ZeroSkin+

product booklet

Universidade do Minho

NORTE-01-0145-FEDER-000058
co-funded by the European Regional Development Fund
(FEDER) through Norte Regional Operational Programme

isise Institute for Sustainability and Innovation in Structural Engineering

iPC INSTITUTE FOR POLYMERS AND COMPOSITES

UMINHO CMEMS CENTER FOR MICROELECTROMECHANICAL SYSTEMS

CENTRO ALGORITMI

NORTE 2020 PROGRAMA OPERACIONAL REGIONAL DO NORTE

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Development of a 3D printed modular panel for holistic renovation of residential buildings, based on recycled plastic and natural mater

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Summary

The project ZeroSkin+ - Development of a 3D printed modular panel for the holistic renovation of residential buildings, based on recycled plastic and natural materials - addresses the development of an adaptive modular panel for the holistic renovation of residential buildings. The project uses recycled plastic, recyclable plastic, or a combination of both, as matrix and natural materials, such as nano clay or graphite derivatives, as reinforcement to produce 3D printed renovation panels. Furthermore, the project aimed to contribute to product and process innovation from a circular economy perspective by addressing two significant challenges.

The first challenge is related to the urgency of renovating the existing building stock to help achieve carbon neutrality by 2050. Besides that, building renovation should be done holistically to improve not only energy performance but also address seismic vulnerability. The energy efficiency improvement was addressed by investigating the potential to bring the building's energy performance levels to those of a nearly zero-energy building (nZEB), a net-zero-energy building (NZEB), or a positive energy building (PEB). Carbon neutrality was addressed by analysing the integration of renewable energy sources (RES), specifically photovoltaic cells, on the renovation panels. Together with RES integration, the integration of temperature and humidity sensors on the external envelope linked with the building's HVAC control system was also studied to provide data related to the building's thermal performance. Addressing these issues holistically can improve the existing building stock and the lives of those who inhabit it.

The second major challenge is the need to reduce plastic waste. Since 1950, only 9% of the plastics used have been adequately recycled, and almost half have ended up in landfills or dumped in the wild, contaminating the freshwater system and the oceans. Moreover, since construction is the largest resource-consuming industry, it has a high potential to use wastes in the construction materials, promoting a circular economy.

Thus, the ZeroSkin+ project aimed to address this issue by developing a building renovation panel made of recycled or recyclable plastic. With the development of the renovation panels, the project sought to find a purpose that could incite the research about additive construction techniques used to reduce waste materials and provide a cost-effective renovation option for the existing building stock.

The project team developed a building renovation prefabricated panel using recycled plastic and natural materials with an additive manufacturing (AM), patentable construction solution. This panel was tested for its energy efficiency and seismic performance, the opportunity to integrate renewable energy sources, sensor integration for data provision, parametrisation via building information modelling (BIM) software, and waste reduction using recycled materials in manufacturing. The final goal was to achieve a product that could be used to improve the existing building stock cost-effectively.

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The existing building stock is responsible for a noticeable part of greenhouse gas (GHG) emissions (36%) and of the final energy consumption in the European Union (40%), mainly due to the poor thermal performance of construction envelopes (Figure 1). The last European Roadmap for Carbon Neutrality 2050 is clear about the urgency to reduce carbon emissions: Europe must go net-zero carbon until 2050 to limit global warming to 1.5 ºC. Therefore, the decarbonisation of buildings is an environmental priority.

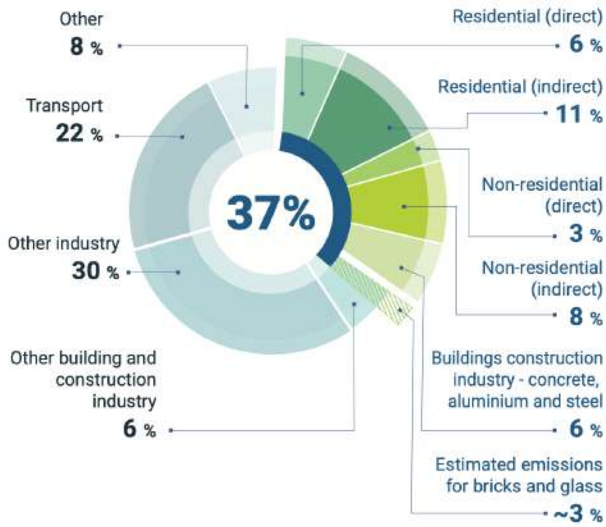

Figure 1 - Building stock CO_2 emissions 2021 share. Adapted from GlobalABC releases 2022 Global Status Report for Buildings and Construction

Additionally, most of the residential buildings are old. In Portugal, approximately 15% date back from before 1945, and about 70% were built before 1990, before the implementation of the 1st energy performance regulation. According to the energy performance certificate rating, about 87% of the residential buildings have a C rate or less (from A+ to F, where F corresponds to the lowest performance), resulting in poor energy performance. In this context, a deep energy building renovation is needed. However, the EU energy renovation rate of the building stock is below 1% per year. According to the European Commission's "Renovation Wave Strategy", to achieve carbon neutrality by 2050, the energy renovation rate should be at least double the current one. Thus, a significant shift from the current approach to energy renovation will be needed to achieve this ambitious goal.

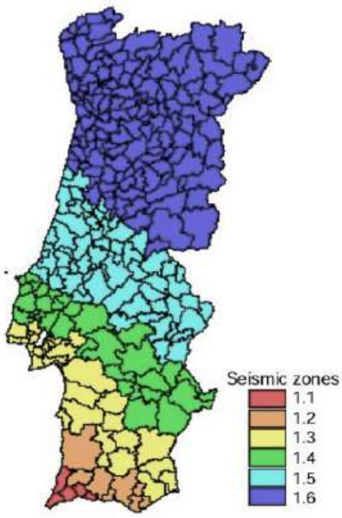

Figure 2 - Seismic map of mainland Portugal. Seismic action type one (zone 1.1 to 1.6) characterises earthquakes with their epicentres mainly offshore, whereas type two (zone 2.1 to 2.6) refers to events with

In addition, recent earthquakes in several European countries have shown the low structural safety of existing buildings, which urgently need renovation. This is particularly evident in Southern Europe due to the medium to high seismic risk and, therefore, also in Portugal. Seismic risk in Portugal is recognised by the Decree-Law n.º 95/2019, which requires the potential reinforcement of buildings in renovation interventions. Figure 2 shows the seismic Zones in Portugal. From such deficiencies in existing constructions, it is possible to seize the opportunity of an integrated approach to energy and seismic retrofit, reducing occupancy disruption, cost, and work duration at the same time.

The construction and building renovation industry stands at the forefront of transformation in a world increasingly recognising the urgent need for sustainability, eco-conscious solutions, and seismic retrofit. The renovation of building facades has long been seen as an opportunity to enhance energy efficiency and environmental and seismic performance. However, the quest for an ideal solution has been marked by challenges related to cost-effectiveness, time efficiency, and sustainability.

Transitioning to a market of industrialised and holistic renovation interventions could help foster building energy transition. In this context, one of the strategies being promoted to support this transition is prefabricated modular systems for energy renovation. Prefabricated retrofit modules have the potential to enhance performances (energy efficiency and indoor climate) and quality, increase safety (workers and building occupants), reduce construction waste, costs, and construction time, and diminish impacts and disturbance for occupants.

On the other hand, the production of plastic has been growing steadily over the last years, and Europe is the second-largest producer of this material. Figure 3 shows the destination for plastic waste produced in 2021. In Portugal, the low recycling rates – only a third of the post-consumed plastic waste is recycled – aggravates the environmental problems and represents a valuable waste of resources. Therefore, it is urgent to reduce the amount of plastic waste produced by integrating them into value chains that allow reuse and recycling.

