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INTEGRATED APPROACHES FOR LARGE SCALE ENERGY RETROFITTING OF EXISTING RESIDENTIAL BUILDING THROUGH INNOVATIVE EXTERNAL INSULATION PREFABRICATED PANELS

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Abstract

This paper shows the result of a research project aiming at the development of a systemic approach for the energy-efficient and cost-effective façade retrofitting of buildings deploying the potential of external insulation prefabricated panels.

In particular, an innovative composite panel (an EPS panel coated on both sides with two layers of Textile Reinforced Concrete - TRC) has been developed taking into account different parameters (mechanical properties, hygrothermal properties and environmental impact) and the potential of application on existing residential buildings in Europe. As a matter of fact, issues as lightness, fast and easy assembly techniques were also a major concern of the Research & Development process: the application without fixed scaffolds has been considered so as to reduce impact on inhabitants' life.

Besides, considering some limitations on interventions of existing European building stock, the concept of the innovative panel has been developed so as to allow for the preservation of the building envelope exterior features or at improving the architectural features with a reduced extra-load on the existing structure.

Cost-effectiveness of the solution has been demonstrated considering optimization through the whole design and construction process, also exploiting the application of advanced design tools and Building Information Modelling (BIM).

The installation process and the real performances of the panels are investigated on a test-façade at Politecnico di Milano Campus: the first outputs of the test campaign are shown in this report, as well.

Keywords:

Integrated approach; outer solution; energy retrofitting; precast multilayer panel

1 INTRODUCTION

In recent years, the interest of the scientific community toward energy performances of buildings is more and more increasing due to the urgent need of effective solutions to the reduction of energy demand. Latest European Union programs related to energy efficiency underline the need for retrofitting existing buildings, which are responsible for 40% of EU final energy consumption. In this context, interventions on buildings dated between 1925 and 1975, constructed in an era where there was little or no consciousness about energy related issues, therefore with high energy demand, offer the higher benefit/cost ratio. This building category counts about 10 million buildings in EU-27, the majority of them located in Central and Southern Europe [1]. A large part of this building stock requires façade retrofitting in general and this can be an opportunity to add an extra to improve the insulation and overall energy efficiency.

This paper shows some outputs of the EU funded EASEE research project which aims at the development of a systemic approach for the energy-efficient and cost-effective façade retrofitting of buildings deploying the potential of external insulation prefabricated panels. In particular, section 2 provides an overview of the research project and the design process of the outer façade retrofitting. Section 3 shows the results of the analyses carried out on the panel solution with reference to mechanical properties,

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hygrothermal behaviour and environmental impact, including also the production of lab scale samples for preliminary testing. Section 4 presents the EASEE building retrofitting process and its application on a test-façade at Politecnico di Milano. Finally, conclusions are summarized in Section 5.

2 THE EASEE PROJECT AND THE INTEGRATED APPROACH

The goal of the EASEE (Envelope Approach to improve Sustainability and Energy efficiency in Existing multi-storey, multi-owner residential buildings) research project is to deliver new modular and fault tolerant solutions for the envelope retrofitting of multi-storey and multi-owner buildings, ensuring an important reduction of building energy demand through off-site prefabricated components and simplified construction processes and installation procedures, while at the same time reproducing the original façade and reducing at minimum the discomforts for the occupants [2].

The focus on the vertical opaque envelope takes into account the comparatively limited surface of the roof in these buildings and the fact that single-glass windows have been very often already replaced by owners with insulating glass. Another assumption of the project is that the slow rate of renewal of existing buildings is also a consequence of the process these retrofit operations are conducted, with non-skilled workforce and labour-intensive procedures that make costs escalate. The discomfort caused to inhabitants by long construction times, installation of scaffolding and the related dust and noise are other reasons that limit the diffusion of retrofit operations in practice. The EASEE project promotes a new holistic approach (Fig. 1) to the energy-efficient envelope retrofitting of multi-storey and multi owner buildings through a combination of integrated tools for building assessment and monitoring, innovative technological solutions for envelope insulation and building information modelling intended to pursue cost effectiveness throughout the design and construction process. The ultimate goal is to develop an EASEE Toolkit integrating affordable solutions and guidelines.

