropriate insulation.

The following sections present a review on the most commonly used insulation building materials and solutions today, which are classified in four categories: (a) Conventional insulation materials; (b) State-of-the-art insulation materials; (c) Nano insulation materials and (d) Smart insulation materials. Table 3.2 summarises the main properties of conventional, state-of-the-art and nano insulation materials.

Table 3.2 Comparison of conventional to the state-of-the-art thermal insulation materials; Sources [60, 65].

Material	Thermal conductivity (mW/mK)	Cutting to adapt for construction (Performance if perforated)	Resistance fire, water and chemicals	Cost per thermal resistance	Environmental impact of production and use	A thermal insulation material and solution of tomorrow?
Conventional insulation materials						
Mineral wool	30-40	Yes (Same)	Low	Low	Low	No
Expanded polystyrene (EPS)	30-40	Yes (Same)	Low	Low	High	No
Extruded polystyrene (XPS)	30-35	Yes (Same)	Moderate	High	High	No
Cellulose	40-50	Yes (Same)	Low	Low	Low	No
Polyurethane (PUR)	20-30	Yes (Same)	Moderate	High	High	No
State-of-the-art insulation materials						
Vacuum insulation panels (VIP)	4-8	No (Worse)	Low	High	Moderate	Near future
Gas-filled panels (GRP)	10-40	No (Worse)	Low	High	Moderate	Probably not
Aerogels	13-14	Yes (Same)	Moderate	High	Moderate	May be
Nano insulation materials (NIM)	<4	Yes (Same)	Moderate	High	Moderate	Yes

3.2.1.1 Conventional insulation materials

3.2.1.1.1 Mineral wool

Mineral wool covers glass wool (fibre glass) and rock wool, which normally is produced as mats and boards, but occasionally also as filling material. Light and soft mineral wool products are applied in frame houses and other structures with cavities. Heavier and harder mineral wool boards with high mass densities are used when the thermal insulation is intended for carrying loads, i.e. on floors or roofs. Mineral wool may also be used as a filler material to fill various cavities and spaces. Glass wool is produced from borosilicate glass at a temperature around 1400 ^{o}C, where the heated mass is pulled through rotating nozzles thus creating fibres. Rock wool is produced from melting stone (diabase, dolerite) at about 1500 ^{o}C, where the heated mass is hurled out from a wheel or disk and thus creating fibres. In both glass wool and rock wool dust abatement oil and phenolic resin is added to bind the fibres together and improve the product properties. Typical **thermal conductivity** values for **mineral wool** are between **30 and 40 mW/(mK)**. The thermal conductivity of mineral wool varies with temperature, moisture content and mass density. As an example, the thermal conductivity of mineral wool may increase from **37mW/(mK) to 55mW/(mK)** with increasing **moisture content from 0 vol% to 10 vol%**, respectively. Mineral wool products may be perforated, and also cut and adjusted at the building site, without any loss of thermal resistance.

3.2.1.1.2 Expanded polystyrene (EPS)

Expanded polystyrene (EPS) is made from small spheres of polystyrene (from crude oil) containing an expansion agent, i.e. pentane C_6H_{12}, which expand by heating with water vapour. The expanding spheres are bond together at their contact areas. The insulation material is casted as boards or continuously on a production line. EPS has a partly open pore structure. Typical thermal conductivity values for EPS are between **30 and 40 mW/(mK)**. The thermal conductivity of EPS varies with temperature, moisture content and mass density. As an example, the thermal conductivity of EPS may increase from **36mW/(mK) to 54mW/(mK)** with increasing **moisture content** from **0 vol% to 10**

vol%, respectively. EPS products may be perforated, and also cut and adjusted at the building site, without any loss of thermal resistance.

3.2.1.1.3 Extruded polystyrene (XPS)

Extruded polystyrene (XPS) is produced from melted polystyrene (from crude oil) by adding an expansion gas, i.e. HFC, CO_2 or C_6H_{12}, where the polystyrene mass is extruded through a nozzle with pressure release causing the mass to expand. The insulation material is produced in continuous lengths which are cut after cooling. XPS has a closed pore structure. Typical thermal conductivity values for XPS are between **30 and 35 mW/(mK)**. The thermal conductivity of XPS varies with temperature, moisture content and mass density. As an example, the thermal conductivity of XPS may increase from **34mW/(mK) to 44mW/(mK)** with increasing **moisture content** from **0 vol% to 10 vol%**, respectively. XPS products may be perforated, and also cut and adjusted at the building site, without any loss of thermal resistance.

3.2.1.1.4 Cellulose

Cellulose (polysaccharide, $(C_6H_{10}O_5)_n$) comprises thermal insulation made from recycled paper or wood fibre mass. The production process gives the insulation material a consistence somewhat similar to that of wool. Cellulose insulation is used as a filler material to fill various cavities and spaces, but cellulose insulation boards and mats are also produced. Typical thermal conductivity values for cellulose insulation are between **40 and 50 mW/(mK)**. The thermal conductivity of cellulose insulation varies with temperature, moisture content and mass density. As an example, the thermal conductivity of cellulose insulation may increase from **40mW/(mK) to 66mW/(mK)** with increasing **moisture content** from **0 vol% to 5 vol%**, respectively. Cellulose insulation products may be perforated, and also cut and adjusted at the building site, without any loss of thermal resistance.

3.2.1.1.5 Polyurethane (PUR)

Polyurethane (PUR) is formed by a reaction between isocyanates and polyols (alcohols containing multiple hydroxyl groups). During the expansion process the closed pores are filled with an expansion gass, HFC, CO_2 or C_6H_{12}. The insulation material is produced as boards or continuously on a production line. PUR may also be used as expanding foam at the building site, i.e. to seal around windows and doors and to fill various cavities. Typical thermal conductivity values for PUR are between **20 and 30 mW/(mK)**, i.e. considerably lower than mineral wool, polystyrene and cellulose products. The thermal conductivity of PUR varies with temperature, moisture content and mass density. As an example, the thermal conductivity of PUR may increase from **25mW/(mK) to 46mW/(mK)** with increasing **moisture content** from **0 vol% to 10 vol%**, respectively. PUR products may be perforated, and also cut and adjusted at the building site, without any loss of thermal resistance.

It should be noted that even if PUR is safe in its intended use, it raises serious health concerns and hazards in case of a fire. During a fire PUR will when burning release hydrogen cyanide (HCN) and isocyanates, which is very poisonous. The HCN toxicity stems from the cyanide anion (CN^-) which prevents cellular respiration. Generally, hydrogen cyanide may be found in the smoke from nitrogen (N) containing plastics.

At this point, to further highlight the need for energy retrofitting of old building envelopes, the thermal conductivities of common load-bearing building materials are quoted. As a comparison, typical examples may be <u>wood (100–200), carbon steel (55,000), stainless steel (17,000), aluminium (220,000), concrete (150–2500),</u>

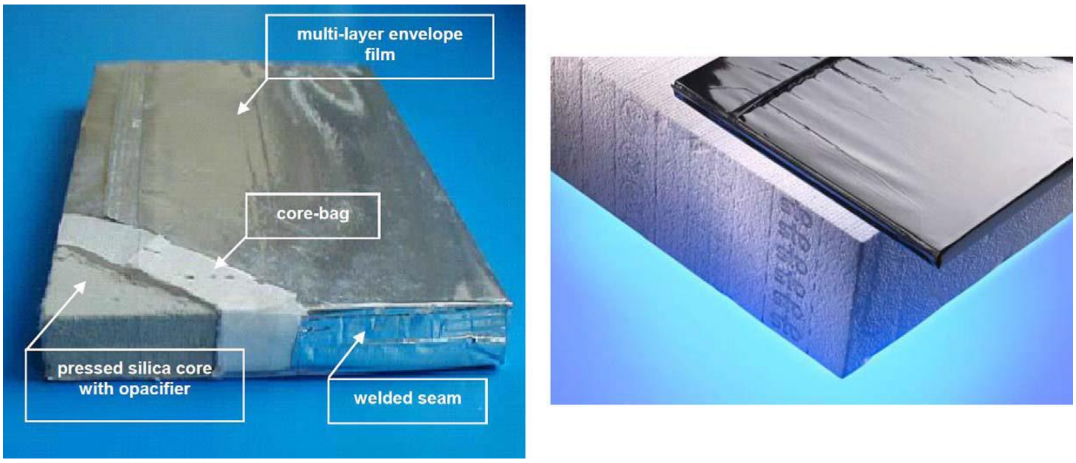
lightweight aggregate (100–700), brick (400–800), stone (1000–2000) and glass (800), all values in brackets given in mW/(mK).

3.2.1.2 State-of-the-art thermal insulation materials

A brief review on the state-of-the-art thermal insulation materials and solutions of today, namely those with the lowest thermal conductivity today, follows.

3.2.1.2.1 Vacuum insulation panels (VIP)

Vacuum insulation panels represent an evacuated, open porous material that is enveloped into a multilayer film (Fig. 3.14a). A special structure of VIP makes it the best material in terms of thermal conductivity in pristine condition: 3–4mW/mK [60]. However, ageing has a detrimental effect on VIPs thermal conductivity. As illustrated in Fig. 3.14, the thermal conductivity is typically doubled (i.e. around 8mW/mK) after 25 years ageing, due to water vapour and air diffusion through the VIP envelope and into the VIP core material which has an open pore structure. Depending on the type of VIP envelope, the aged thermal conductivity after 50 and 100 years will be considerably higher than the value (see i.e. Fig. 3.15). Apart from the increase with time, an increase in the thermal conductivity (to about 20 mW/mK) takes place when VIPs are punctured or perforated. As a result, VIPs cannot be cut for adjustment at the building site or perforated without losing a large part of their thermal insulation performance. To the above drawbacks of VIPs someone should also consider their high costs, which although might not be critical in energy retrofitting applications where the land is at premium.



(a) (b)

Figure 3.14 (a) Typical VIP structure showing the main components [61]; (b) Comparison of equivalent thermal resistance thickness of traditional thermal insulation and VIP; Source [62].