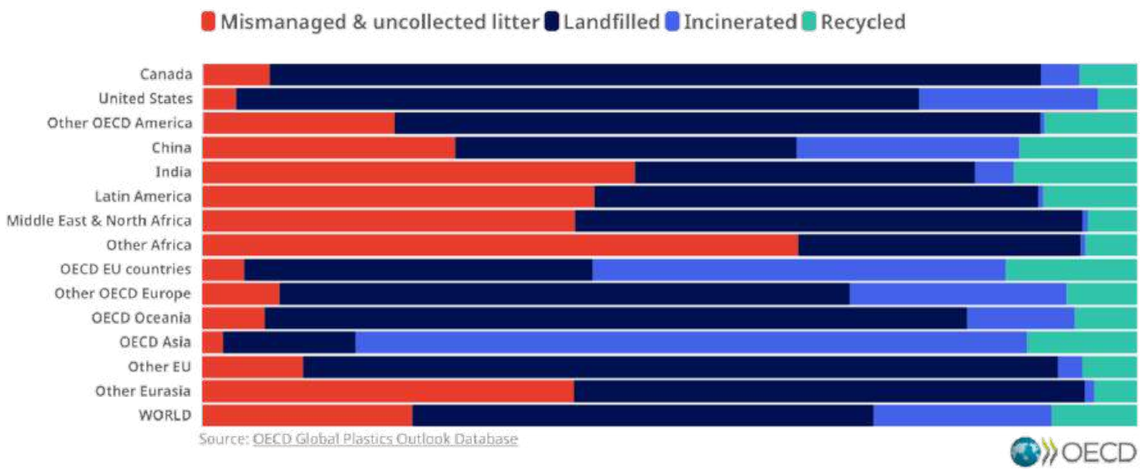

Figure 3 - Plastic recycling rates from OECD 2021 report.

In this context, the ZeroSkin+ project aimed to reduce building energy consumption and mitigate CO_2 emissions using 3D printed recycled plastic panels. Hence, the ZeroSkin+ project output is a renovation solution to be added to the building's original façade to improve its thermal and seismic performance while also addressing the possibilities of implementing renewable energy sources and sensors locally. The additive manufacturing of the panel, aligned with the reuse of plastic waste, promotes the development of a circular economy by consuming plastic waste and decreasing the embodied emissions related to transportation, manufacturing and waste management. In addition, the additive manufacturing process also allows the adaptability of the panel design for each renovation scenario, ensuring cost-effective and sustainable use of the material.

The prefabricated modular system complies with physical, cost, and thermal criteria such as mechanical strength, UV resistance, fire resistance, water resistance, vandalism, the possibility to integrate renewable energy sources, different thermal gradients resistance, seismic performance, and cost-effective levels during the building life cycle.

This document offers a comprehensive summary of ZeroSkin+ panel module characteristics and performance.

Panel Module Key Performance Indicators

The key performance indicators (KPIs) of the ZeroSkin+ solution served as a reference point for product development and development measurement.

The ZeroSkin+ integrated renovation solution **KPIs** are shown in Table 1.

Table 1 – ZeroSkin+ integrated renovation solution KPIs

KPI	Indicator
Thermal transmittance (U-value) with the original building façade	0.43 W/m².°C to 0.30 W/m².°C
Thermal Resistance (R-value) on panel (thinnest to thickest version)	1.14 K.m²/°C to 2.13 K.m²/°C
Resistance to high dry bulb temperature	47.3 °C
Resistance to low dry bulb temperatures	-16 °C
Be nZEB capable when simulated with common renovation solutions for the Portuguese market	Yes
Integrate renewable energy sources	Yes
Cost optimality compared to common opaque envelope renovation solutions in Portugal	Yes
Recycled plastic as a primary material	Yes
Optimised to prefabrication process	Yes
Optimised to the additive manufacturing process	Yes
Comply with the Watertight connections in heavy rain conditions and Seismic Regulation Decree-Law n.º 95/2019	Yes
Achieve toughness and resistance to vandalism according to ISO 179-1:2010	Yes
Resistance to theft and unauthorised removal	Yes
Watertight connections in heavy rain conditions and pressurised water exposure conditions	Yes
Resistance to UV radiation according to the expected life cycle and annual average UV radiation in Portugal	2368.8 kWh/m².y
Fire resistance classification according to the Portuguese regulation for opaque envelope elements and European standard EN 13501	Fire resistance classification between B-s2 d0 and C-s2 d0
Achieve self-support structural capacity	Yes

Support structure

To improve the seismic behaviour of the building's façade, the ZeroSkin+ project developed a new solution to avoid the out-of-plane collapse of infill walls. The solution consists of vertical steel profiles connected to the reinforced concrete beams of the existing frames that guarantee that the infill walls do not collapse out of their plane due to seismic action. The ZeroSkin+ solution does not need additional foundations as it is anchored directly to the RC members and presents a limited need for extra space around the building since it adheres to the construction. The use of steel as a base material for the reinforcement structure is mainly due to the versatility of this material and the reversibility of the intervention carried out in this way.

Additional horizontal profiles are used to reduce the risk of buckling in the vertical elements if necessary. The 3D printed panels are directly connected to the vertical pieces, realising the link between the existing substrate and the modular façade. A possible configuration of the system is shown in Figure 4.

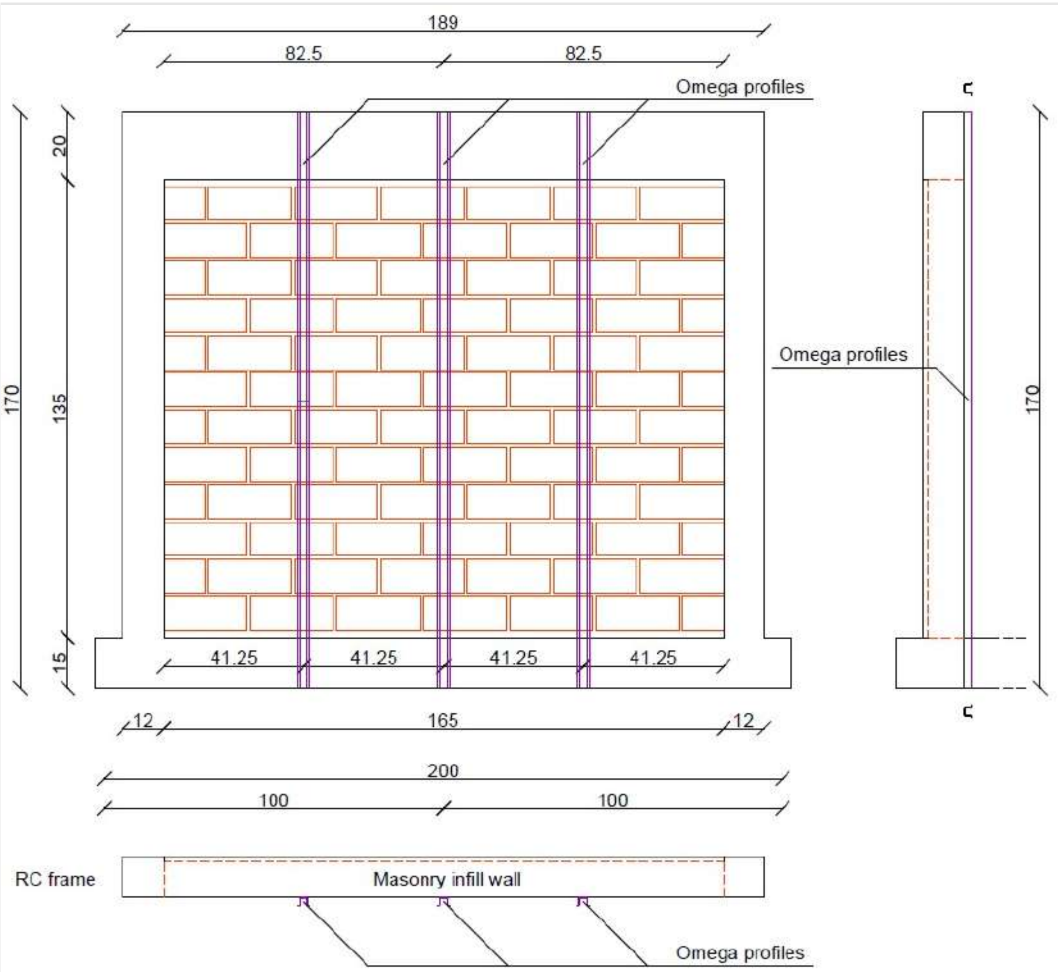

Figure 4 - Generic configuration of the ZeroSkin+ system steel grid.

