Innovative techniques integrating advanced and biocomposite materials for energy and seismic retrofitting of built heritage

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Abstract

Cultural heritage is recognized as a driver of the sustainable development. The UNESCO's 1972 World Heritage Convention has addressed key topics that link heritage practices to sustainability objectives. Historic buildings make up a considerable part of EU building stock, and their renovation and safeguarding require retrofit solutions that balance safety, energy efficiency, human comfort, heritage value preservation and environmental sustainability. This article tries to throw light on innovative techniques for heritage restoration based on sustainability, reuse, and recycle principles through non-invasive interventions. The work outlines the progress in the field of advanced materials obtained through the reuse of recycled materials, showing outcomes from MIRACLE research carried out by University of Florence on the development of an innovative fiber-reinforced bio-composite matrix to be applied for energy plus seismic retrofitting of existing masonry buildings built before 1945.

Keywords Building heritage, deep renovation, technological innovation, bio-composite materials, environmental impact.

Introduction

Historic buildings represent a considerable part of EU building stock, and their safety and regeneration are progressively becoming a significant activity for the construction sector. The current European policies establish a long-term renovation strategy for all EU countries to support the national building stock refurbishment into a highly energy efficient and decarbonized building stock by 2050[1].

About 35% of the EU's buildings are over 50 years old and almost 75% of the building stock is energy inefficient. Moreover, the built heritage needs continuous care and maintenance to ensure buildings operation and indoor comfort for users over time.

The sustainable strategy to improve the performance of existing buildings is typically addressed by focusing on reducing energy consumption and using low-carbon materials in the renovation process without accounting for safety related to seismic actions. However, in contexts of high historical value, proper design strategies and effective solutions are necessary to enhance the structural resistance while ensuring energy saving and indoor comfort requirements through non-invasive interventions to preserve the historic and aesthetic values of the architecture.

A current issue is that interventions for energy saving often include criteria that are inapplicable on historic buildings due to the limitations of the regulations concerning preservation of architectural heritage. This is even more felt in Italy, where a large part of the historic heritage consists of masonry buildings built before the introduction of anti-seismic standards (i.e., Eurocodes) and energy requirements (i.e., EPBD) and subjected to the provisions of the Code of Cultural Heritage and Landscape.

Compared with other EU countries, rates of new building activity in Italy are among the lowest in Europe and well below the EU average. Therefore, the efforts to advance NZEBs will remain centered on the challenge of existing buildings and deep retrofit, according to the national policies for building-sector decarbonization, which includes the Long-Term Strategy (LTS) for the Reduction of Greenhouse Gas Emissions by 2050 and the National Energy and Climate Plan (NECP). Accordingly, the technologies that will be developed have to meet the guidelines set by the European Commission (Energy Performance Directive, 2018; New Circular Economy Action Plan for a Cleaner and more Competitive Europe, 2020), which promote the development of technological solutions that can be used in interventions of regeneration and refurbishment in the perspective of Life Cycle Thinking.

Enhancing the safety, comfort and resource efficiency of existing heritage represents the most sustainable option in the near future, but it would be prohibitively expensive, increasing substantially the intervention cost. A BPIE report categorizes the energy renovations options (Fig.1) together with average total project costs (€/m^2) directly related to energy efficiency measure[2]. For deep renovation concerning hybrid structural-plus-energy retrofitting, the intervention cost does not exceed the 25% of the value of the building to ensure cost-effectiveness renovation.

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

Fig. 1 Energy renovation type and cost estimates (Source: BPIE report, Brussel, 2011)

The European Standard EN 16883:2017 for improving the energy performance of historic buildings acknowledges the importance of the assessing the whole life cycle of a historic building with respect to the existing materials and construction, discouraging the removal or replacement of materials as they cause resources and energy consumption with additional carbon emissions. This standard provides guidelines to be used by building owners, practitioners and institutions to select appropriate measures in the planning stage in order to find a sustainable balance between the use of the building, its energy performance and its conservation. This standard is not limited to listed buildings but also includes historic buildings of all types and ages.

Fiber-reinforced bio-composite matrices for building renovation

For what concerns energy retrofitting, a simple and effective way to improve the energy efficiency of a building is to improve the thermal insulation of its envelope. The integration of different insulation materials to the textile reinforcement could result to various hybrid retrofitting solutions. In this perspective are included the studies concerning the use of Phase Change Materials (PCM) and aerogel for the realization of thermal-plasters suitable for the use of redevelopment interventions in historic buildings.