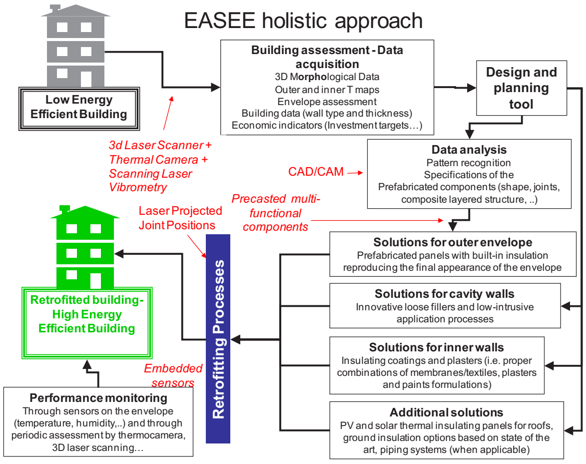

Fig. 1: EASEE approach to envelope retrofitting.

2.1 Outer envelope solution

The paper shows the developed key technological concepts addressing solutions for the refurbishment of the outer envelope and exploiting the potential of standardisation and prefabrication. Considering also previous experiences in other European countries – several of these are presented and analysed in the framework of EBC Annex 50 Prefabricated Systems for Low Energy Renovation of Residential Buildings [3] – the main goal of EASEE is to combine insulation and external finishing in one large prefabricated panel, deploying the production potential of the European precast concrete structures industry that primarily suffered from the recent economic crisis of the building sector.

The main concept was to combine insulation and finishing in integrated façade panels. The conceptual design of the prefabricated insulation panels was based on the main typological, morphological and technological features of the typical residential buildings dated between 1945-1975. These are mainly characterized by a reinforced concrete framed load-bearing structure and cavity brick walls. During the first stage of the project, different options for the panels were investigated, tested and evaluated considering performances in the service life in order to choose the best one to be brought forward for the demonstration activities. The selected solution is a prefabricated concrete sandwich panel obtained by coupling a layer of Expanded Polystyrene (EPS) with two layers of Textile Reinforced Concrete (TRC) 10 mm thick. TRC is a cementitious composite in which the matrix is reinforced with one or more layers of glass, carbon or aramid fabrics.

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3 EVALUATION ANALYSES AND DATA OPTIMIZATION FOR PREFABRICATED SHAPEABLE PANELS

3.1 General remarks on analyses

The investigation focused on the panel characterization by high residual strength after cracking as well as light weight. The insulation material considered had not only a hygrothermal role, but it was also chosen taking into account its mechanical characteristics. Moreover, high strength and ductility allow the designers to adopt large panels.

3.2 Assessment of mechanical properties

The assessment of mechanical properties was conducted within two tests which permitted to establish also dimensional stability:

- Four point bending test;
- Bending test after freezing and thawing cycles.

The four point bending tests were carried out by using an electromechanical press INSTRON 5867 with a maximum load capacity of 30 kN. Four 50x150x5 mm aluminium plates were glued on each specimen at the supports and under the load knives to prevent localized failures. The tests were displacement-controlled by imposing a constant stroke rate of 3E-3 mm/s. The test highlighted that the panel is suitable to reach the desired dimensions (height of a storey about 3 m and variable width up to 3m) and the panel remains in the elastic regime when exposed to SLS wind [4].

The durability of the solution was checked on 550x150 mm panels thermally treated and then tested according to the four point bending scheme previously discussed. The thermal treatment consisted in 150 freezing and thawing cycles in a climatic chamber according to the Procedure A of the ASTM C 666 Recommendation. The specimens were exposed to several thermal cycles ranging between +4°C and -18°C with both cooling and heating rate of 11°C/h and a 30 minute rest phase both at +4°C and at -18°C. The external side of each specimen was completely surrounded by a water layer when subjected to the thermal cycles. The test demonstrated that the mechanical behaviour is not largely affected by the thermal treatment.

Summarizing the analyses conducted on the multilayer panel, it is clear that, after the test some cracks were visible, but the maximum crack opening was less than the one allowed at the Serviceability Limit State by the codes and it is such to maintain the global response of the cross section in the initial linear phase. Since the maximum thermal gradient at which the panels were exposed is not so large. It is worth noting that, thanks to the thermal inertia of the multilayer panel, the external surface temperature was significantly higher.

3.3 Assessment of 1-D transient hygrothermal response

The hygrothermal risk assessment for the precast panels was performed with numerical simulations of dynamic heat and moisture transport by means of the software model WUFI 5.1 [5]. As a reference wall, a 34 cm thick brick wall has been considered (Fig. 2). The precast sandwich panel taken into account consists of an expanded polystyrene (specifically EPS 250) between two skins of TRC.