Cold-formed commercial profiles for the steel sections of the vertical elements, specifically Omega shapes (see Figure 5), are used. The main constraints regard the height of the profiles since the total thickness of the holistic solution depends on it. For this reason, a maximum size of 50 mm has been imposed for the steel section height.

Another advantage of the proposed solution is the system's adaptability according to the value of the seismic loading. So, having fixed the height of the section, the steel grid can support growing seismic actions by reducing the horizontal spacing between the vertical elements. In this way, it is possible to optimise the size of the section and, therefore, reduce its height based on the specific requirements.

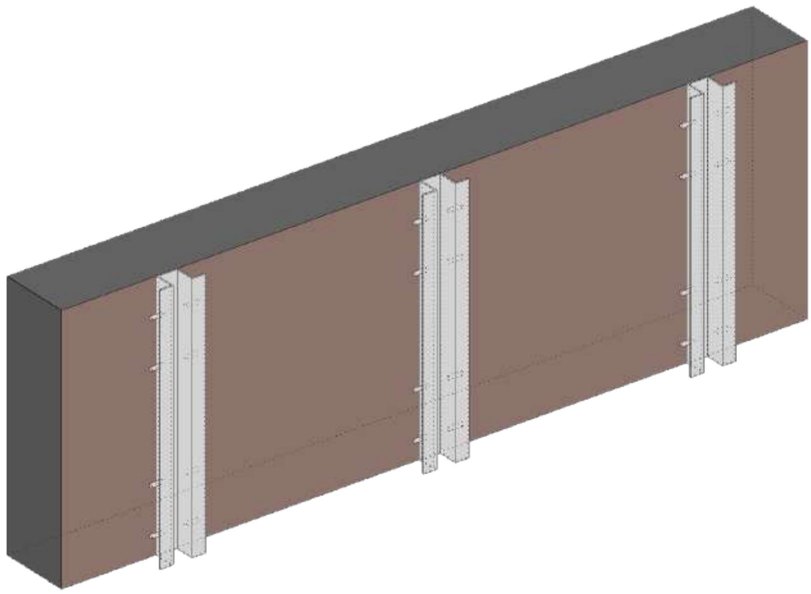

Figure 5 - Profile section considered for the vertical elements of the steel grid.

Additional details regarding the design and development of the ZeroSkin+ building seismic renovation solution are available in Deliverable 5.1 - Report on the structural and seismic performance.

ZeroSkin+ panel modules were designed to address other issues in the ZeroSkin+ project's holistic approach beyond thermal and seismic renovation. These panel modules were designed to be added to the existing building's opaque envelope, and they could be able to integrate renewable energy sources and sensors to provide building information to the user while improving the building's thermal performance. In addition, the panels should provide a recycled plastic output to incorporate waste material in a circular and sustainable utilisation. The novel manufacturing process of 3D printing was used to achieve such goals, allowing the renovation solution to be modular and adaptable for each building renovation.

The renovation panel was thought in three versions to accommodate different building renovation requirements. The versions are 61mm, 86mm, and 111mm, which are named according to their total thickness. This variation allows the ZeroSkin+ panel to better take advantage of the 3D printing as a manufacturing method, allowing production customisation according to each case. A section of each panel version is shown in Figure 6.

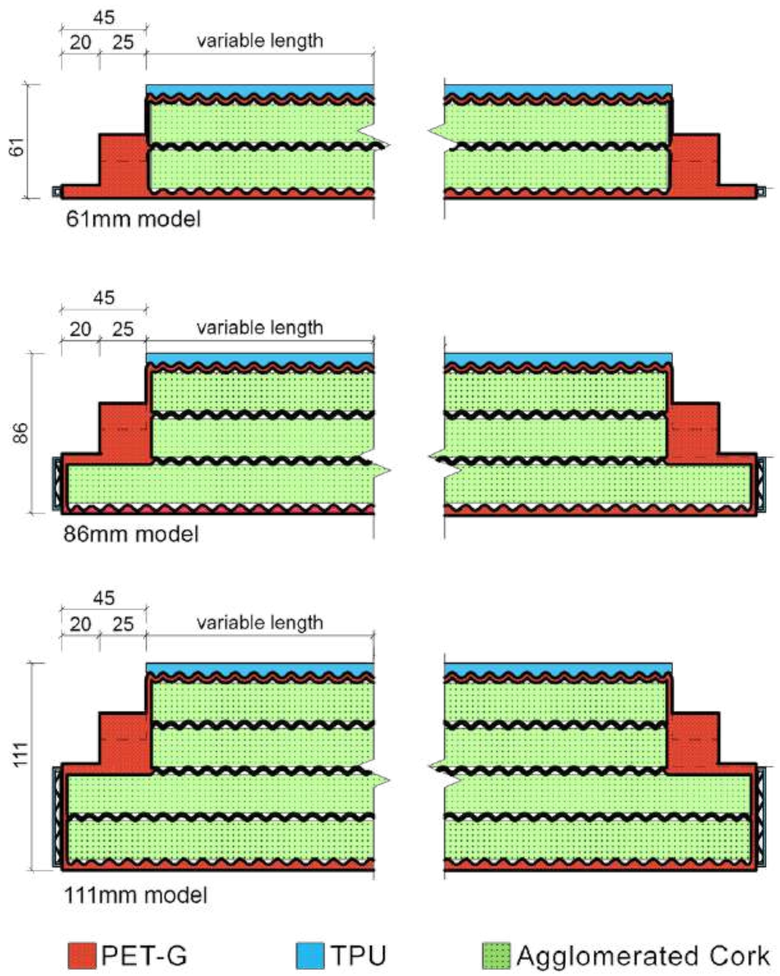

Figure 6 - ZeroSkin+ panel versions sections displaying material composition and total thickness.

The outcomes obtained from the experimentation revealed that the most favourable results were related to using a combination of insulation material, corkboards, and recycled plastics. The plastic 3D printing achieved an *R-value* of 1.25 K.m^2/W with a 100mm thick panel and an approximate weight of 54 kg/m^2. The combined version of the panel performance ranged from 1.14 K.m^2/W 1.63 K.m^2/W 2.13 K.m^2/W, depending on the panel model thickness. Figure 7 shows the panel module prototype integrated with a PV panel for the generation of renewable energy sources.

