Sandwich structures for sustainable buildings

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Abstract. The growing interest in cost-effective solutions for the structural upgrading of existing buildings and infrastructures has gradually oriented research towards the optimization of high-performance cement-based composites conceived for new lightweight constructions. These materials, known as textile reinforced concretes (TRCs) and/or fabric-reinforced cementitious mortars (FRCMs) in their recent developments are generally employed in the form of thin layers and have proven capable to significantly enhance the load-bearing and deformation capacities of underperforming structures.

Considering the large surfaces targeted by the retrofitting interventions, a primary objective is to avoid material wastage; in this sense, there is a major need of guidelines and simplified predictive models that can effectively assist the identification of optimum design solutions. Being the tensile behaviour of TRC strongly influenced by the matrix composition, the geometrical and chemo-mechanical characteristic of the embedded fabrics and the possible presence of short fibres, in this paper we aim at tracing the sustainable potentialities of TRC sandwich solutions as multifunctional light structures for façades and roofing.

Introduction

A great part of the existing residential and industrial stock in Europe is characterized by un-satisfactory structural and energy performance, not in compliance with updated Standards [1].

The structural weakness is particularly relevant in countries like Italy, whose ground is highly exposed to seismic hazard [2]. Recent major earthquakes (Emilia Romagna 2012 – magnitude 6.1 and 5.8) demonstrated the relevance of structural safety of buildings also in regions traditionally considered less exposed to seismic events.

For what concerns the energy subject in EU, building sector results the most impacting one on total energy consumption (40%) and CO_2 emission (36%), with its old and inefficient stock [3]. According to the EU building database, the 35% of buildings are over 50 years old and the 75% of buildings are inefficient. Suffice it to say that about 50% of residential buildings in the EU countries were built before 1970, when the first thermal regulations have been introduced [1].

Renovation, which now involves only about 0.4-1.2% of buildings each year [1], could effectively increase the overall quality of the building stock, enhancing the energy and structural performance and limiting soil consumption and CO_2 emission.

Textile reinforced concrete (TRC) [4,5] represents a great opportunity for a sustainable development of structures and buildings, as it can be employed in order to enhance their service life. The composite is characterized by improved tensile performances, showing a considerable peak strength combined with a strain hardening behaviour. The tensile behaviour is strongly influenced by the matrix composition, the geometrical and chemo-mechanical characteristic of the embedded fabrics and the possible presence of short fibres [6-9].

Exploiting TRC excellent tensile behaviour, it can be applied in form of a single thin layer bonded to underperforming existing structural elements, with the aim of enhancing the load-bearing and deformation capabilities [10-12], or as a part of a precast multilayer structure, applied as secondary element on the building envelope, with energy and – eventually - structural purposes [13-16]. Among economy, ease of application, fire safety, durability and compatibility with the hosting substrates, one of the main advantages of TRC is the limited increase in the global mass and hence, as a consequence, the containment of the inertial forces activated during seismic motions.

In the case of sandwich panels, a limited increase in mass is accompanied by an integration between structural and energy function.

The paper is aimed at highlighting the great sustainable potential of TRC sandwich panels designed as façade and roofing solutions, with particular reference to the experience developed in the field at Politecnico di Milano.

Sustainable potentialities of TRC sandwich solutions

In order to extend the service life of residential and industrial buildings, it is necessary to implement measures aimed at enhancing the hygro-thermal, acoustic, structural, aesthetic and durability properties of existing envelopes, acting on both roofing and façades. With this aim, a wide research focused on the design of precast lightweight TRC sandwich panels has been developed at Politecnico di Milano. The research activity was supported by regional and European funding in the framework of the following three projects: the regional project “Sinergie Attive” concerning roofing; the European project “EASEE” and the regional project “Smart P.I.QU.E.R.” concerning façades.

Proposed façade and roofing multilayer panels are characterized by thin external faces made of advanced cementitious composites and an inner insulation core able to transfer shear stresses between layers only through bond, without any connector or gluing.