The water vapour diffusion resistance factor and the water absorption coefficient of the TRC concrete have been assumed based on laboratory tests. The thermal conductivity has been assumed considering the low porosity of the material (Tab. 1).

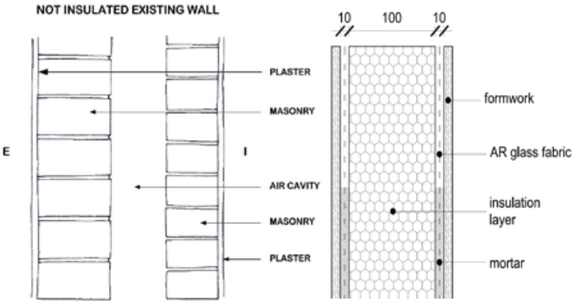

Fig. 2: Scheme of the existing masonry wall considered for the simulations (left) and of the retrofit panel (right).

Finally, as for the radiative properties of the exterior surface the thermal emittance was assumed equal to 0.90, while parametric simulations were performed with regard to the solar absorbance Asol, thus assumed equal to 0, 0.25, 0.50, 0.75, and 1.00. Solar absorbances equal to 0 and 1 have no physical meaning, and they have been included to help identifying the limits of the contributions of solar radiation. However, the simulations with solar absorbance equal to zero approximate a condition relative to a shaded wall (e.g. wall having low solar absorbance, within an urban canyon, or with trees in front of it). The total porosity for the TRC has been assumed equal to 0.01, after mercury intrusion porosimetry tests.

Layer	**t** **(m)**	**$\lambda_{10°C,dry}$** **($W\ m^{-1}\ K^{-1}$)**	**ρ** **($kg\ m^{-3}$)**	**p** **(-)**	**$A_{w,24}$** **($kg\ m^{-2}\ s^{-0.5}$)**	**μ** **(-)**
Plaster	0.02	0.80	1900	0.24	0.03	19
Clay brick	0.08	0.12	600	0.77	0.095	16
Air cavity	0.05	0.071	1.3	0.999	-	1
Clay brick	0.12	0.12	600	0.77	0.095	16
Plaster	0.02	0.80	1900	0.24	0.03	19
Air cavity	0.01	0.071	1.3	0.999	-	1

TRC	0.01	2.00	2311	0.01	0.0001	15000
EPS 250	0.10	0.04	30	0.95	-	50
TRC	0.01	2.00	2311	0.01	0.0001	15000

Tab. 1: Layers and material properties. All the properties of the existing wall and of the EPS have been assumed from the WUFI database. The properties of the TRC have been measured in the lab or estimated. ρ is bulk density, p is total porosity, and μ is the diffusion resistance factor.

Hourly weather data from Meteonorm for Milano were used to describe the outdoor boundary conditions. The interior climate was defined according to Annex C of EN 15026 [6], thus with 20°C when the exterior temperature is lower than 10°C, 25°C when higher than 20°C, and linearly interpolated values in between. Two conditions of normal and high indoor moisture load, as defined by the standard. The start day for all the simulations was set as Oct 1st. Driving rain was computed according to ASHRAE Standard 160P [7] with rain exposure factor equal to 1, rain deposition factor equal to 0.5, and adhering fraction of rain equal to 0.70.

First, 25 years of hygrothermal exposure for the existing non-insulated masonry wall with intermediate solar reflectance finishing (i.e. 0.50) and with built-in moisture as in the WUFI's database for the selected materials were simulated. Second, the moisture contents averaged over the 25th year of simulation in the existing wall for the whole assembly including the precast panel were assumed. Then, 10 years of exposure of the whole assembly (i.e. existing wall + air cavity + precast panel) were simulated.