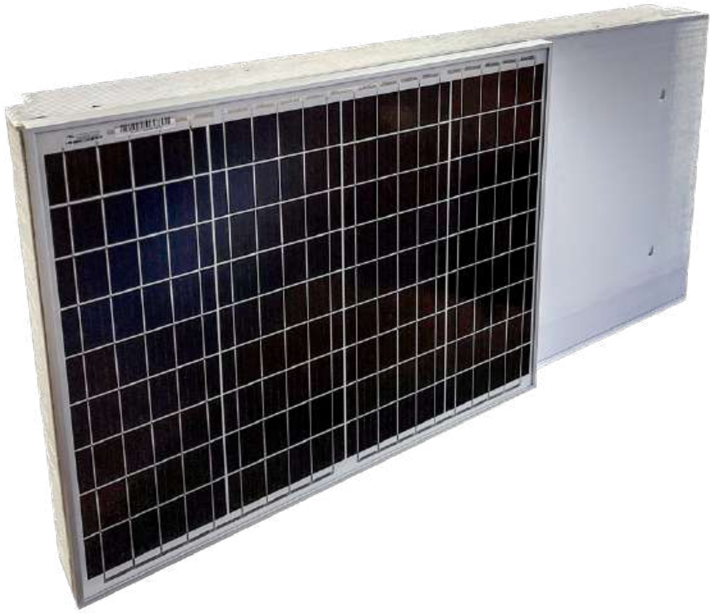

Figure 7 - ZeroSkin+ panel prototype with the integration of a PV panel.

Materials

The primary material used in the ZeroSkin+ panels (Figure 8) was recycled rigid polyethylene terephthalate glycol (rPETG). The thermoplastic rPETG is a recycled composite of PET, the same as widely used in packaging and clothing, which is more resistant to UV radiation compared to regular PET. The selected plastic is biocompatible and non-toxic, which also benefits its use in the construction sector. Furthermore, PETG is a versatile composite that can be integrated with fire-retardants to improve its fire performance and conform to construction regulations.

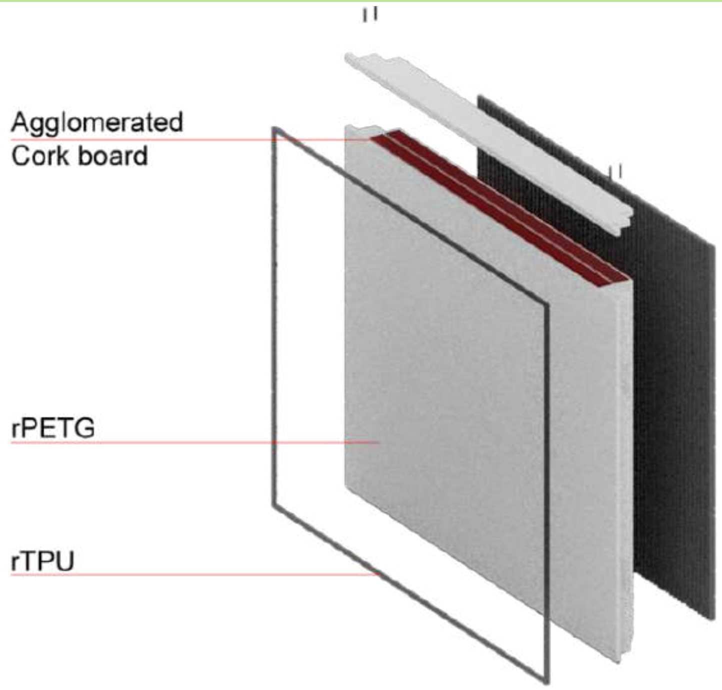

Figure 8 - Panel module material uses and combination.

As a thermal insulating material, agglomerated corkboard was used, a natural source material with low CO_2 emissions. The cork was designed to be surrounded by the plastic that would protect it from the environment while also supporting it (Figure 9). Cork is a natural material with good thermal performance, low environmental impact, is locally available, and is recyclable.

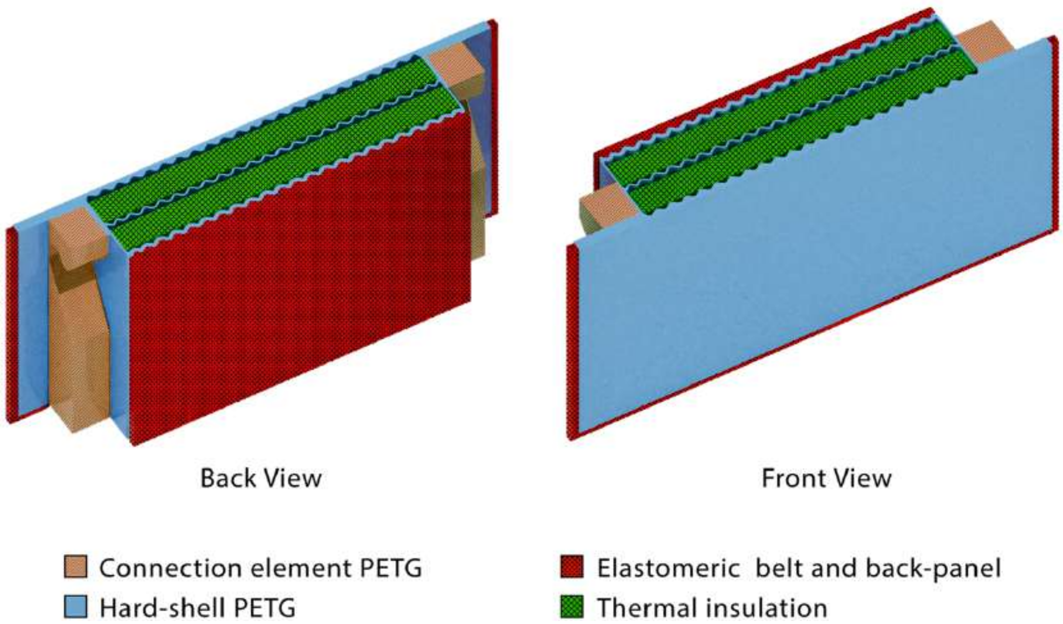

Figure 9 - ZeroSkin+ panel (61mm version) section showing the materials with the placement of the agglomerated cork as a thermal insulation material.

The ZeroSkin+ panel prototype weight is less than 30 kg/m^2 due to the combination of materials used. This combination takes advantage of the recyclability of the materials consumed, aiming for a recyclable and circular building renovation solution.

Meanwhile, the recycled thermoplastic polyurethane (rTPU) was used as an additional plastic to be 3D printed due to its elastomeric properties. The ability of the rTPU to shock absorptance and plasticity allowed the use of a 3D printed rubber-like thermoplastic for the panel. The material is recycled and recyclable and is designed to be printed separately to maximise its recyclability at the end of its life cycle. The primary objective of this thermoplastic was to create a seal through pressure between panel modules. This seal avoids water infiltration while accommodating the module's expansions and retractions throughout the panel's life cycle. The material consumed and manufacturing time per panel version are shown in Table 2.

Table 2 - ZeroSkin+ prototype characteristics.

Model	rPETG weight	Printing Time	TPU weight	Printing time
61 mm	12.24 kg/m^2	118 h/m^2	1.39 kg/m^2	50 h/m^2
86 mm	15.36 kg/m^2	184 h/m^2	1.64 kg/m^2	56 h/m^2
111 mm	18.21 kg/m^2	202 h/m^2	1.87 kg/m^2	63 h/m^2

The assembly and disassembly processes were carefully considered when selecting materials. The panel material composition and assembly process (Figure 10) was designed to facilitate the reuse and recycling of the consumed material after the ZeroSkin+ life cycle. The panel development without adhesives and welding allows the materials to be separated without contamination after their life cycle.