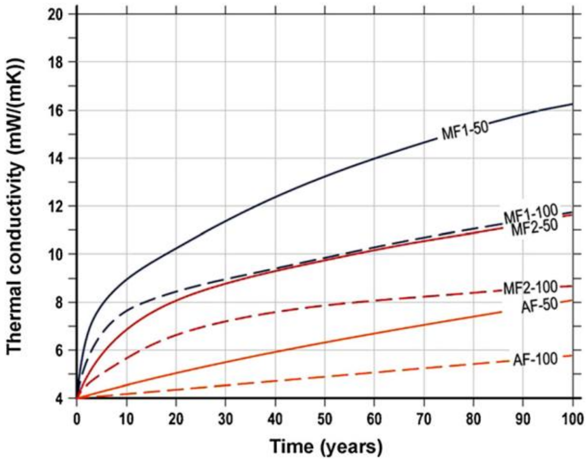


Figure 3.15 Vacuum insulation panel thermal conductivity as a function of time; Source [63]. *Temperature, humidity and porosity are assumed constant. Gas pressure is set at 0 bar. No getters, desiccants or pacifiers are used*.

Even if VIPs possess the above drawbacks, their thermal conductivity remains between 5 and 10 times (depending on ageing time), lower than traditional thermal insulation materials (i.e. mineral wool and polystyrene products), and therefore is a retrofitting material which could contribute to reach the requirements of passive (nearly zero energy) houses for existing buildings. Thick building envelopes, which require thermal insulation thicknesses up to 50 cm in walls and roofs, are not preferred, as they cover more land area and might require costly construction techniques. In addition, transport of thick building elements leads to increased costs. As an example, height restrictions may apply for passing under several bridges and through tunnels, i.e. thinner elements will bring about a more efficient transport to a reduced cost. The need for thinner high performance insulation material becomes even more pronounced during retrofitting of existing buildings projects, where the use of lightweight materials could address construction restrictions (i.e. minimum obstruction of resident occupancy). Furthermore, in areas with a high living area market value per square meter, a reduced wall thickness may involve large area savings and thus a higher value of the real estate. Simple calculations show that for such areas the application of VIPs may actually result in an economic profit [60].

Thus, even if the VIPs are not the ultimate solution for the future, they may be the best solution for many thermal building envelopes today and in the near future, both from a thermal energy savings and an economical point of view. VIP research and advances should be concentrated towards developing VIP envelopes capable of preventing far better air and water vapour from entering into the VIP core for longer time periods up to at least 50–100 years. Besides, the research on and application of VIPs contributes to increased knowledge and idea generation about the thermal insulation solutions of tomorrow. An extensive review on VIPs studying several aspects that affect their performance in building applications has been made in [64].

3.2.1.2.2 Gas-filled panels (GFP)

Gas-filled panels use a combination of thin polymer films and low-conductivity gases to achieve lower thermal conductivity rates. GFPs are airtight plastic bags of different shapes and sizes that are filled with an inert gas having low thermal conductivity, such as argon (Ar), xenon (Xe) or krypton (Kr). A low-emissivity barrier envelope is used to enclose the gas and to decrease the heat transfer due to radiation, while a low-emissivity baffle structure is included to decrease inner gas convection and radiation. As a result, both flexible and stiff GFPs are possible [65]. The barrier foil and baffle structure inside a GFP are shown in Fig. 3.16. GFPs, as thermal insulators, have been actively studied in past two decades [66]. So far, however, experimental thermal conductivities achieved from GFP (40 mW/mK) have only been comparative with those of the traditional materials, although theoretical investigations predicted values as low as 10mW/mK. Hence, the GFPs hold many of the VIPs advantages and disadvantages. Nevertheless, the future of GFPs as thermal building insulation may be questioned or even doubtful, as compared to them the VIPs seem to be a better choice both for today and tomorrow. A comprehensive review of GFPs for building applications is given by Baetens et al. [67].

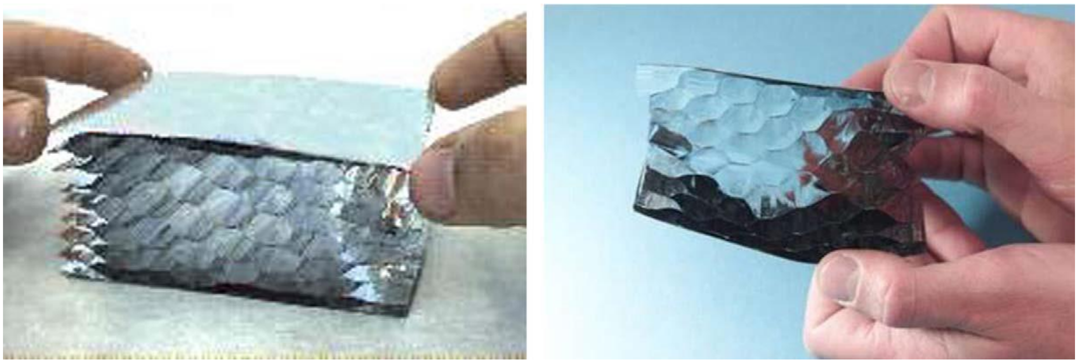


Figure 3.16 Barrier foil and baffle structure inside a GFP; Source [68].

3.2.1.2.3 Aerogels

Aerogels are dried gels with a very high porosity that represent one of the most promising thermal insulation materials with possibly the highest potential, have been studied by [69, 70] among several others. By adding carbon black to the aerogel, (i.e. before or after the critical drying, that either absorbs or scatters infrared radiation), thermal conductivities as low as 4mW/(mK) may be reached at a pressure of 50 mbar, whereas state-of-the-art commercially available aerogel insulation for building purposes has a thermal conductivity of around 13.1 W/(mK) at ambient temperature and very little affected up till a temperature of 200 ◦C [69]. The production costs of aerogels are still very high. Aerogels have relatively high compression strength, but is very fragile due to its very low tensile strength. The tensile strength may be increased by incorporation of a carbon fibre matrix. A very interesting aspect with aerogels is that they **can be produced** as either opaque, translucent or **transparent** materials, thus **enabling** a **wide** range of possible **building applications**.

Although aerogels are very promising materials for thermal insulation in buildings, their commercial applications are limited because of high cost of production (€214*/m^2 on average as reported by [71]) and fragility because of low tensile strength. For aerogels to become a widespread thermal insulation material for opaque applications, the costs have to be lowered substantially [60].

Baetens et al. [69] presented different building applications with aerogel insulation. Two examples of translucent aerogel insulation applied over large areas in new buildings for daylighting purposes are depicted in Fig. 3.17. **Aerogel insulation** applied as **retrofitting of an old brick building** is shown in Fig. 3.18, which in another example also shows a timber wall with aerogel insulated studs (top floor), demonstrating by infrared thermography the thermal bridge differences to the non-aerogel insulated studs (ground floor) in the same building (Fig. 3.18b).

Figure 3.17 Two examples of translucent aerogel insulation as a high performance thermal insulation solution for daylighting; Source [69].

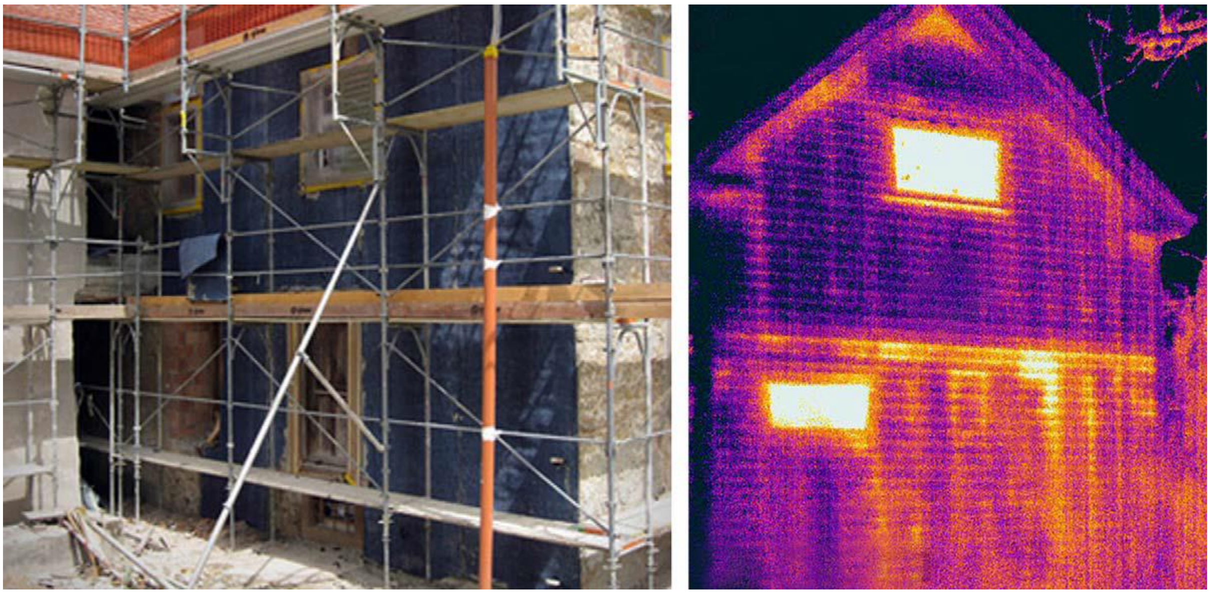


Figure 3.18 (a) Aerogel insulation for retrofitting of an old brick dwelling; (b) thermographic image of a timber wall where the studs of the top floor are insulated with thin layer of aerogel insulation whereas the ground floor is not; Source [69].

3.2.1.3 Nano insulation materials (NIM)

In a recent work Jelle [60] reported that nanotechnology may be applied as a scientific tool to make high performance thermal insulation materials. The normal focus in nanotechnology is to control matter, typical particles, of **dimensions between 0.1nm and 100 nm**, i.e. at an atomic and molecular scale. However, for nanotechnology applied for making thermal insulation materials, the focus is shifted from particles to pores in the nano range. These aspects were visualized by Jelle [60] as shown in Fig. 3.19.