To assess the risk of increase in water content the 10 cm multilayer panel was divided into 10 layers of 1 cm and, from the results of the simulations, the highest moisture content across the EPS panel is concentrated in the first centimetre from the exterior. The focus is on water content, as it is a proxy of possible issues concerning the durability of a building component and of loss in thermal resistance. The relative importance of the different water sources is evident in Fig. 3 for a north facing wall with solar absorbance equal to 0.50 and with high indoor moisture load in different conditions:

- with a wet substrate (WETsub, moisture content in the substrate wall as at the end of a 25 year simulation) or dry substrate (DRYsub, moisture content in the substrate wall as 10 years after the retrofit)
- considering (Yrain) or excluding rain (Nrain)
- considering the capillary conduction of water (Ycap) or only water vapour diffusion (Ncap)

Condensation was estimated to weigh less than 4 kg m^{-3} (and about 50% of the total) for the first 0.01 m of EPS. Considering all orientations, internal conditions, and radiative properties of the exterior surface, within the first 0.01 m from the exterior of the EPS panel, the highest water content is of roughly 12 kg m^{-3} for a north facing wall with zero solar absorbance (i.e. with high reflectance and no or very limited solar access) and high indoor moisture load. In more common cases, the moisture content in the most external 0.01 m of EPS is always lower than 10 kg m^{-3}, displaying a decreasing trend (Fig. 4).

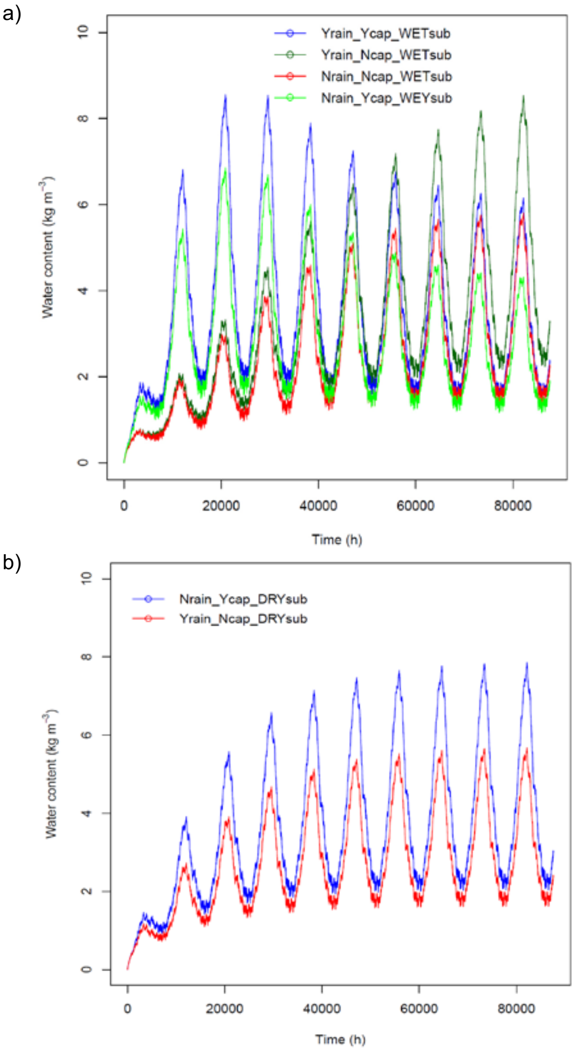

Fig. 3: Moisture content over 10 years in the 0.01 m of EPS, for north exposure, with high moisture load with (a) wet or (b) dry substrate.

Condensation does occur only in the most external section of the multilayer panel. The amount of condensed and absorbed water is not worrisome for the thermal performance, but it may affect the adhesion of the external skin of the panel (the TRC). After 10 years the moisture content within the whole assembly (pre-cast panel + wall substrate) gets to stable harmonic trends.