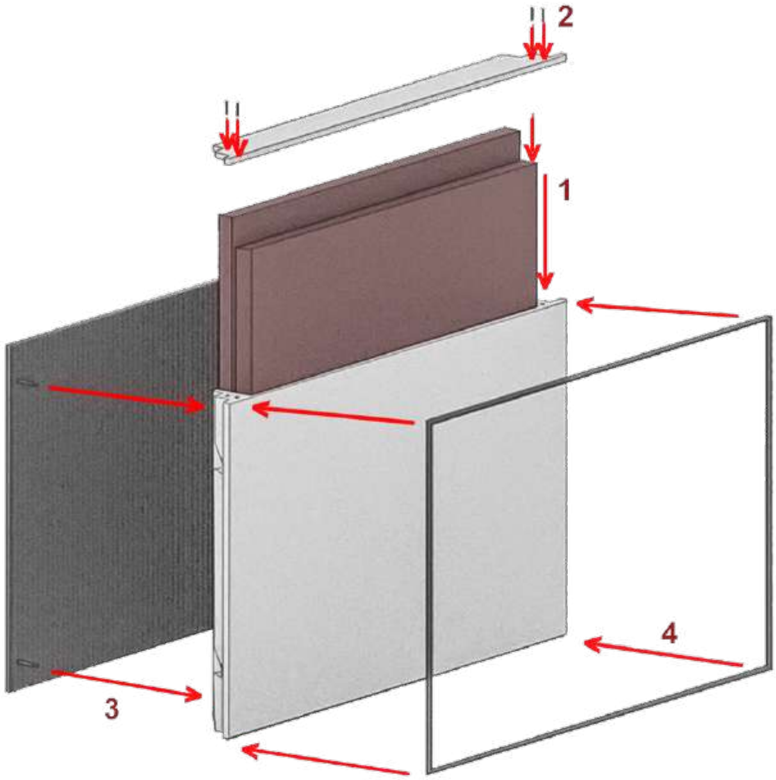

Figure 10 - ZeroSkin+ module assembly process with assembly order numbered from 1 to 4.

Panel characteristics

The ZeroSkin+ panel was designed to overcome the challenges of developing the renovation solution. Since an essential feature of the renovation panel is its modularity and adaptability, it was designed as a basic version, which was later converted into specific variants capable of accommodating the many building features. This basic panel module has four main features that are present in all module variations. These features were essential for the panel development.

Strong but light

One of the first issues encountered during the 3D printing of the renovation panel was how to do something light and strong enough not to bend during the 3D printing process. This issue was tackled by minimising the panel perimetral 3D printed layers to decrease material consumption while making the panel's internal perimeters a wavy line. This perimeter wall in a wavy pattern (Figure 11 and Figure 12) ensures enough support to avoid the panel's deformation during 3D printing while only using single or double perimeter layers. The wall structure is designed to be wavy only in the perimeters that are not visible when the panel modules are installed, thus avoiding aesthetic impact. This wavy wall perimeter is a single perimeter for the internal border and a double perimeter on the external edges.

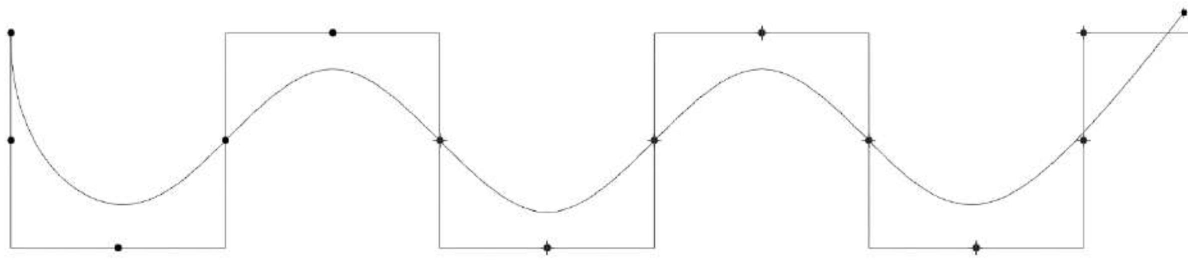

Figure 11 - Wavy patterns polyline alignment.

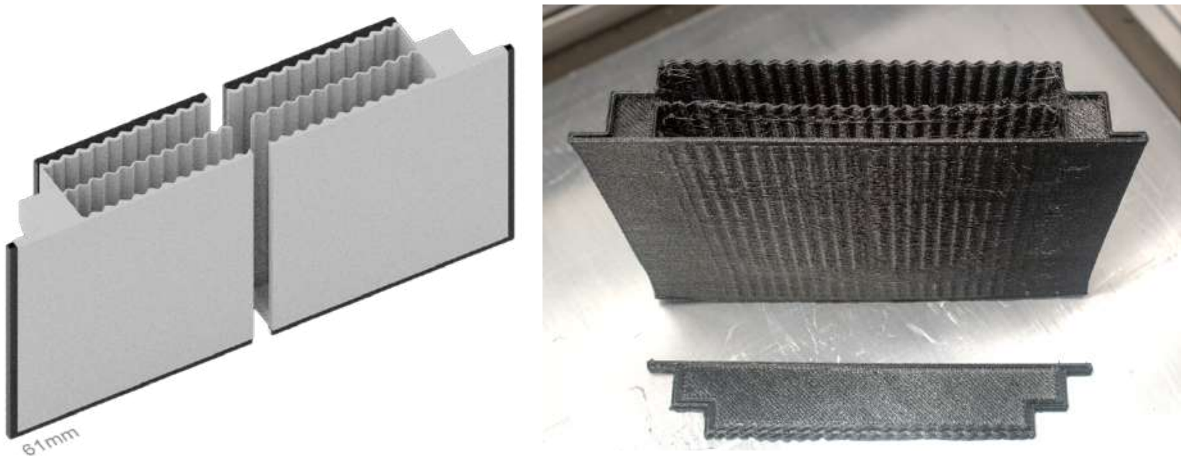

Figure 12 - Wavy walls are shown in a section of the centre 61 mm module.

Plug & Play

The circularity of the ZeroSkin+ is a differential of the panel compared to existent renovation solutions. Therefore, not only should the connections within the panel be easily assembled and disassembled, but the panel itself should be easily connected to the building façade. This issue was tackled by connecting the ZeroSkin+ renovation panel to its supporting structure, which also works as a seismic reinforcement structure, in a plug-and-play way, as shown in Figure 13. The panel attached to the support structure should be easily attached, and its connection should be secure to avoid module damage and unauthorised removal while facilitating its repair and replacement.

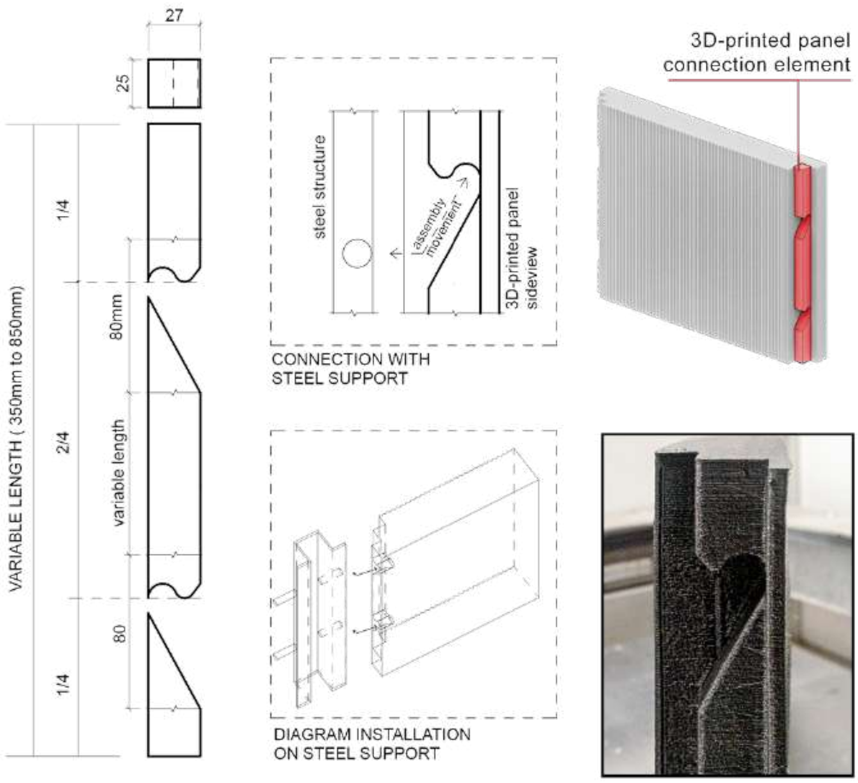

Figure 13 - ZeroSkin+ module connection design to the seismic renovation solution.