The main idea of these solutions is to exploit the advantages related to the traditional sandwich technology (integration between thermal insulation and structural element, quality control and fast mounting due to prefabrication) [17] together with the following aspects [18]:

- lightness obtained thanks to the reduction of concrete layer thickness, which positively impacts on production, storage, transportation, mounting and dismantling costs and safety;
- solving of corrosion problems;
- reduction of thermal bridges usually caused by the presence of shear connectors;
- high quality of the finishing;
- durability;
- possibility of embedding sensors for the regulation of the internal environment.

The core plays a key role as it accomplishes different functions: structural (transferring shear stresses), thermal, guaranteeing a low global density and a suitable lever arm to obtain a proper bending inertia of the solution related to the sandwich behaviour [19].

To have a complete overview of the potential of lightweight TRC sandwich solutions it is also important to consider the environmental impact of high-performance cement-based structures. As preliminary investigated in [20], the use of innovative cementitious materials leads to a reduction of the overall structural volumes and structural costs, with an extension of the construction lifetime thanks to the low water/cement ratios ant the crack bridging offered by short fibres and textiles. Even though material indexes such as the Global Warming Potential (GWP) and the not renewable Primary Energy Demand (PED n-r) show a significant environmental impact due to the presence of greater amounts of cement (if compared to traditional concrete), global analyses targeting the entire structure clearly prove that, by accounting the reduced structural volume and the improved durability, a significant reduction of the environmental indicators can be achieved.

Multifunctional lightweight sandwich structures for roofing. In the framework of the regional project "Sinergie Attive", Politecnico di Milano was involved in a consortium devoted to the development of a sustainable cement-based secondary roof element characterised by lightness, structural safety, thermal efficiency and compatibility with photovoltaic devices. This element is thought to substitute existing cement-based roofing system in industrial buildings, frequently characterised by a poor insulation level, presence of asbestos components and significant self-weight (2-3 kN/m^2). As already underlined, a global reduction of inertia-induced forces is desirable, especially in countries like Italy, where the increase in structural safety of existing industrial buildings is necessary. The product can find a large spread on the market: Italy counts 650,000 industrial buildings (more than 120,000 located on Lombardy Region), being the second largest country for number of industries in Europe [21].