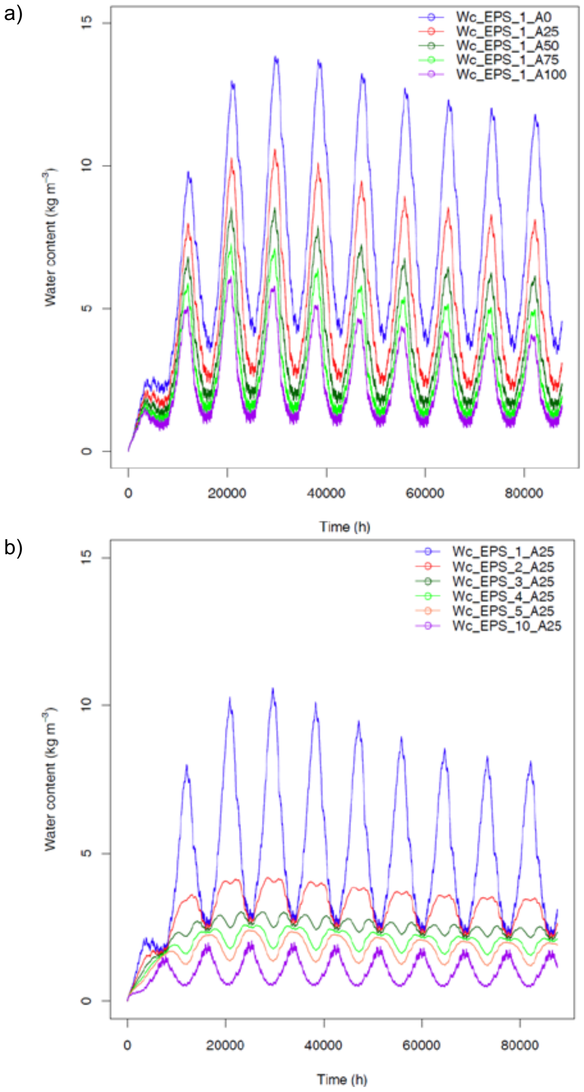

Fig. 4: Moisture content over 10 years in the 0.01 m (from the exterior) of EPS for north exposure with high moisture load (a) as a function of solar absorbance, and (b) for all EPS sections with solar absorbance of 0.25.

3.4 Preliminary Life Cycle Assessment (LCA)

LCA models the life cycle of a product as its product system, which performs one or more defined functions. In this case the multilayer panel provides the function of retrofitting a façade with a precast structure with a high thermal performance. The analysis has been developed following ISO 14040-14044 standards that codifies LCA method [8] and ISO 14064-14067 and PAS 2050 to evaluate carbon footprint. An LCA evaluation has been conducted on the panel within the retrofit operations and these evaluations have to be read as an indication of the potential environmental impacts that the assembly/production of the panels generates. Production wastes and hand labour are neglected. The functional unit chosen is 1 m^2 of panel. Singularities have not been evaluated because the analysis has been focused on the current section. The transportation is accounted for separately and with the functional unit of 1 ton per kilometre. Primary data for materials, water and electrical energy consumptions were gathered directly from the assembly processes. SimaPro 7.3.3. software with the EcoInvent database is used. Material and energetic consumptions for the production of panels are quantified thanks to primary data. Electrical energy is referred to the Italian energy system, considering national performances and the various sources of origin.

For the impact analysis the indicators adopted were:

- Greenhouse gas protocol (GGP) – Carbon Footprint: global warming potential over 100 years for the evaluation of emissions and savings of CO_2eq in atmosphere [kg CO_2eq]
- CED: cumulative energy demand to calculate the renewable and non renewable energy consumptions of the process considering also feedstock energy [MJeq]

Greenhouse gas protocol provides CO_2eq emissions divided into four contributions:

- Fossil: indicates the quantity of fossil fuels in the energy mix
- Biogenic: indicates the quantity of natural/biomass fuels in the energy mix
- From land transformation: indicates direct CO2eq emissions connected to some previous transformation applied to the material.
- Uptake: indicates the total CO_2eq stored in the material during its life.

Table 2 summarizes the results obtained from the LCA analyses.

On the basis of this evaluation on a multilayer panel appears that the greatest amount of the impact of global warming potential is generated by concrete; from the energy side EPS still remain the material responsible of the major part of the impact.

Material energy	**CO_2 fossil** [kg CO_2eq]	**CO_2 biogenic** [kg CO_2eq]	**CO_2 from land transfor-mation** [kg CO_2eq]	**CO_2 uptake** [kg CO_2eq]	**EE non ren.** [MJeq]	**EE ren.** [MJeq]
EPS	10,43	0,098	7,73^{E}-05	0,032	262,36	2,52
Concrete	19,58	0,321	9,64^{E}-05	0,068	180,62	6,96
Net	0,16	0,002	3,84^{E}-06	0,002	3,32	0,07
Electrical energy for mixer	0,12	0,001	3,78^{E}-07	-0,001	1,99	0,17
Electrical energy for compressor	2,26	0,024	6,62^{E}-06	-0,001	34,82	3,11

Tab. 2: Multilayer panel impact assessment.

The best results in terms of environmental impacts could be obtained using EPS instead of XPS and using as little concrete as possible. The longer the transportation route is the greater is the impact. The kind of lorry chosen for transportation affects the results: bigger lorry can deliver much more panels with little impact.