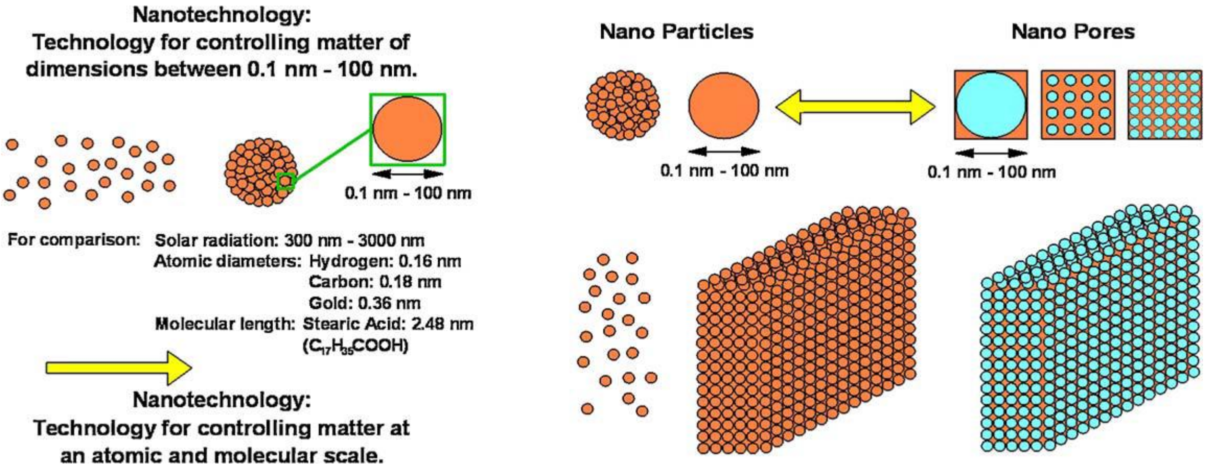


Figure 3.19 Nanotechnology and its application on high performance thermal insulation materials [60].

The development from VIPs to *nano insulation materials* (NIM) was illustrated by Jelle et al. [72] as shown in Fig. 3.20. In the NIM the pore size within the material is decreased below a certain level, i.e. 40nm or below for air, in order to achieve an overall thermal conductivity of less than 4mW/(mK) in the pristine condition. That is, a NIM is basically a homogeneous material with a closed or open small nano-pore structure with an overall thermal conductivity of less than 4mW/(mK) in the pristine condition. The grid structure in NIMs does not, unlike VIMs and GIMs, need to **prevent air and moisture penetration** into their pore structure during their service life **for at least 100 years**.

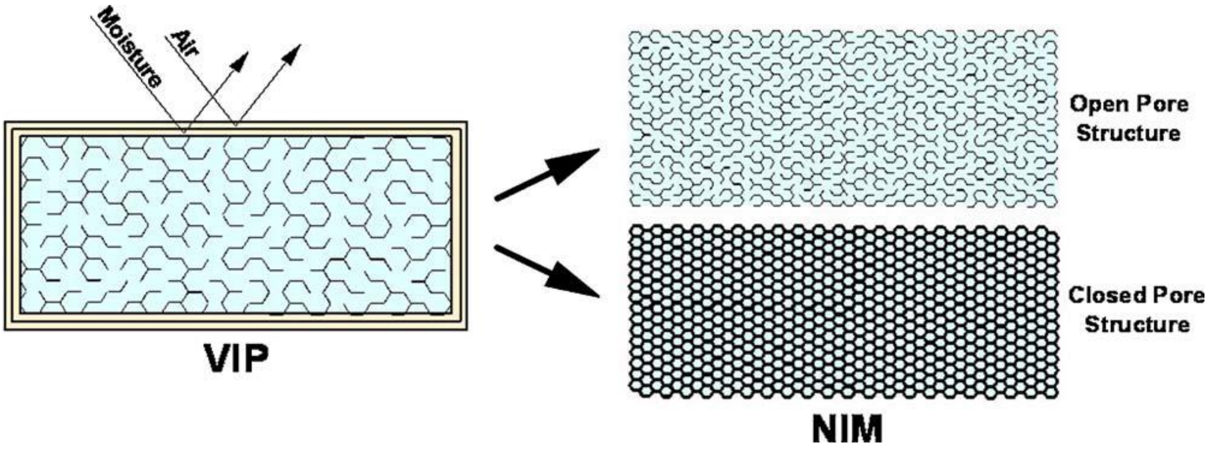


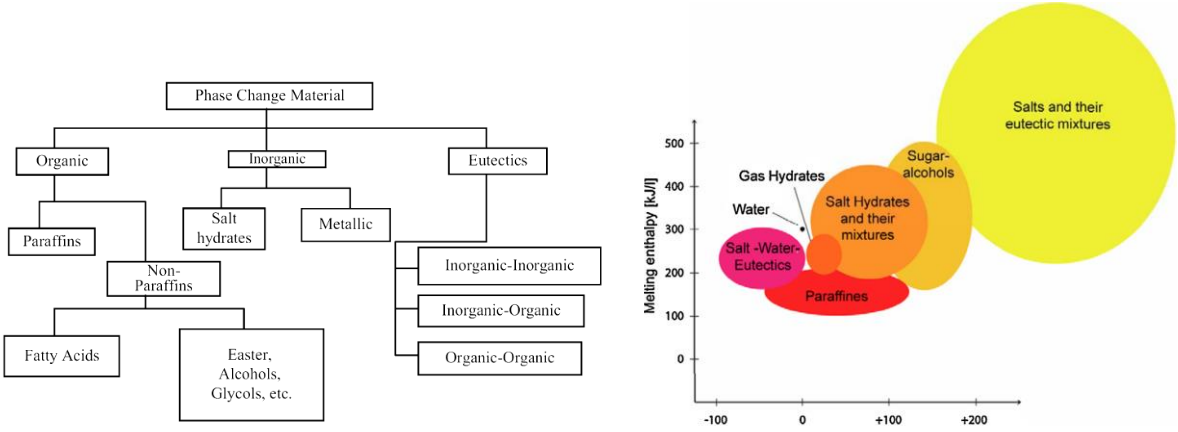
Figure 3.19 The development from VIPs to NIMs [72].

3.2.1.4 Smart Materials and Systems

3.2.1.4.1 Phase change materials (PCM)

Phase change materials (PCM) are not really thermal insulation materials, but since they are interesting for thermal building applications, they are mentioned within this context. PCMs have received considerable attention over the last decade for use in latent heat thermal storage (LHTS) systems. PCMs give the ability to store passive solar and other heat gains as latent heat within a specific temperature range, leading to a reduction of energy usage, an increase in thermal comfort by smoothing out temperature fluctuations throughout the day and a reduction and/or shift in peak loads. PCMs change phase from solid state to liquid when heated, thus absorbing energy in the endothermic process. When the ambient temperature drops again, the liquid PCMs will turn into solid state materials again while giving off the earlier absorbed heat in the exothermic process. Such a phase change cycle stabilizes the indoor building temperature and decreases the heating and cooling loads [60]. An overview of the main PCMs has been given in [73], whereas other reviews on PCMs may be found in works by (i.e. [74], [75]). A very recent review on PCM and products for building applications was done by Kalnaes and Jelle [76].

There are several materials that can be used as PCMs. A common way to distinguish PCMs is by dividing them into *organic*, *inorganic* and *eutectic* PCMs. These categories are further divided based on the various components of the PCMs, as shown in Fig. 3.20a. Figure 3.20b shows the difference in melting enthalpy and melting temperature for some of the most common materials used as PCMs.



(a) (b)

Figure 3.20 (a) General categorization of PCMs [77]; (b). Melting enthalpy versus melting temperature for various materials used in PCMs [76].

A suitable phase change temperature range, depending on climatic conditions and desired comfort temperatures, as well as an ability to absorb and release large amounts of heat, are important properties for the selection of a specific PCM for building applications. Cabeza et al. [78] has listed several tables of PCM properties where the potential areas of use have been divided by the PCMs' phase change temperature. For use in buildings, three temperature ranges were suggested: (i) up to 21◦C for cooling applications, (ii) 22–28◦C for human comfort applications, and (iii) 29–60◦C for hot water applications.

At this point it should be explained that the materials incorporating PCMs will normally melt during the day time and solidify during night time. This prevents rooms from overheating during the daytime in warm months and may also reduce the need for heating during night time in the winter. An issue that has been brought up is the importance of getting passive PCM systems to completely discharge during night time in warm periods. If the PCM is not able to completely solidify, its effectiveness is considerably reduced. This point makes **PCMs** more **effective in climates with large daily variation in temperatures**. For areas where the discharge does not happen naturally, cool air has to be supplied during night time to reset the PCMs completely.

Another significant benefit of using PCMs is associated with shifting of the energy required at peak times. Peak loads that hit during the day put pressure on the electrical grid and also lead to the need for HVAC systems being dimensioned for higher heating or cooling loads. Ultimately, this could lead to a need for more power generation facilities being built. By shifting the peak load away from the peak hours of electrical demand using PCMs, the peak load may be divided throughout the day reducing the highest peaks (Halford and Boehm [79]). Fig. 3.21 illustrates how the peak may be maybe both reduced and shifted by the use of PCMs.

The PCM technology seems promising; however there are still some hurdles which need to be overcome for a large-scale application of this technology. Standards which state test methods and can help identify the correct PCMs for various climates, to enable proper cycling and optimization of PCM systems, are needed. Research into new PCM technologies is also of major importance, i.e. the possibility of having a dynamically adjustable and even controllable phase change temperature [76].