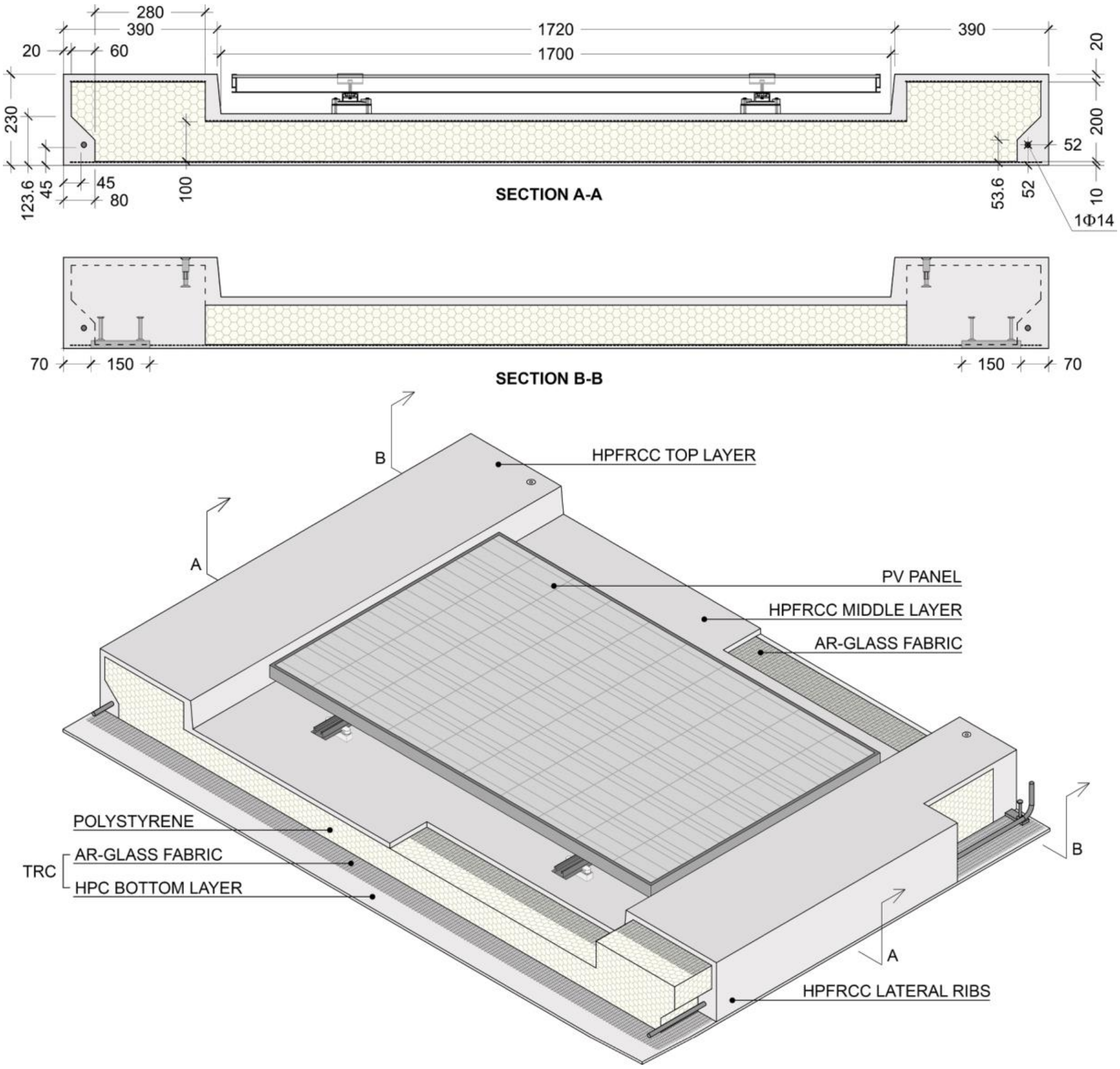

Fig. 1 - Multilayer precast roofing panel (measures in mm) [14].

The proposed multilayer panel (Fig.1) has size of 2.5 x 5 m^2 and is characterized by external thin high-performance cementitious composites and inner polystyrene core, commercially known as EPS100. The upper and lower cementitious layers are respectively made of 20 mm thick high-performance fibre reinforced cementitious composites (HPFRCC), reinforced with high-carbon steel microfibers, and 10 mm thick textile reinforced concrete (TRC), reinforced with one alkali-resistant (AR) glass fabric.

Specific advantages of this solution are:

- a reduced self-weight (1.2 kN/m^2) if compared to existing cement-based secondary roofing components;
- possibility of seismic retrofitting by maintaining the existing bearing structure, thanks to the lower weight of the new roofing. In fact, it does not imply additional horizontal forces with respect to those adopted in the design phase, because a significant reduction of inertia-induced forces is achieved, thus improving the structural safety of existing structural elements (beams, walls, columns and foundations);
- consequent elongation of the building service life connected to a change of use of the building, since the existing bearing structure can be indirectly retrofitted (without additional energy or material consumption);
- integration of photovoltaic systems (PVs);
- water-tightness without any waterproofing membrane.

Additional characteristics are an average thermal transmittance of 0.42 W/(m^{2}K) and a fire classification R30 (minimum requirement for Industrial buildings in Italy). All the details concerning materials, prototypes preparation, mechanical characterization in bending and plane-section analysis can be found in [14].