3.5 Building physical assessments of critical façade points

The criteria and method for the building physical assessment used and applied in the retrofitting process can be summarized as follows:

- Thermal performance of the envelope: reduction of the heat losses through the envelope by adding external insulation and minimizing thermal bridges
- Moisture performance of the envelope: ensuring drying capacity and avoiding condensation by choosing the proper materials and thickness layers
- Durability of the constructions: reduced risk of mould and decay by making the right choice of materials and ensuring the good moisture performance of the envelope

All the concepts were modelled with a hygrothermal simulation tool – MOLD SIMULATOR v.2, a software for the dynamic calculation of thermal bridges (ISO 13786 – validated ISO 10211) and mould and condensation risk assessment according to ISO 13788 [9]. With the help of the output result for temperature, relative humidity and moisture, a set of performance key values were determined for the critical parts of the constructions.

In particular, the detailed panel design has taken into special account joints between panels, which represent the very critical points of the façade. Dedicated analyses on the joint solutions between panels have been studied and tested on small prototypes to ensure that joints will not represent thermal bridges, maintaining at the same time the desired aesthetics of the façade.

One of the most critical point of the detailed panel definition was the design of the panel connection being influenced by many factors, playing an important role in the joint details. The design and execution of these joints is one of the utmost importance and must be accomplished in a cost-effective and efficient manner.

The isotherm diagrams in Figure 5 and 6 are relative to the details of the test façade presented in the Section 4. The colour diagrams show that critical heat flux occurs on the connection panels, however, since the isotherms are parallel towards the end, it indicates that heat transfer is essentially 1D, which is a good performance indicator and also that the chosen joint solution avoids thermal bridges between panels.

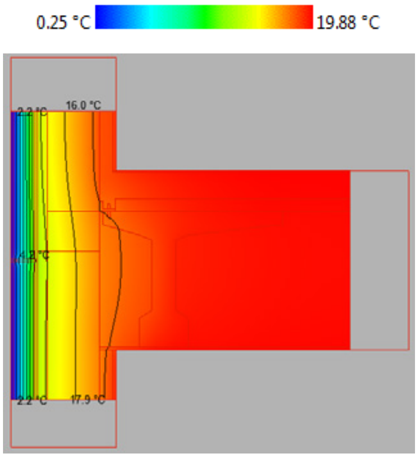

Fig. 5: Detail vertical section of the envelope regarding joint panels' connections.

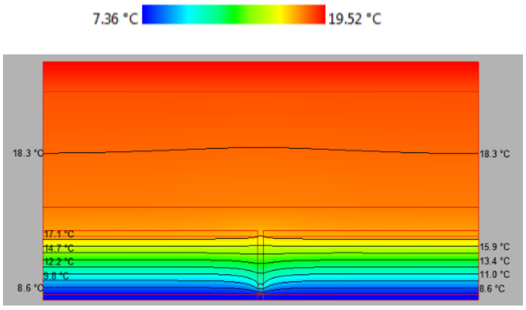

Fig. 6: Detail horizontal section between panels.

4 THE EASEE RETROFITTING PROCESS

The first step of the EASEE retrofitting process consists of the careful assessment of the existing envelope from both the structural and energetic point of view.

The geometry of the existing building is obtained through 3D laser scanning technique that allows acquiring a very detailed model and geometrical relief of the building. These are respectively elaborated through a Design Tool and a Retrofitting Planner that have been specifically developed during the EASEE project. Together with novel insulation systems, EASEE project delivered an integrated set of tools and services supporting the different stages and the different actors of the retrofitting process from the preliminary assessment of building geometry, to the panels' design and optimization for their manufacturing and installation.

The Building Information Modelling (BIM) process of gathering the right data at the right time during the EASEE retrofitting process was very challenging to create a robust connection between design, manufacturing and construction. The Design Tool (Figure 7), main output of the EASEE BIM approach, is an application devoted to construction purposes, allowing to place virtual panels on the buildings surface in a 3-D space referring to a grid which permits to control and modify all the panels parameters in order to optimize their number and size. The final data can be then exported into the design documentation for both manufacturing and installation purposes.