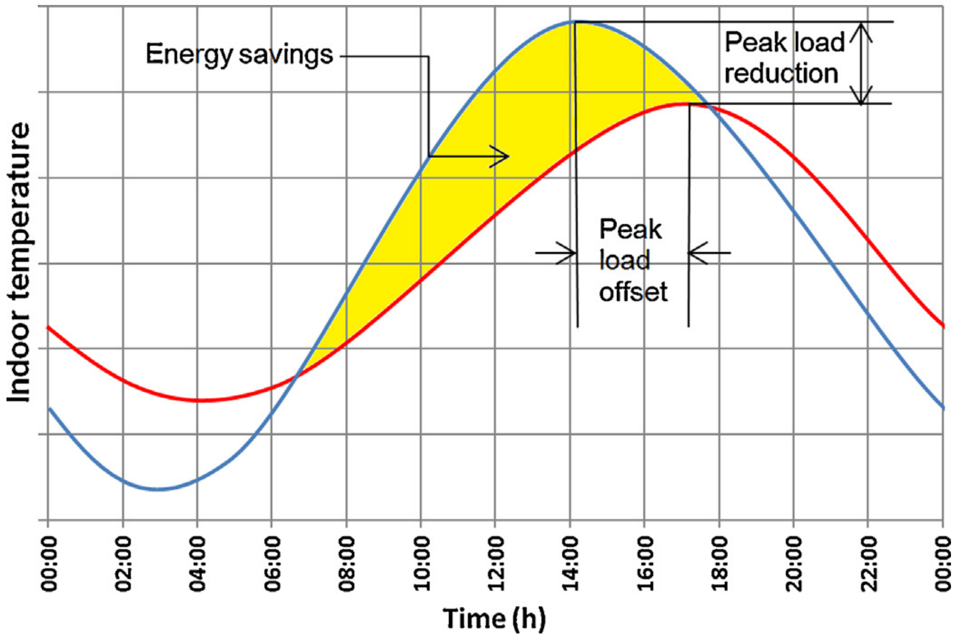


Figure 3.21 Illustration of peak load offset and peak load reduction; Source [79].

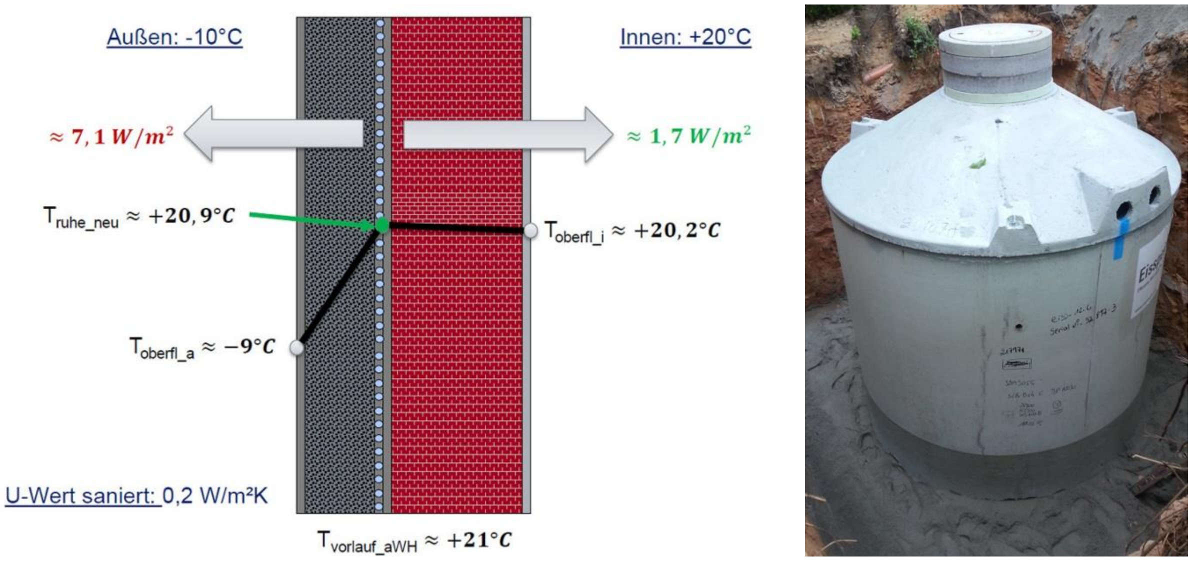
3.2.1.4.2 Heating buildings via their exterior walls

Surface heating systems facilitate the integration of renewable energy sources and reduce energy costs. However, since the retrofitting of underfloor heating is very expensive, thermally activated walls provide an option for existing buildings.

Until now, capillary tube mats have been principally used in interior walls, ceilings and underfloor heating systems. The innovation lies in their use into exterior walls. As part of a current research project at the Institute of Industrial Automation and Energy Systems at Saarland University (under Professor Georg Frey), the mats are being applied to a 160m^2 concrete façade, as illustrated in Fig. 3.22. Once they are installed they will disappear under a thin layer of mortar with good thermal conductivity. This enables a homogeneous temperature distribution in the wall and is also required because a final layer of thermal insulation will then be applied on top. The capillary tube mats are made of six-millimetre-thick tubes. These contain a water-glycol mixture and lead to supply and return lines at the base of the façade.

To achieve heating with low supply temperatures, the thermal activation of the 34 cm-thick concrete wall enables low supply temperatures. Since the transfer area is relatively large, the heat transfer medium does not have to be heated so much as with conventional heating systems. In addition, a large thermal mass is available as shown in Fig. 3.23. This therefore enables the heat generation and consumption to be better decoupled time-wise, which facilitates the integration of renewable energies into the system. The location of the radiant heating system, between the existing wall and the new thermal insulation, enables very low supply temperatures to be used, namely 20 to 25°C. This is because supply temperatures that are only slightly above the idle temperature in the heating plane can change the heating flow through the existing wall. The idle temperature refers to the temperature in the heating plane in the idle state; in other words when the wall is not thermally activated. Supply temperatures greater than the room temperature can compensate for transmission heat losses from the covered wall surfaces and, in addition, supply the room with heat to meet the remaining heat losses.

Figure 3.22 Surface heating under thermal insulation is being installed on an exterior wall for the first time as part of a renovation project, whereby the capillary tube mats (pictured) are applied to the concrete facade and then plastered over with adhesive mortar. © *IZES gGmbH*.



(a) (b)

Figure 3.23 (a) With 21 °C, the supply temperature is greater than the room temperature, so that an effective flow of heat is created through the existing wall into the room. Around 2 W/m2 of heat is fed into the room. (b) The ice storage tank consists of a ten-cubic-metre, water-filled concrete cistern that is sunk into the ground next to the building. © *IZES gGmbH*.

One of the objectives of the research project at Saarland University is to meet the heating requirement with as little electricity as possible. To achieve this objective, 12 PV collectors with a total gross area of approximately 20 m^2 help to provide the necessary energy. They provide both solar thermal heat and solar electricity. To achieve this, they are coupled to a brine-water heat pump that is partly electrically driven by the PV system; the rest of the electricity requirement is met by the grid. The heat pump produces heating or cooling energy as required. It draws energy from an ice storage tank that is sunk into the ground next to the building, as shown in Fig. 3.23b. The storage system regenerates itself partly from the soil, but mainly via the solar thermal system. It is stated that in terms of the energy efficiency, this combination is ultimately aimed at achieving the highest possible annual performance factors for the system. These depict the ratio between the useful energy for the building heating and the electricity requirement of the system. This therefore provides with precise information about the direct thermal utilisation of the solar thermal energy and the efficiency of the heating provided by the heat pump system.

A plant room controls and monitors the system on the basis of measurements, whereby it is continuously fed with data from all the important parameters. In addition to values from the temperature sensors in the outer wall, these also include values for the room temperature, humidity and occupancy. Since all the rooms have their own exterior wall heating circuit, they can be individually controlled and regulated. In addition, the entire hydraulic system and the electrical components are also metrologically recorded.

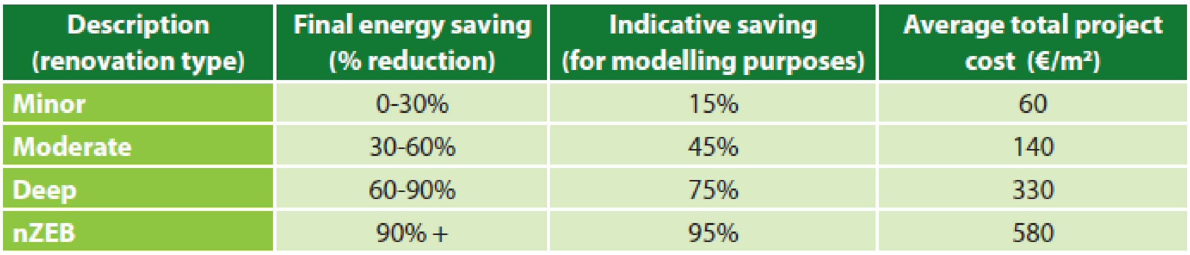
4 Challenges in building retrofitting and recommendations for expanding unit's activity/projects to innovative structural materials

4.1 Challenges in building retrofitting projects

4.1.1 Cost

A major issue of energy retrofitting interventions on existing buildings is that the adopted refurbishment solution does not provide extension of the structural service life, and structural safety is not guaranteed in the case of an earthquake. Depending on the intensity of the seismic event either small or extensive repair measures, inhabitants' relocation or building's collapse could be experienced. Therefore structural and seismic safety should be considered, especially in deep energy renovation projects. **The main challenge to provide seismic plus energy retrofitting is naturally the total cost of the intervention**. To put the intervention cost in a context, the energy renovations are categorised together with average total project costs for energy efficiency measures. Table 4.1 summarises four energy renovation types, together with their average total project costs, expressed in €/m^2 floor area. The costs reflect the total installed costs of measures, i.e. **materials, labour and professional fees**, but do not include any costs not directly related to improving the energy performance of buildings (BPIE, [15]).

Table 4.1 Energy renovation type and cost estimates [15].



Description (renovation type)	Final energy saving (% reduction)	Indicative saving (for modelling purposes)	Average total project cost (€/m²)
Minor	0-30%	15%	60
Moderate	30-60%	45%	140
Deep	60-90%	75%	330
nZEB	90% +	95%	580

Similar cost estimates were calculated by Saheb et al. [3] in a JRC report. Investment needs were calculated on the basis of an average 100 m^2 for houses and 75 m^2 for apartments and average of housing prices in individual Member States. Given these parameters, '**economically feasible**' technological solutions are those costing no more than **€ 300/m^2** in MS dominated by well-established property markets. It was considered that deep renovation options make economic sense and are feasible if their cost does not exceed the 25 % of the value of the building. The authors assumed that, above this level, it might be more sensible to construct a completely new building than to renovate the existing one.

For MS of south Europe (i.e. Greece, Portugal, Italy) that the building and property market has declined considerably the last decade, the average project cost for achieving moderate energy retrofitting could be as low as 60-120 €/m^2. As explained earlier though, the majority of the south Europe regions are seismic (see Fig. 2.2) and consequently energy must be accompanied by seismic retrofitting, increasing substantially the intervention cost. Therefore, to make seismic plus energy retrofitting economically feasible **novel solutions based on combination of advanced materials and systems need to be developed**.