Therefore, the connection element was designed to fulfil these requirements. Four welded steel pins were added for each panel to the seismic reinforcement structure. These pins are 20mm in diameter and its addition to the steel profiles can be automated in prefabrication and are designed to hold the panels in place. The connection is done through a sliding movement matching the connection element openings to the support pins. Its 45º connection allows for an easy install of the panel while being secured by the upper panel. This way, the upper panels would have to be removed to remove a module, hence being easy to install and disassemble.

Watertight

It is vital for the building's health that any renovation panel prevent water infiltration. Therefore, the connection between panels should be watertight. To address this crucial requirement, a 5 mm thick bezel (Figure 14) sealant made from an elastomeric thermoplastic polyurethane (TPU), surrounds each panel module. When installed, this rubber-like plastic is compressed between panels and can deform to ensure the connection seals through pressure. This bezel is hollow with a triangular internal structure to provide extra layers of material and add redundancy to the sealing solution. This feature's main role is to seal the panel connection through pressure, avoiding water infiltration.

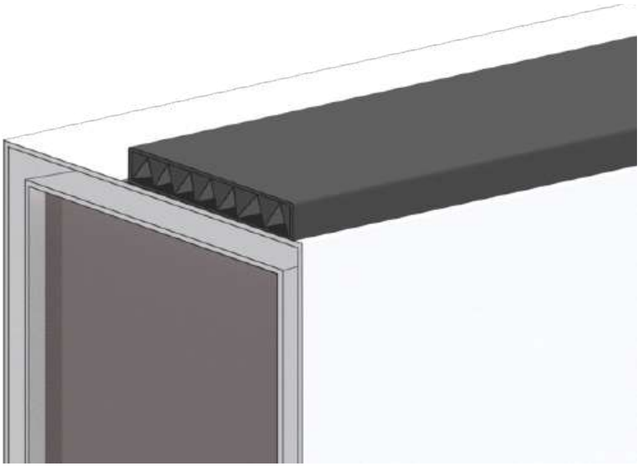

Figure 14 - Elastomeric polymer belt with its internal triangular geometry.

Accommodate imperfections

Unlike the digital fabrication in which the ZeroSkin+ panels are manufactured, the buildings to be renovated are bound to have imperfections in their façades. To avoid gaps between the panel and the building façade, it was used the same rubber-like plastic as the water-proof seal as a cushion to accommodate the imperfections of the building's original façade. This back part ranges from 7 mm to 5 mm thick due to the wavy patterns of the rigid polymer walls. This layer is 3D printed to be completely hollow, with four support structures modelled inside the layer. Its fixations to the hard shell were done through a plug connection (Figure 15) that was forced into the rigid body.

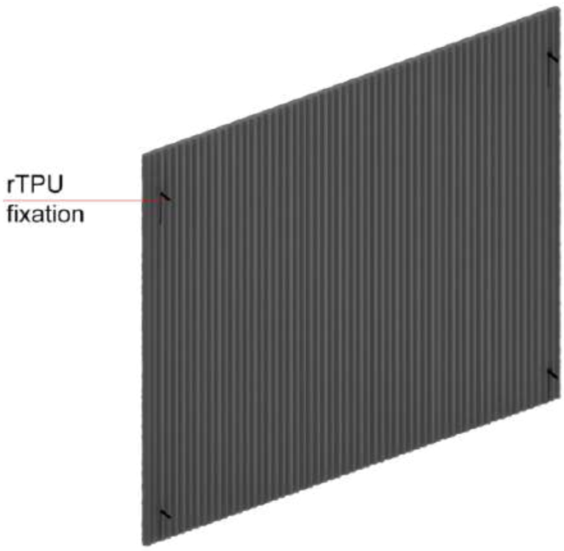

Figure 15 - Elastomeric 3D printed back panel.

There are two main plastics in the panel composition. Although plenty of 3D printers are capable of handling multiple material printing, the manufacturing process is designed to be done separately, avoiding material waste and contamination. The panel modules should be assembled after all the parts made with different polymers are complete. The rTPU parts are shown in red in Figure 16.

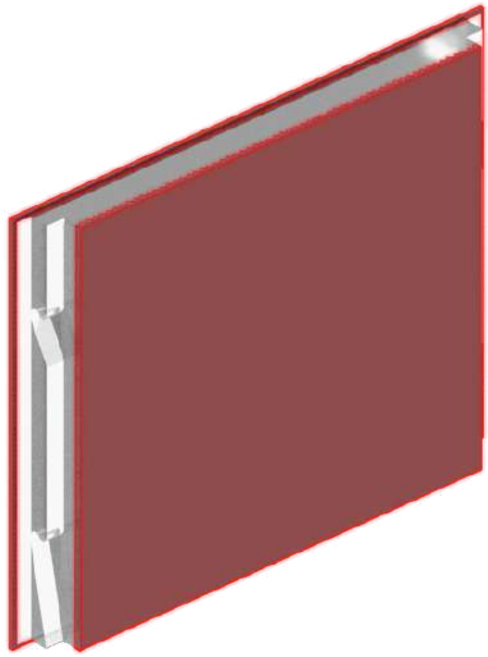

Figure 16 - rTPU parts in the ZeroSkin+ building renovation solution shown in red.

Right size for every occasion

The renovation module size should be adaptable according to the support spacing, building opening dimensions, and limitations regarding the module's workability. The printing equipment and workability also limit the module size. Disregarding the printing limitations, the workability limitations set the optimal 3D printer characteristics. The maximum size of the module is 1100 mm wide to 800 mm tall for linear modules and 500 mm wide, 500 mm thick, and 800 mm tall for the corner modules. These maximum dimensions were defined to avoid a piece being too large or heavy to handle without heavy machinery.

The minimum module dimensions are limited to the minimum required space for printing all four supporting structures into the renovation panel. Nevertheless, this minimum size value is considered only in extreme scenarios where the minimum size is required to ensure the maximum utilisation of the support structures. The minimum dimension of 230 mm in height and 110 mm in width is considered the minimum size for the connections and supports of the module. The minimum and maximum dimensions are shown in Figure 17.

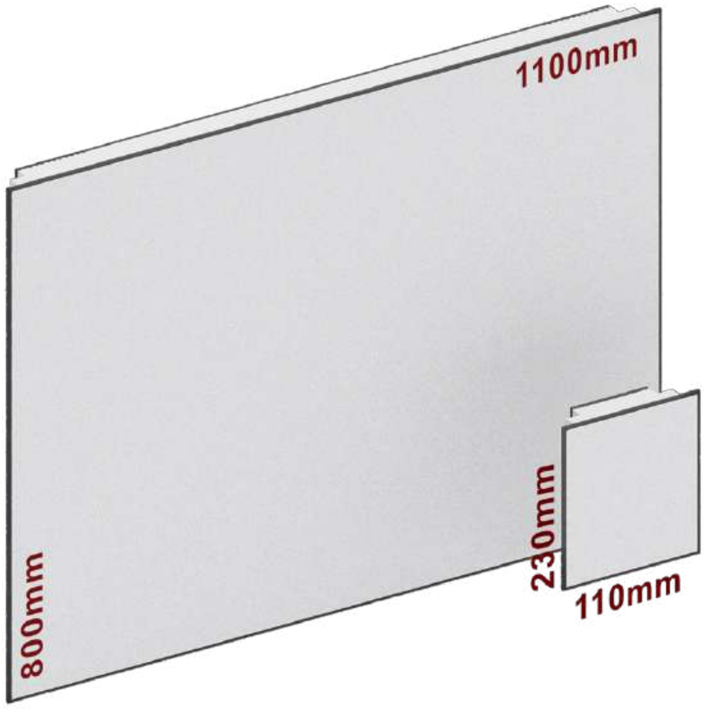

Figure 17 - ZeroSkin+ building renovation modules with maximum and minimum size displays.