Multifunctional lightweight sandwich structures for façades. In the 7th Framework Programme for Research and Technological Development, the European Commission financed the project EASEE - Envelope Approach to improve Sustainability and Energy Efficiency in existing multi-storey multi-owner residential buildings (2012-2016). Politecnico di Milano was involved in the design of a TRC sandwich façade panel for the energy retrofitting of the outer building envelope. This element is thought to be applied on existing façade by fixing it at the existing building concrete frame, with a negligible increase of dead load (0.7 kN/m^2), in such a way that the structure could be kept unvaried.

The proposed multilayer panel (Fig.2) has maximum size of 1.5 x 3 m^2 and is characterized by external thin TRC layers, obtained reinforcing a high strength fine grain mortar with one AR-glass fabric, and inner expanded polystyrene core, commercially known as EPS250. The thickness of each TRC layer varies in the range of 12÷14 mm, according to the tolerances due to production process. The thickness of the insulation core can be chosen in order to guarantee the required thermal transmittance fixed by Standards (a minimum of 100 mm ensures a proper lever arm to guarantee the mechanical performances of the composite).

Few shear connectors are introduced and become active only if the insulation material loses its mechanical function due to extreme conditions, e.g. fire.

Specific advantages of this solution are:

- optimization of costs related to both production and application of the solution on the existing façade thanks to the large size of the panels;
- mounting without using scaffolding, but only by means of a crane, thus minimizing both the timing of installation and the inconvenience for inhabitants;
- high durability of the panel guaranteed by the external TRC layer, which is waterproof, protects the insulation core against environmental agents and is characterised by a high durability in the case of freezing and thawing cycles and sun radiation exposure;
- desired panel finishing (use of pigments and formliners allows obtaining the desired colour and texture; the mortar is able to reproduce any texture);
- high strength to local concentrated load, if compared to traditional external thermal insulation composite systems;
- elongation of the building service life, thanks to the adjustment to the current energy Standard.