4.1.2 Sustainability and Environment

Another major challenge is to ensure the sustainability of renovation scheme both in terms of environmental burden (i.e. CO_2) and economic investment in seismic regions. As very recently reported by Belleri and Marini [80], the sustainable renovation of existing buildings is typically addressed focusing on the reduction of the operational energy consumption and on the use of low-carbon materials in the refurbishment process, without accounting for the structural deficiencies, which could leave the building seriously unsafe and hamper the refurbishment investment, particularly in seismic prone areas. In fact the majority of these structures were built before the enforcement of modern seismic codes and before updated seismic classification of the European territory, and they are typically vulnerable with respect to seismic actions (see section 2.2).

Recent earthquakes in the European territory have emphasized this aspect, evidencing damage on many buildings, some of which previously undertook energy efficiency upgrades taking advantage of national subsidies. This situation highlights how, in the renovation process of existing buildings, in order to foster the transition toward an actually low-carbon society, the design-leading concept of eco-sustainability should be integrated by taking into account the assessment and mitigation of possible building structural vulnerabilities, especially in seismic prone territories.

Belleri and Marini [80] presented a very illustrative map (Fig. 4.1), depicting three possible scenarios of an existing building requiring energy renovation measures. In addition, the building is considered vulnerable to seismic loads and having exhausted its structural service life (50 years for ordinary buildings).

The first scenario considers **demolition and reconstruction**, given the extremely poor performance of the considered RC building stock. Upon completion of the intervention, the new building performance meets all up-to-date requirements on both energy consumption and structural safety; the new building end of life scenario includes selective dismantling and possible reuse or recycling of the construction materials. Noteworthy, however, if extensively practiced, demolition and reconstruction may be not sustainable; indeed, the impact of such approach on the environment would be unbearably high, both in terms of raw material consumption and hazardous-waste production. Furthermore, this approach would require relocation of the inhabitants.

The second scenario depicts common interventions targeting the **sole energy refurbishment**. This solution does not provide extension of the structural service life, and structural safety is not guaranteed in the case of an earthquake. Depending on the intensity of the seismic event either small or extensive repair measures, inhabitants' relocation or building's collapse could be experienced. Ultimately, no virtuous recycling and reuse can be foreseen in post-earthquake emergency management, but rather all debris of collapsed constructions maybe disposed in landfills, increasing the environmental impact of the end-of-life phase.

The third scenario considers a more innovative approach involving **energy plus seismic retrofitting** (see proposed solutions in section 4.2.2). In particular, the structural renovation regards the introduction of new lateral force resisting systems embedded in the building new, or improved envelope. This solution does not require inhabitants' relocation and meets safety requirements in the case of seismic loads. Noteworthy, the structural intervention allows lengthening the building structural service life, which would be left unchanged by any intervention aimed at upgrading the sole architectural and energetic performances. This integrated solution reduces the equivalent annual impact of the embodied energy given that the environmental load can be spread over a much longer time span.

The significance of accounting for seismic risk in the environmental assessment is discussed in section 5.2, where the energy consumption, operational cost, and carbon emission, among other variables, are expressed as a function of the building life (the time elapsed since its construction); the seismic impact is represented as an expected loss, expressed as annual energy consumption, being the seismic event uncertain in nature [80].

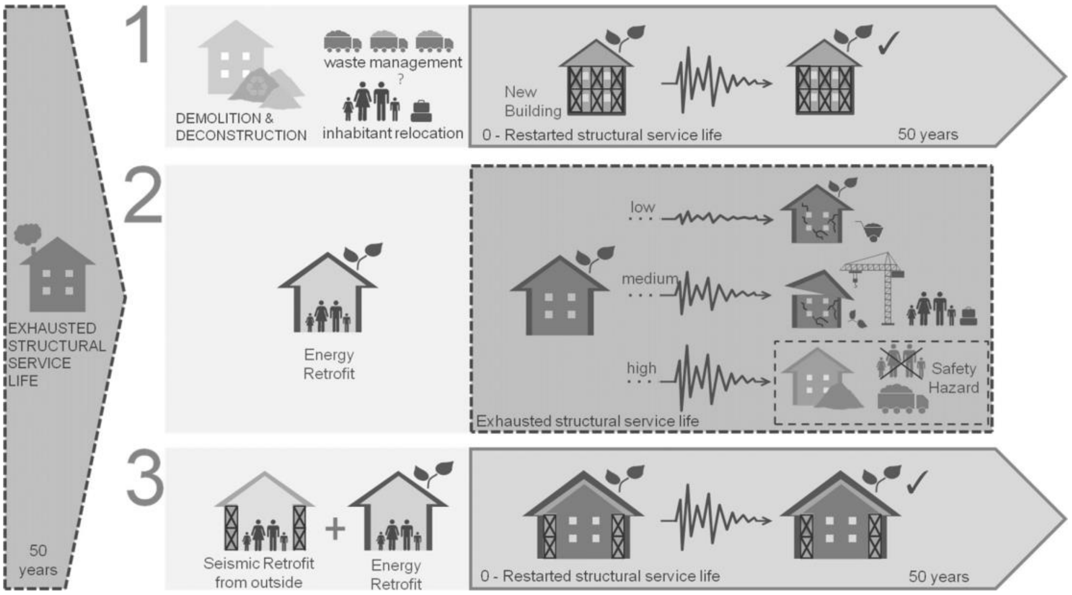


Figure 4.1 Conceptual map of possible retrofit scenarios: (1) demolition and reconstruction; (2) sole energy upgrade and (3) coupled energy and structural renovation; Source [80].

4.1.3 Durability and Fire Safety of the building materials

Both **durability** and **fire resistance** should be considered in envelopes retrofitting. The *EU action plan for the Circular Economy (2015)* apart from addressing the whole materials cycle, towards '*closing the loop*' of product lifecycles through greater recycling and re-use, it also emphasises that design improvements to buildings are needed to increase their durability. Similarly, the *Construction Products Regulation (2011)* set as of its basic requirements the '*durability of the construction works'.* Therefore the materials and solutions used to refurbish the building envelopes should bring additional functionalities (composites and ultra-thin or elastic multifunctional ceramics or other insulation materials; nanotechnologies for new materials and surface properties) which improve durability and reduce maintenance needs.

Furthermore, the **fire safety of the building envelope should not be compromised by the adopted retrofitting solution**. As discussed in Chapter 3, various building materials used either in seismic retrofitting (i.e. composites bonded with epoxy resins, Section 3.1.3) or energy retrofitting (i.e. Polyurethane, section 3.2.1) projects, have poor performance at high temperatures or fire. To make matters worse, burning of resin or polyurethane emits gases which could put people health at considerable risk. In consequence, novel retrofitting materials and solutions should be developed and promoted which are non-combustible and have high resistance to high temperatures (i.e. up to 400 °C). Unfortunately, fire safety is not always adequately addressed in energy renovation projects of existing buildings due either the lack of proper standards and/or the use of inappropriate materials, especially for high-rise buildings. The Grenfell Tower fire was a dramatic incident that caused 71 deaths, after undergoing a major renovation which was completed in 2016, including energy retrofitting by means of a new façade to the building envelope. Further information can be found in [81].

4.2 Research needs and recommendations towards new projects on innovative structural materials for building retrofitting

4.2.1 Durable, sustainable and cost-effective materials for structural retrofitting

As already analysed in sections 3.1.2 and 3.1.3, the problems associated with conventional strengthening techniques (*intensive labour and skilful detailing-high cost, large quantities of raw materials-higher embodied CO_2 emissions, more energy in manufacturing, disrupt the occupancy of the building under renovation*) and FRP materials (*poor behaviour at high temperatures, high costs, inapplicability on wet surfaces or low temperatures, health and safety issues for manual workers, mainly attributed to the organic resins used to bind and impregnate the fibres*), could be successfully addressed using novel inorganic composite materials. To this end, a number of cement-based composites, such as Engineering Cementitious Composites (ECC), Ultra High Performance Fibre Reinforced Concrete (UHPFRC), and Textile Reinforced Mortar (TRM) have been developed the last decade. Among them the last has been the most effective in strengthening and seismic retrofitting of concrete and masonry structures, as, contrary to the other cement-based composites, TRM combines the inorganic binders with continuous fibres.

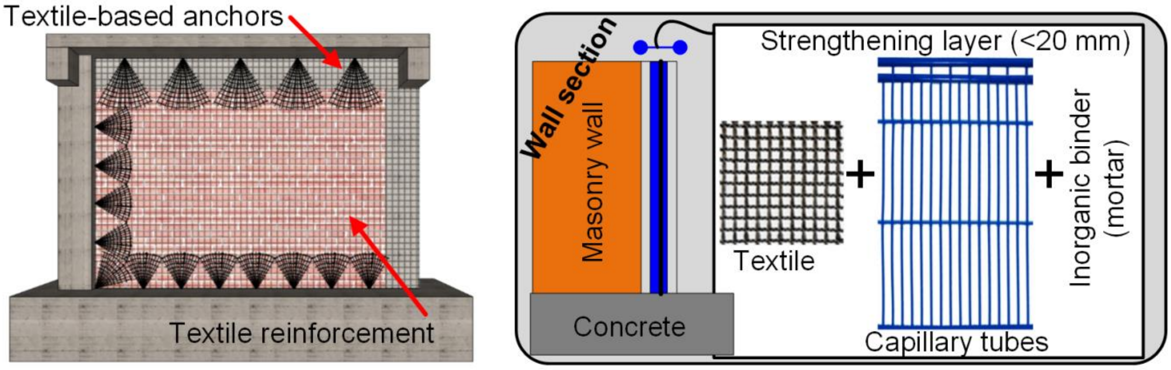
TRM is a promising user - and environment - friendly material to strengthen existing deteriorated RC structures, as if compared with FRP systems; TRM offers enhanced durability, resistance to high temperatures, lower cost and compatibility with the substrate material. However, TRM is not yet well understood and major opportunities for boosting TRM in strengthening applications are being missed. Future research projects should seek to provide an overall understanding of TRM and allowing the benefits of these systems to be realised and full impact to be delivered. This will be achieved by investigating a number of unknown parameters associated with the effectiveness of TRM materials that need to be quantified before scaling up, and which can then be used to underpin the widespread application of these novel materials in construction. The issues in question include:

(i) The **performance of TRM** systems **at high temperatures or fire**
(ii) The **fatigue behaviour of TRM strengthening systems**
(iii) The assessment of TRM effectiveness in seismic retrofitting of a building in real-scale
(iv) The **development of a set of design specifications and standards** for the use of TRMs as strengthening systems for RC structures in practical retrofitting applications
(v) The development for smart multifunctional textile fabrics (see next section)

4.2.2 Seismic plus energy retrofitting

To make **seismic plus energy retrofitting** economically feasible novel solutions based on combinations of advanced materials and systems need to be developed. Therefore, new research should go several steps beyond the current state-of-the-art and aim to answer how can the seismic and energy retrofitting systems be combined to an integrated retrofitting solution. Such a challenge could only be addressed if a **multidisciplinary and inter-sectorial approach** is adopted, combining for example expertise on structural engineering; building physics; and advanced manufacturing techniques of composite materials.