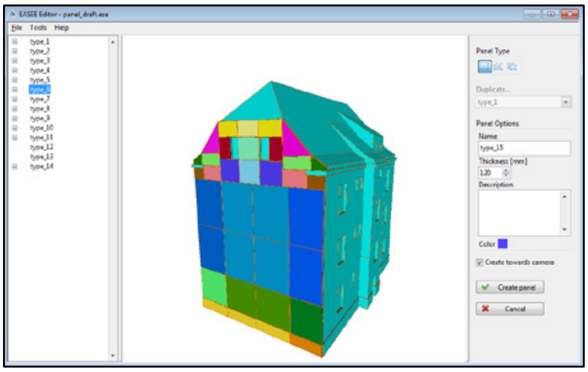

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Fig. 7: Screenshot of the Design Tool.

4.1 Test façade at Politecnico di Milano

The building chosen for the installation of the concrete sandwich panel prototypes is a university building built in the early '70s at Politecnico di Milano Campus in the city of Milan (Figure 8).

Fig. 8: Aerial view of the building.

The building hosts classrooms, research laboratories and departmental offices. The portion of the building that has been selected as test façade is the West front façade (first two floors). This façade is characterized by a rough concrete finishing since it was designed considering future expansion of the building towards the garden. From a structural point of view, the building has a concrete structural frame with prefabricated pillars and beams. The wall of the west façade between the pillars is made of cast-in-place concrete.

4.2 Guidelines steps for the panels' installation

The first step regarded the survey of the existing building through the laser scanning technique (Figure 9).

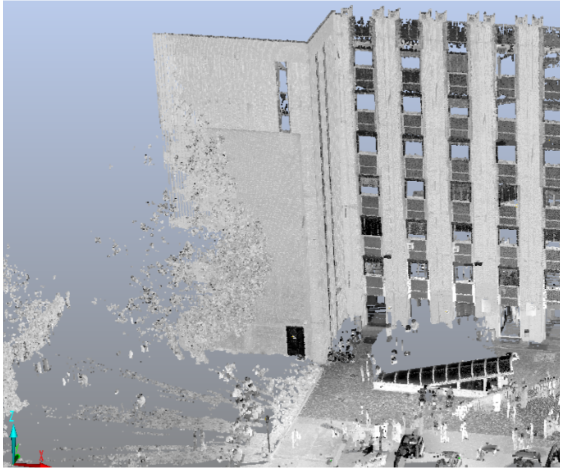

Fig. 9: Point cloud image from laser scanning relief.

Through the correct georeferencing of the executive 2D design, a building 3D model has been developed in order to identify and locate discontinuities, projections and out of plumb of the façade and the correct positioning of the anchors (Figure 10).

Fig. 10: individuation of the bubble and entire anchoring system set-up on the test façade.

After these first set of operations, the panel installation started per rows on the façade (Figure 11).

Fig. 11: Installation and levelling of the panels on the test façade.

For the specific testing purpose only two rows of panels were installed (Figure 12). The joints between the panels were made using a low elastic modulus neutral-curing silicone sealant with outstanding ageing resistance. The silicon has been placed on polyurethane backfill material in order to reduce the danger of cracking.

The elasticity remains constant at temperatures ranging from -50°C to +100°C. The high resistance to UV rays and atmospheric agents foresees that after 20 years of service under normal conditions, the joints show no trace of superficial cracks.

Fig. 12: Installation and levelling of the panels on the test façade.

5 CONCLUSIONS

The EASEE research project developed an integrated approach for the energy retrofit of existing multi-storey and multi-owner residential buildings, which represent a large part of the existing European building stock. The technical development of the innovative insulation solutions for the existing walls was carried out in the first two years of the project and in the final two years these solutions were tested at real scale in demonstration activities, together with the whole integrated retrofitting process and the related software tools.

This paper summarizes the process from the design and preliminary analyses (mechanical, hygrothermal and environmental impact) to the final installation on a test façade of an innovative concrete sandwich panel (an EPS panel coated on both sides with two layers of Textile Reinforced Concrete - TRC) before its application on three occupied existing residential buildings selected in three different European countries as pilot cases.

The whole analysis on the prefabricated panel highlighted the high potential of the EASEE envelope retrofitting solutions.

The panels were developed to preserve the existing building envelope exterior features – or to improve the architectural features whenever possible – with a reduced extra-load on the existing structure and a reduced impact on the occupants because of the fast installation procedure without scaffoldings. This solution offers high insulation value, air tightness, excellent comfort and visual quality and contributes to the reach of the energy standards for existing building under major renovations as underlined by the EPBD directive.

6 ACKNOWLEDGMENTS

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