Panel variations

The panel modules designed for the ZeroSkin+ building renovation solution were created in two main steps. First, the basic module, the most frequently used module on the current wall area, was developed. Then, some panel module variations were developed.

The first design is a simple module, which is the most common panel model, and it incorporates all the features required while addressing the project KPIs.

The ZeroSkin+ simple module was then adapted to the design variations expected in the building renovation scenarios.

Thickness

The module thickness is defined by how many cavities are inside the panel to place the insulation material. Using three different thicknesses and compositions allows the ZeroSkin+ building renovation solution to achieve different levels of thermal insulation while consuming different quantities of material. Thus, the ZeroSkin+ panel thickness options create a more versatile solution for buildings with distinctive requirements. There are three thicknesses: 61xmm, 86 mm, and 111 mm (Figure 18).

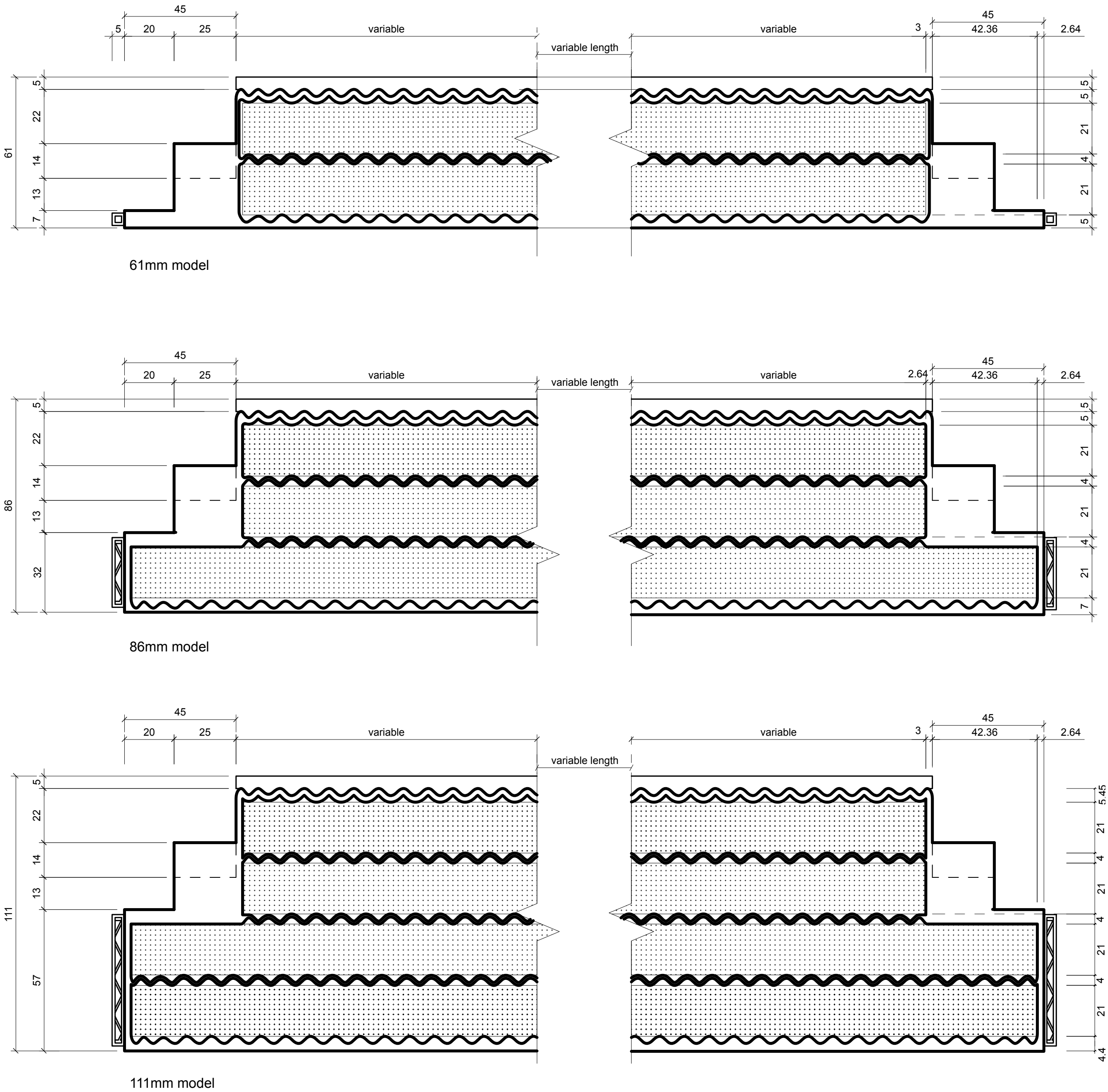

Figure 18 - ZeroSkin+ panel module sections showing the thickness variations and different compositions on the insulation space in between pieces.

Location

Location defines the position of an opening according to the panel. These identify where the connection element with the exterior is. Each model location informs where a reinforced zone connected to an opening part is placed in the panel module. The opening type specifies this reinforcement. However, there is an exception for the central model, which does not have a special connection to an opening. Therefore, the "opening type" characteristic does not apply to this model. Figure 19 shows the panel location naming.

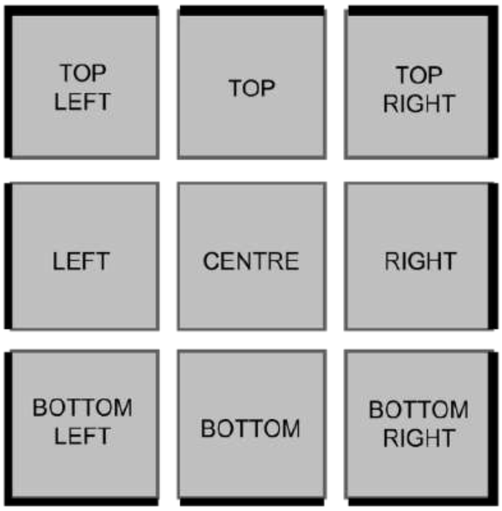

Figure 19 - Module location chart.

Opening type

Panel modules can have different opening types, which must adapt to their relation to the building and other panel modules. Therefore, the connection of a module to the façade was designed for scenarios where the opening connection should extend to the entire panel length or partially adapt to a building's opening when a module is placed in an intersection with another panel module. This feature has been divided into the following characteristics to differentiate designs: complete and partial (Figure 20).

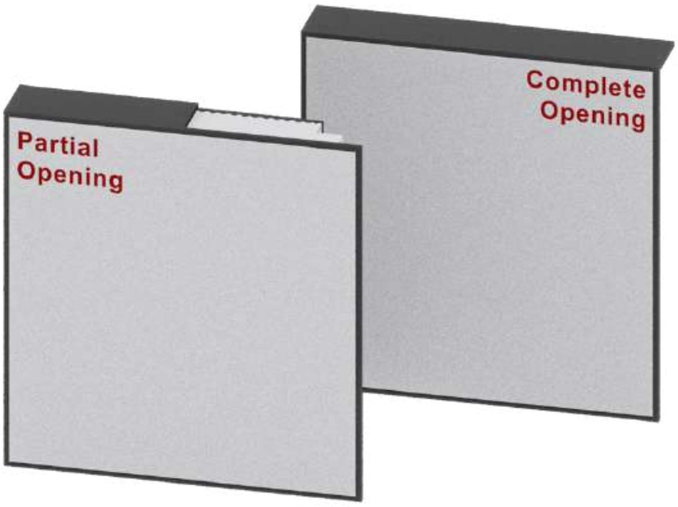

Figure 20 - Complete and partial panel module connection to a building opening.