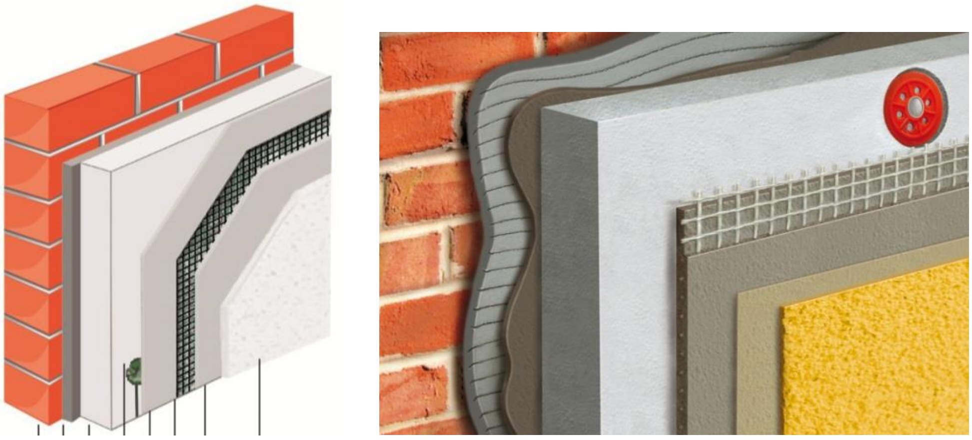
The proposed novel concept to achieve simultaneous structural and energy retrofitting in a building envelope is presented in Fig. 4.2, for the case of RC framed structures with masonry infills and/or unreinforced masonry structures. This solution simply combines high strength lightweight reinforcement for seismic retrofitting (of both structural and non-structural members), whereas an additional insulation material or heating system are integrated to the reinforcement to achieve energy retrofitting. The bonding of the reinforcement to the building envelope is realised by using an inorganic cement-based mortar to provide durability and fire resistance to the hybrid retrofitting system. The intervention concept is similar to existing retrofitting solutions on building envelopes either seismic (i.e. Fig. 3.9) or energy (i.e. Fig. 3.18 and Fig. 3.22), as the externally applied reinforcement, insulation material or energy heating systems are bonded to concrete or masonry surfaces using inorganic mortars. This allows with **one intervention** to achieve both of the required **safety and energy** performance, while keeping the overall cost low (as explained in section 5.1.1), by **dramatically reducing the labour cost**.



(a) (b)

Figure 4.2 (a) Seismic strengthening configuration; (b) Textile reinforcement combined with capillary tubes will be integrated and embedded into a thin mortar layer.

The integration of different insulation materials to the textile reinforcement could result to various hybrid retrofitting solutions, such as TRM+PUR, TRM+VIP, TRM+NIM, TRM in a matrix containing PCM, or TRM + heating system as illustrated in Fig. 4.2b. The strengthening procedure starts with the seismic strengthening of the masonry-infilled RC frames with TRM (as described in Fig. 3.9), and then, the thermal insulation material is added straight afterwards, while the mortar is still in a fresh state. Such a strengthening system is similar to External Thermal Insulation Composite Systems (ETICS, Fig. 4.3), which represent a novel solution for building rehabilitation in order to upgrade indoor thermal and acoustic conditions, but it requires that first high strength textile fibres (i.e. carbon, glass, or aramid) are bonded to connect the masonry infills to the RC frame or reinforce the unreinforced masonry in order to provide the required seismic upgrading.



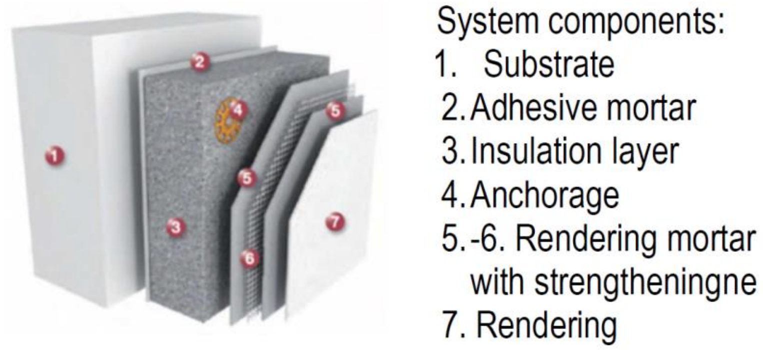
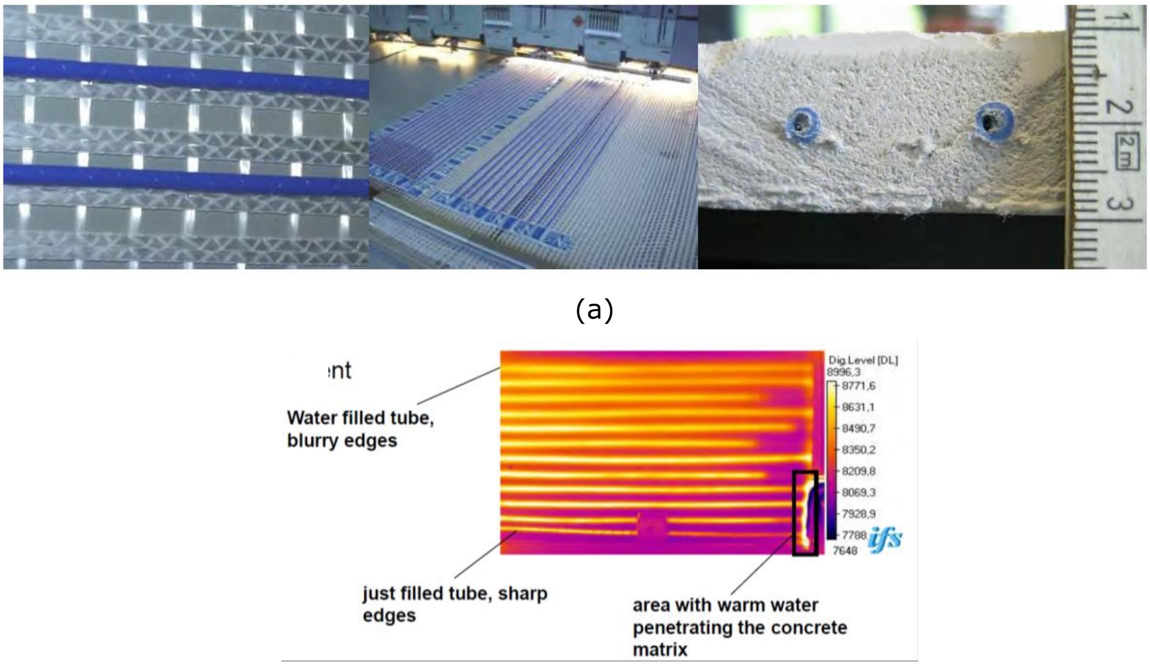


Figure 4.3 External Thermal Insulation Composite Systems.

Very recently, Triantafillou et al. 2017 [82], proposed a new system combining polymer-coated glass-fibre textile with expanding polystyrene (EPS) for the structural and energy retrofitting of masonry walls, concluding that TRM jacketing may be combined effectively with thermal insulation.

Advanced and automated processes will favour the use of <u>prefabricated modular solutions and smart materials</u> for high performance works. A solution of great potential in both new buildings and refurbishing existing ones is the use of Textile Reinforced Concrete (TRC) prefabricated modules with smart textiles to integrate additional functions. For example, as discussed in previous sections, if capillary tubes are combined with the textile reinforcement by stitching process (Fig. 4.4a), energy harvesting and distribution for heating and cooling of building components (walls and roofs) are possible (Fig. 4.4b).



(a)

(b)

Figure 4.4 (a) Capillary tubes stitched to glass fibre textile reinforcement and TRC panel (b) Infrared thermal camera scanning of a TRC module with warm water. (Institut für Textiltechnik (ITA), RWTH Aachen University).

4.2.3 NanoCon

Jelle [60] envisioned NanoCon as new structural material which could have a huge impact. NanoCon is basically a homogeneous nano-insulation material (NIM) with a closed or open small nano pore structure with an overall thermal conductivity of less than 4W/(mK) and exhibits the crucial construction properties that are as good as or better than concrete (Fig. 4.5).

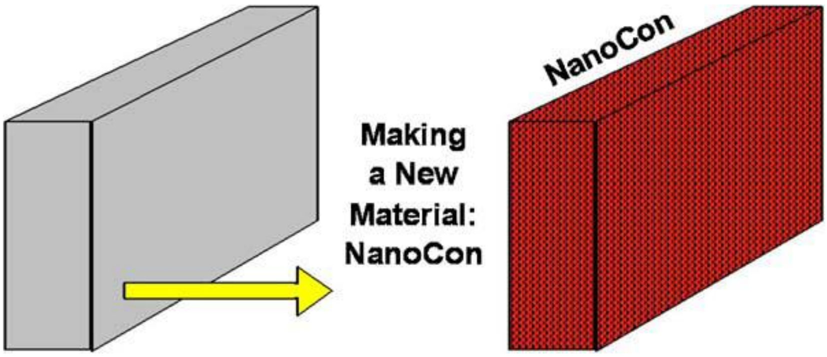


Figure 4.5 NanoCon is essentially a NIM with construction properties matching or surpassing those of concrete. [60].