After the introduction of advanced materials in the construction sector, numerous researches have been carried out at the national and international level focusing on energy and environmental efficiency, even through the use of bio-derivative and/or biodegradable polymer matrices and natural fibers[3].

In recent years, studies have moved towards the development of durable, sustainable and cost-effective cement-based composites materials for structural retrofitting such as Engineering Cementitious Composites (ECC), Ultra High Performance Fiber Reinforced Concrete (UHPFRC), and Fiber Reinforced Cementitious Matrix (FRCM).

Among all these methods, the FRCM are becoming the most suitable technique for building rehabilitation as a valid alternative to FRP, combining high strength lightweight reinforcement of continuous fibers (organic or inorganic) with a matrix made of synthetic or natural materials, such as thermal-plasters integrated to the reinforcement to achieve energy retrofitting, improving durability, fire resistance, and indoor thermal comfort[4]. They appear to be very promising for energy plus seismic retrofitting of existing buildings because allow with one intervention to improve both the mechanical strength and the inertia and thermal transmittance of building envelope, without increasing the dead loads on the vertical resistant structure.

MIRACLE research Project

In consideration of recent developments in the field of fiber-reinforced bio-composite matrices for building renovation, the research MIRACLE aims to develop an innovative bio-composite material to be applied in integrated energy plus seismic retrofitting projects of existing masonry buildings built in Europe before 1945. This composite material was obtained by coupling reinforcing fibers with a natural hydraulic lime-based matrix (Fig. 2), compatible with the wall support and ideally in line with the sustainable principles set by the European directives on the energy renovation of EU historic buildings.

Fig.2 Samples of fibre-composite matrices for experimental campaign (left) and preparation of a sample for laboratory test (right).

The MIRACLE research methodology consists of the following phases:

- The first phase concerns the identification of a limited numbers of products available on market in relation to their mechanical and thermal properties declared by the manufacturers. As result, 11 thermal plasters was selected based on compressive strength σ and thermal conductivity λ, including only those made of natural sustainable mortars or obtained from recycled materials and waste processing.
- As second phase, an extensive experimental campaign was carried out concerning: - bending tests on the matrices received in the laboratory.; - evaluation of the thermohygrometric properties through dynamic simulations using the WUFI®Pro software with regards to the total water content inside the wall [kg/m^3] and inside the internal plaster layer [kg/m^3]
- The third phase concerns the estimation of the mechanical properties of the basalt fabric and, subsequently, those of the composite made of reinforcing fabric embedded in the better matrix by means of direct tensile test on three test samples.
- The fourth phase, as a final, evaluates the structural behavior of a non-reinforced masonry panel (NRP) and a reinforced masonry panel (RP) subjected to diagonal compression tests by means of numerical simulations using the finite element software (FEM) Abaqus CAE.

As results, among the investigated samples, the products containing minerals have the better mechanical and energy performances[5]. In particular, the thermo-plaster selected to realize the MIRACLE prototype is made of pure expanded mineral sands with low specific weight, and shows a compressive strength of 2.48 [N/mm^2] and low percentage of water content inside the wall below 10-11 kg/m^3.

For the future developments, solutions that include organic and vegetable materials will be investigated to improve energy and environmental performances without compromising mechanical characteristics of an FRCM matrix, with the aim to optimize the environmental impact of MIRACLE matrix.

Conclusions

The UNESCO's World Heritage Convention indicates the importance of sustainable approaches to manage the existing building stock and the role of built heritage in this process. Traditionally, the built heritage preservation mainly focused on curative conservation and restorative interventions regardless of minimizing their environmental impact related to the building long term use. More recently, extensive progress has been made in technological research on innovative products and processes aimed at energy retrofitting of historic buildings, highlighting the positive contribution that heritage management and conservation can make to sustainable development.

In this framework, MIRACLE research aims to promote the ecological re-orientations of processes and products - based on sustainability, reuse, and recycle principles - related to conservation of the building heritage towards the achievement of Green Deal´s sustainable targets. Making use of the contribution from a range of interdisciplinary fields, through the study and advancement of knowledge in the sector of innovative bio-composite materials and their application to the entire building system in a non-invasive way, the results of the study demonstrate how is possible to raise both seismic and energy requirements and to meet the principles of environmental protection, reducing significantly the overall costs related to the enhancement and preservation of the existing building heritage.

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