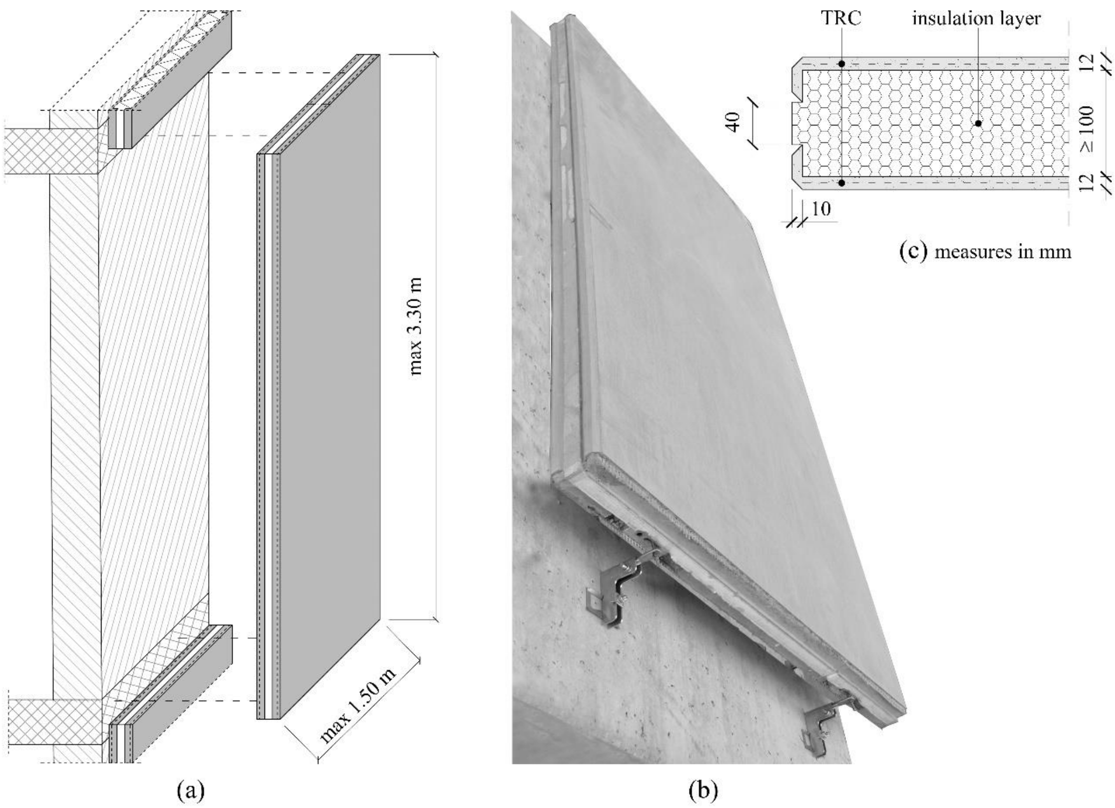

Fig. 2 - Multilayer precast façade panel: sketch (a), picture (b) and stratigraphy (c) (measures in mm) [22].

Concerning energy retrofitting of existing façades, the panel could be a valid alternative to the external thermal insulation composite systems (ETICS) and ventilated façades. Comparing to ETICS, even if the target cost will be about 50% higher, it is balanced by the many advantages already mentioned, especially those related to durability and installation.

A further project in which Politecnico di Milano is now involved (“Smart P.I.QU.E.R.”) is aimed at solving some critical issues emerged in the European project, related in particular to the panel sustainability and behaviour in case of fire.

Expanded polystyrene is crucial for both aspect as it is not an eco-friendly material and loses its mechanical properties in case of fire, causing – at the same time – smoke.

For this reason, a new insulation material, based on diatomite (natural source), characterized by a high level of sustainability, multiscale porosity, low thermal conductivity, lightness and good mechanical behaviour, even in case of fire, has been developed [22]. In order to obtain proper thermal and mechanical characteristics of the core material, a density 10 times higher than that of EPS is needed. Hence, lightweight TRC layers were developed by adding lightweight sustainable aggregates in the mortar (fillite and plastic waste particles) to keep the weight of the solution unvaried. The choice of a proper coating for the fabric is also crucial considering fire condition (e.g. epoxy coating).

Prediction of the mechanical behaviour of the sandwich solution – strengths and limitations. For what concerns the presented roofing solution, plane-section [14] and preliminary finite element analyses were proven capable to simulate both the sectional and the structural bending responses. Despite the complexity of the layered solution and the uncertainties associated to the behaviour of the soft core and the interfaces amongst different materials, the box-like characteristic of the panel ensures the applicability of simplified kinematic models with adequate accuracy. Further research concerning the non-linear modelling of the shear and the fire responses is still in progress.

For what concerns façade solution, analytical and numerical approaches have been applied in order to predict the mechanical behaviour of lab-scale sandwich beams [23] and full-scale sandwich panels [16] when static loads are applied. The main features of the models, that account for material non-linearity, are that TRC is modelled as a homogeneous material over its thickness and that perfect-bond is assumed at TRC/EPS interfaces. Both approaches allow a proper prediction of the mechanical behaviour and the identification of the failure mechanisms: in particular, it is possible to appreciate that shear deformability of the insulation core governs the behaviour in case of deep beams, while the membrane and bending behaviour of TRC faces becomes the more relevant parameter for the mechanical response with the increasing in slenderness.

Conclusions

On the basis of the previous considerations, it is possible to draw the following conclusions:

1. Environmental sustainability can be improved by integrating thermal insulation and energy production within the same structural component. In this field, advanced cement-based materials can play an important role, since the lightness associated to the reduced structural thickness positively impacts production, storage, transportation and dismantling costs.
2. TRC can be effectively employed in multilayered panels, thanks to the excellent tensile behaviour provided by the embedded AR-glass textiles. The bending behaviors exhibited by the full-scale prototypes are characterized by a remarkable structural response, in terms of strength, ductility and robustness.
3. New construction technologies based on high-performance cementitious materials open interesting frontiers and vast possibilities to the designers. The greater cost and the greater environmental impact at the material scale should not restrain their employment, since a reliable evaluation of the overall construction sustainability can be addressed only at the structural scale.

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