Essentially, NanoCon is a NIM with construction properties matching or surpassing those of concrete. Depending on the mechanical or construction properties of NanoCon, it may be envisioned either with or without reinforcement or rebars. In the above definition of NanoCon, a homogeneous material is stated, although the first attempts to reach such a material might be tried by piecing or mixing several different materials together, i.e. with a final material product which on a nanoscale is not homogeneous. For example, joining NIM and carbon nanotubes in one single material might enable a very low thermal conductivity due to the NIM part and a very large tensile strength due to the carbon nanotube part. In this respect it should be noted that carbon nanotubes have a very large thermal conductivity along the tube axis. Furthermore, it is noted that the extremely large tensile strength of carbon nanotubes (63,000MPa measured and 300,000MPa theoretical limit) surpasses that of steel rebars (500 MPa) by more than two orders. As a comparison concrete itself without rebars has a tensile strength of 3MPa and a compressive strength of 30 MPa [60].

The cost of such a material is currently prohibitively high, however the potential of using a **nano-modified mortar without reinforcement** for simultaneous **structural** and **energy** retrofitting might to cost effective solutions. The grand challenge for researchers will be to provide high tensile strength in the direction of major principal stresses without using continuous reinforcement and while keeping the cost sustainable.

5 Expected impacts

The ability to seismic and energy upgrade the existing concrete buildings will have a great impact on society, economy, environment knowledge and people.

5.1 Economy

The benefits of building retrofitting are significant: in EU countries alone, the annual cost of repair and maintenance of the infrastructure, as a result of problems associated with deterioration and energy retrofitting, is around than €300 billion. The use of inorganic composites in rehabilitation of existing structures **reduces overall costs** (including time for execution) considerably. The potential of **expansion** in the **composites industry** is very exciting, since this is expected to lead to the **creation of jobs**. Also, since much of the ailing composites industry is in Eastern Europe and Associated countries, this will improve European **economic cohesion**.

Simultaneous seismic and energy retrofitting will provide several European industries with a technology to increase their markets in Europe and abroad. Composites manufacturers, producers of mortars and companies specializing in structural retrofitting interventions (consultants and contractors) will have significant benefits as future research will provide the frameworks to develop a technology to increase and diversify their markets in the EU and abroad. The energy plus seismic strengthening concept could result in the development of an "*Integrated Strengthening System*", that will not only be competitive to other existing European, or imported, solutions, but it will be a leading innovation due to the simplicity of application and the use of user and environmentally friendly materials.

New design guidelines and standards can be directly used to design with TRM systems and hence contribute to the competitiveness of EU consultants and contractors by providing more efficient and cost effective design solutions in retrofitting interventions.

5.1.1 Market in building retrofitting and potential savings from energy plus seismic retrofitting

The review of the existing building stock conducted in chapter 2 revealed that from the 233 of buildings in EU-27, the 174 million (75%) comprise residential buildings (see section 2.1). Also 66% of the current building stock had already been built in the 1970s without seismic and energy provisions (see section 2.3.1). As a result it is estimated that **116 million residential houses need to be retrofitted to meet the requirements of current standards**.

According to other sources there are roughly 207 million buildings in Europe [81] and around 129 million were built before 1970 (representing about 62% of the current building stock). Statistics reveal that the execution of RC buildings before 1945 accounted for 6% of EU 27 building stock, while that percentage increased up to 80% with the construction boom of 1960s [83]. Additionally, 14% of EU-27 building stock dates before 1919. During this period masonry was a common construction material and it can be considered that it represents 80% of the stock. Thus, a potential stock of approximately **81 million of RC and 23 million of masonry buildings demand rehabilitation solutions**.

Therefore very similar numbers occur following independent resources, which add confidence in considering that at least **100 million buildings need retrofitting**. In addition, approximately 1% of the existing building stock is **annually subjected to restoration** within the EU-28 [84], thereby leading to the total annual rehabilitation of around **1 million buildings.** Considering a reference building a multifamily block (3 stories composed of 2 dwelling/story, that is, 6 dwellings/building) and that the average surface of residential buildings is 70 m^2, it is estimated that **70,000,000 m2/year need to be rehabilitated.** By considering average costs for deep energy renovation

330 €/m^2 (see section 4.1.1), a potential annual business niche of 23,1 billion euros can be associated to the rehabilitation market of buildings erected before 1970 and consequently 392,700[6] created or preserved jobs per year in EU-28. By considering a 3% retrofitting rate (which is currently applied through the EPBD for public buildings) the corresponding values triple, namely **business value of 69,3 billion euros and 1,193,100 jobs** per year.

For seismic countries of Europe (see section 2.2.1) the development of seismic plus energy retrofitting solutions (see section 4.2.2) will reduce the total retrofitting cost by at least 30%, primarily through savings associated with the labour cost.

Based on the amount of population living in seismic zones it is estimated that around 25% of the EU-28 building stock is located in seismic zones, which means that **1 million buildings need to be seismic and energy retrofitted annually** (for a 3% renovation rate scenario).

By considering the total cost of seismic and energy retrofitting could be reduced by at least 30% by combining energy with seismic retrofitting due to labour cost savings, it is expected that the development **new seismic plus energy retrofitting solutions** will have a **big economic impact on the EU building sector**.

5.2 Environment

The safety, durability and energy efficiency of buildings is a transnational problem and, as such, a concerted effort is required to address it. This is in direct line with the EU Environment Policy, built into the Treaty by the Single European Act of 1987. Research around the proposed area will contribute to the key aims of the policy – **sustainable growth through the preservation of the environment** – by increasing the lifetime of existing buildings and reduction of consequent occupancy disruption (during the renovation of the building) by 100% and loss of use by 10%, thereby directly minimising the drain on non-renewable natural resources (**reduction of use of cement and aggregate by 50%, oil by 10%**). Also the Kyoto Protocol and the European Vision 2050 is supported through the reduction **of CO_2 emissions from cement and steel production by 50% less concrete usage and lower reinforcement and repair requirements**.

The significance of accounting for **seismic risk in the environmental assessment of** houses underwent either **energy** retrofitting, or **energy plus seismic retrofitting** was presented by Belleri and Marini [80]. Their findings are presented in Fig. 5.1, where the energy consumption, operational cost, and carbon emission, among other variables, are expressed as a function of the building; the seismic impact is represented as an expected loss, expressed as annual energy consumption, being the seismic event uncertain in nature. Figure 5.1a considers a building energy retrofit intervention (R_E) targeting the nearly zero energy building performance. This intervention does not affect the building seismic behaviour, therefore if a seismic event (X) occurs during the building life, there is an additional cost associated to the building post-earthquake repair, which represents the actualization of the expected seismic loss. Interestingly the graph shows that, depending on the relevance of the annual energy consumption associated to the seismic risk, the nearly zero energy performance could be only theoretically attained, whereas actual consumption could be higher. Noteworthy, typical procedures adopted to evaluate the environmental impact of buildings neglect this contribution, which could have even a greater impact when considering the problem at the district level. Figure 5.2b considers both building energy and seismic retrofit intervention ($R_{E,S}$). After the seismic retrofit the expected seismic loss is significantly reduced, therefore if a seismic event (X) occurs after the structural retrofit intervention,

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[6] On average, the studies reveal that 17 new jobs can be created for every €1 million of expenditure at today´s prices.

the additional cost due to the building repair is much lower than in the previous case. It is worth noting that unlike sole energy refurbishment interventions, in the second case the structural retrofit allows the extension of the building structural service life as mentioned before [80].

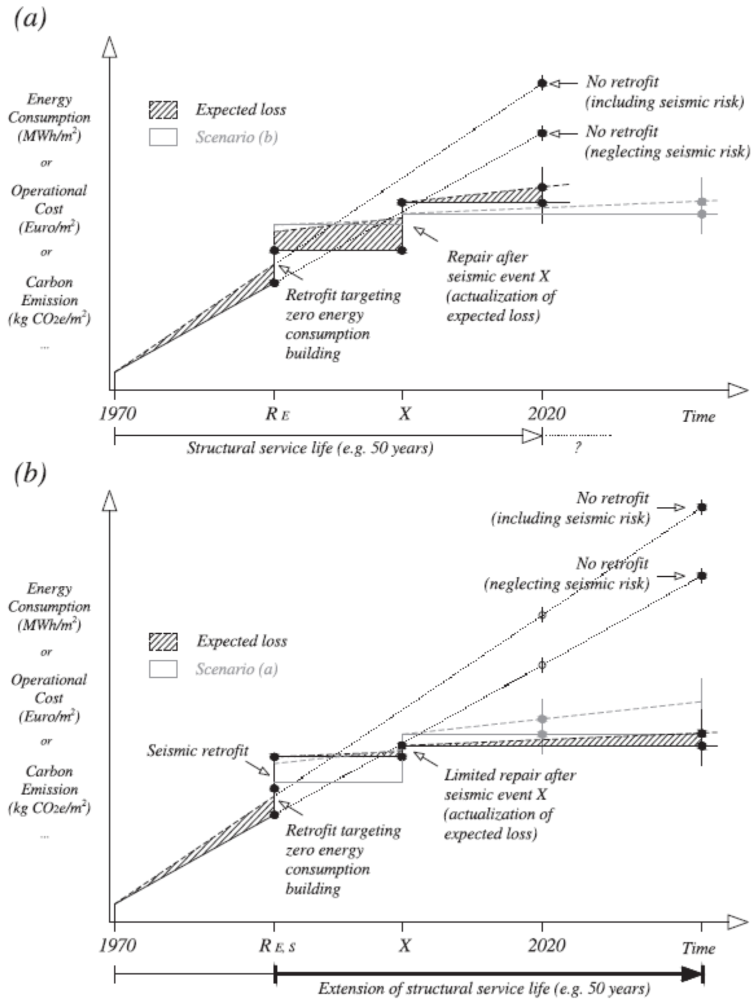

Figure 5.1 Impact of energy consumption, operational cost and carbon emission during building life cycle. (a) Energy retrofit intervention and (b) energy + seismic retrofit interventions. [80].

5.3 Knowledge and People

The novel strengthening solutions to be investigated and developed can eliminate the social risks (i.e., loss of human life and injuries during strong earthquakes, disruption of occupancy in building during the intervention) related to structural deterioration of existing building RC infrastructure. In addition, research activity in the suggested areas will provide training to young researchers, create awareness of new activities and technologies to the general public, contribute to the development of expertise of structural engineers and technicians and educate undergraduate students. Increase in the renovation rates will generate up to 1 million jobs annually by 2020.

The construction industry accounts for 9.2 % of the EU-28 GDP and according to FIEC data employs directly 15 million people in large, medium and small enterprises. Construction is indeed a key sector for job creation. According to the BPIE study [15], a slow but constant **increase in the renovation rates** would **generate** on average **400 000 jobs annually by 2020**, and a fast ramping up would lead to an average 600 000 jobs each year. **The deep scenario would create up to 1 million jobs**. This is in line with the recent consultation by DG Energy on '*Financial support for energy efficiency in buildings'* highlighting the fact that, although often difficult to quantify exactly, increasing the level of investment in building energy efficiency would also have a strong effect on job creation.

For example, the United Nations Environment Programme (UNEP) in its 2011 Green Economy Report [84] states that '*investments in improved energy efficiency in buildings could generate an additional 2 to 3.5 million jobs in Europe and the United States alone*'.

The French Ministry for Ecology, Energy, Sustainable Development and Spatial Planning estimates that **for every EUR 1 million of investment in property-related thermal renovation, 14.2 jobs are created or maintained** in the field of energy performance-related work [87]. Applying these numbers to the above-identified investment need of EUR 60 billion per year would result in the creation or retention of around 850 000 jobs per year in the EU.

Similar figures can be found in the Impact Assessment of the Energy Directive where a more realistic assessment in the Energy Efficiency Plan estimated the employment potential to up to 2 million jobs based on data from the building sector. As the construction sector is in general highly locally oriented [87], this means that job creation in this sector would have a high impact on local employment. The **employment** generated **in** the **construction sector** is indeed rather local and this would provide a **clear boost to local economies** which are struggling in the crisis time, thus **fostering smart specialisation**.

6 Conclusions

The seismic and energy retrofitting of existing European buildings with innovative materials and solutions was addressed in this report. The need for retrofitting of old buildings emanates from their substandard design in terms of earthquake resistance and thermal insulation, as revealed during strong earthquakes or due their high energy consumption (heating and cooling). This report explored innovative methods for the retrofitting of buildings by conducting a state-of-the-art review on advanced materials and solutions for enhancing the safety, energy and resource efficiency of the deficient EU residential buildings. The summary and main conclusions of the report are presented chapter-by-chapter, as follows:

Chapter 1

Construction is the largest European single activity accounting for 9.2 % of the EU-28 GDP and the biggest European industrial employer. In addition, buildings are the largest consumer of energy in Europe, accounts for around 40% of the total energy usage and making buildings responsible for 38% of the EU's total CO_2 emissions. Therefore, the building industry is a key enabler for achieving the 2050 decarbonisation goal of the European economy.

Maintenance of existing buildings is becoming the major activity for the building sector. In EU-28 (2011), the specialized construction activities that included renovation work and energy retrofits accounted for 66 % of total building output. Considering that half of the existing building stock in 2012 is expected to be operational by 2050, it becomes apparent that tackling refurbishment of existing buildings is a top European priority, leading to a big number of relevant EU policies.

Chapter 2

The amount of buildings in EU-27 was estimated to be 233 million in 2013. The residential ones account for the largest share (75%) and have longer life and slower replacement rate. This results in older building stock with high maintenance needs for achieving modern buildings performance both in terms of safety (i.e. Eurocodes) and energy performance (i.e. EPBD).

The seismic activity in in the south-eastern areas Europe is considerable. The most hazardous countries are Greece, Italy, Turkey, Romania and the Balkan region, whereas Spain, Portugal, France, Germany and Belgium are European countries with low/moderate hazard.

Columns are the most vulnerable structural elements, in existing not seismic designed buildings, that can be heavily damaged and/or lead to building collapse; therefore need to be seismic retrofitted. Even when buildings survived collapse, the non-structural damage in masonry infills was excessive, indicating also the need for seismic retrofitting of structural and non-structural elements.

In common with the lack of seismic design, the first energy codes for buildings were introduced in response to the oil crisis in the 1970s, when 66 % of the current EU building stock had already been built.

The energy performance of building envelope components, including external walls, floors, roofs, ceilings, windows and doors, is critical in determining how much energy is required for heating and cooling. Over the years, code requirements on building envelopes have improved significantly, and continue to increase in performance.

Chapter 3

For what concerns seismic retrofitting, the structural assessment of existing buildings defines the retrofit measures and criteria. In general terms, local measures are more appropriate when some elements possess insufficient capacity, whereas global measures are suitable in case of large deformation demands.

Steel or RC jacketing are the most common conventional strengthening techniques which are applied to increase the strength and ductility of RC members. To increase sufficiently the lateral stiffness a global retrofit measure including the addition of shear walls is required. However conventional strengthening techniques, require intensive labour and skilful detailing, considerable quantities of materials, and disrupt the occupancy of the building under renovation.

Such disadvantages are overcome using fibre-reinforced polymer (FRP) materials. FRP are popular in construction, due to their high strength to weight ratio, corrosion resistance, ease and speed of application, minimal change in the geometry. Nonetheless, the FRP strengthening technique entails a few drawbacks (poor behaviour at high temperatures, high costs, inapplicability on wet surfaces or low temperatures, health and safety issues for manual workers), attributed to the organic resins used to bind and impregnate the fibres, which limit their applicability.

To address the problems of conventional strengthening techniques and FRPs, a novel structural material, Textile-Reinforced Mortar (TRM) was proposed. TRM comprise textiles fabric meshes, impregnated with inorganic binders, such as cement-based mortars. TRM is a low cost, friendly for manual workers and fire resistant novel material that is progressively becoming attractive for the seismic strengthening of existing buildings.

For what concerns energy retrofitting, a simple and effective way to improve the energy efficiency of a building is by improving the thermal insulation of its envelope. The selection of thermal insulation thickness depends on the thermal conductivity and thermal inertia of the selected insulation material.

A review was conducted on the most commonly used insulation building materials, namely: (a) Conventional insulation materials; (b) State-of-the-art insulation materials; (c) Nano insulation materials and (d) Smart insulation materials. The main conclusion is that although the conventional insulation materials (i.e. *mineral wool, expanded or extruded polystyrene, cellulose, polyurethane*) are quite cheap and adaptable, they do not appear to be promising as their thermal conductivity is high. On the other hand, some of the state-of-the-art and future materials (*Vacuum insulation panels, nano-insulation materials*), appear to be more promising as their thermal conductivity is approximately 10 times lower. Naturally, more research is needed to reduce their manufacturing cost per thermal resistance. Smart insulation materials and systems such as phase change materials and smart heating of buildings via exterior walls appear to be very promising for existing building envelopes retrofitting.

Chapter 4

The structural and seismic safety should be jointly considered, especially in deep energy renovation projects. The main challenge to provide seismic plus energy retrofitting is the high total cost of the intervention, which could be affordable only if novel solutions based on combination of advanced materials and systems are developed.

The sustainability of the renovation scheme both in terms of environmental burden and economic investment in seismic regions comprises another major challenge. Not considering the structural safety of energy renovated buildings, could leave the building seriously unsafe and hamper the refurbishment investment (even with frequent earthquakes), particularly in seismic prone areas, as proved by recent earthquakes in the European territory.

Both durability and fire resistance should be considered in envelopes retrofitting. To this end, a number of cement-based composites have been developed the last decade or so. Among them TRM seems to be the most effective in seismic retrofitting of applications, as it combines continuous fibres with inorganic binders. Furthermore, TRM is a promising material for seismic retrofitting of existing buildings, as it offers enhanced durability, resistance to high temperatures and lower costs. Future research should seek to provide understanding of TRM effectiveness: at high temperatures or fire, under fatigue loading, and in retrofitting of full-scale structures.

Seismic plus energy retrofitting could be economically feasible if advanced materials and systems are combined. A solution with great potential could combine high strength lightweight reinforcement for seismic retrofitting with an additional insulation material or heating system (integrated to the reinforcement) to achieve energy retrofitting. The bonding of the reinforcement to the building envelope is realised by using an inorganic cement-based mortar to provide durability and fire resistance to the hybrid retrofitting system.

Chapter 5

The ability to seismic and energy upgrade the existing buildings will have a great impact on society and the economy, environment knowledge and people.

For seismic prone EU countries the development of seismic plus energy retrofitting solutions will reduce the total retrofitting cost by at least 30%, primarily through savings associated with the labour cost.

The structural vulnerability of existing buildings, resulting in major damage or even collapse during a seismic event, can substantially jeopardize the energy savings obtained with the solely energy retrofit interventions. Disregarding seismic risk may result in misleading expectations on the actual effect of extensive energy saving measures.

Related and future JRC work

Following this pilot background study presented in this Technical report, the author made a proposal for a new Exploratory Research (ER) project, titled Innovative Seismic and Energy Retrofitting of the ExiSting BuIlding STock (iRESIST+), which was succesfull and will start in 2018. ***iRESIST+* aims to provide a fundamental understanding on whether seismic and energy retrofitting can be jointly achieved** in a cost-effective way, by conducting the initial phase of research which, if successful, will form the ground of more conclusive institutional research in this topic. This aim will be accomplished through the following specific measurable **objectives:**

1. To develop a new system for simultaneous energy plus seismic retrofitting of the existing buildings’ envelopes using advanced construction materials.
2. To investigate experimentally and validate the effectiveness of the proposed retrofitting system in a full-scale RC building.
3. To provide a common approach for the classification of existing EU building stock performance considering energy efficiency and seismic resilience.
4. To make recommendations for future research and standardisation needs in the topic.

This ER project contributes to the JRC mission by providing scientific evidence on a promising idea which is expected to have great impact on future societal and policy challenges.

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