Meanwhile, the finishing connection between the panels and modules must be considered according to their function. This connection can be done using the same 3D printed plastic as the outer panel. In this scenario, this finishing frame can be attached to the building's opening at the end of the assembly process. Figure 21 shows that this finishing was divided into straight segments, which should be printed in a mill FDM printer. Figure 22 shows unlimited Y-axis dimensions, maintaining the piece's integrity.

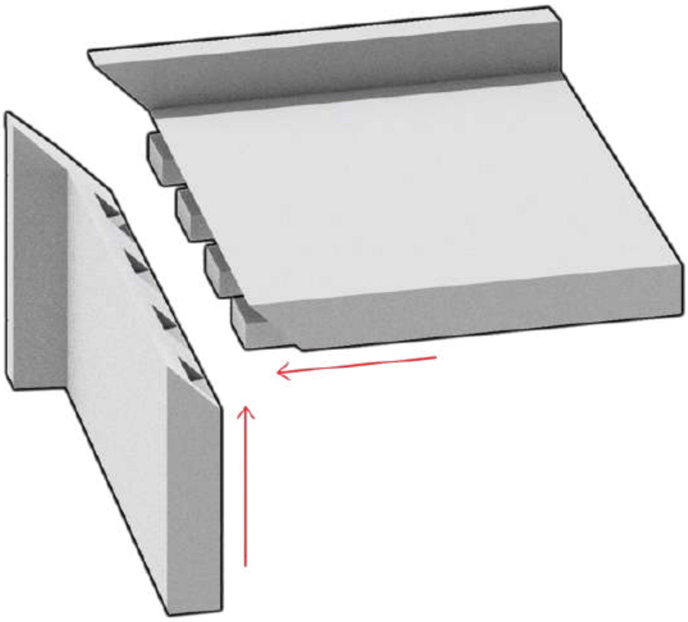

Figure 21 - ZeroSkin+ window connection assembly process.

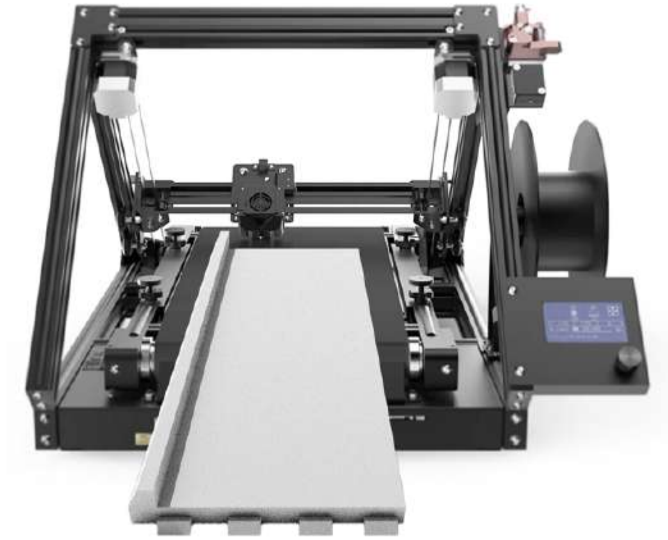

Figure 22 - ZeroSkin+ opening finishing manufacturing technology through mill 3D printing technology.

This frame should be integrated into the opening connection with the ZeroSkin+ renovation solution and original building façade and was attached to the opening, as shown in Figure 23. The watertightness of this solution was done through the larger elastomeric layer in the opening panel.

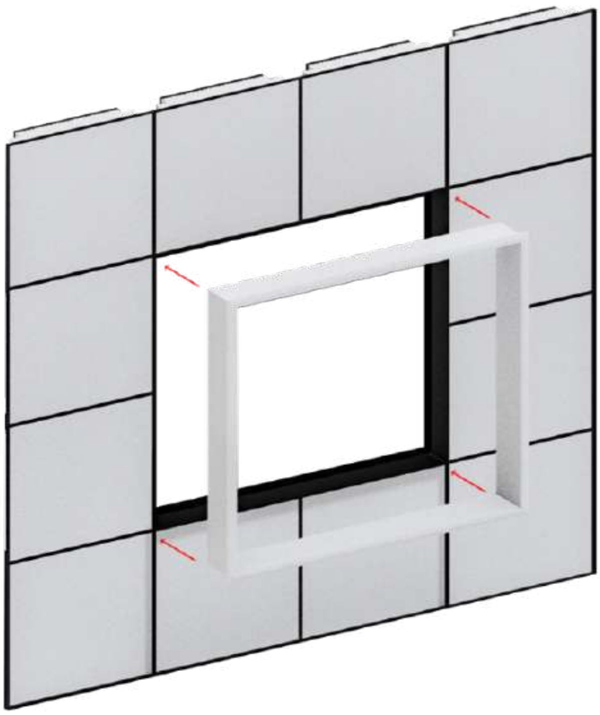

Figure 23 - FDM 3D printed opening finishing attachment to a renovated building façade.

Additionally, there are cases where the ZeroSkin+ building renovation solution is planned in combination with other finishing materials according to the client's specifications. As shown in Figure 24, the specified material should be fixed to a steel profile connecting the panel openings to the building façade.

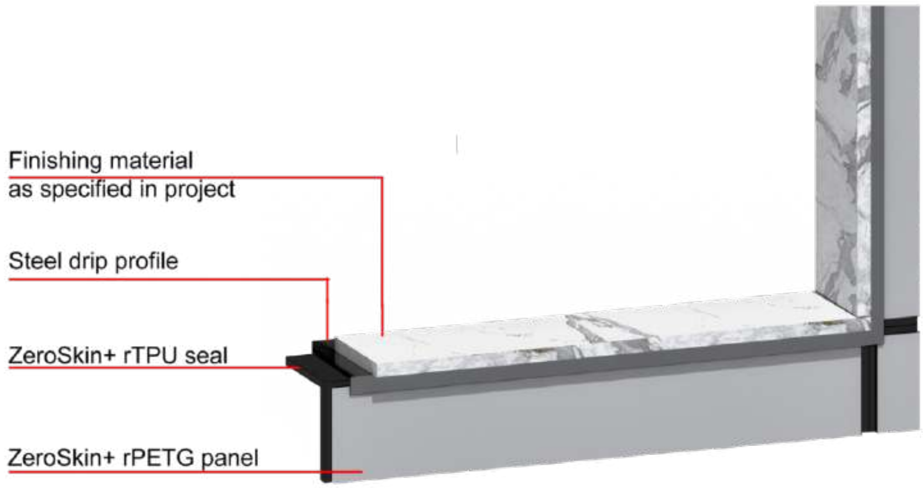

Figure 24 - Attachment of any specified building material as finishing to a connection to a building opening.

Additional openings

Additionally, to the connections to the opening that can be expected in some panel modules, other opening features should be considered in the project's design, such as cuts in panel corners and holes in the panel itself. These additional openings can result from implementing the building renovation solution to a specific placement of any type of connection to the building that could require a link to the outside and inside of the panel. Therefore, the panel design must adapt to four possibilities: no additional opening, a hole in the module, a cut in the module, or both holes and cuts.

The panel with a hole on it, regardless of the function of the hole, should be protected from water infiltration while providing an adaptable connection to the opening. This hole is an adaptation of the design considered for an opening at the extremities of the module. Likewise, it can be integrated with an external finishing material or a 3D printed finishing element, as shown in Figure 25.

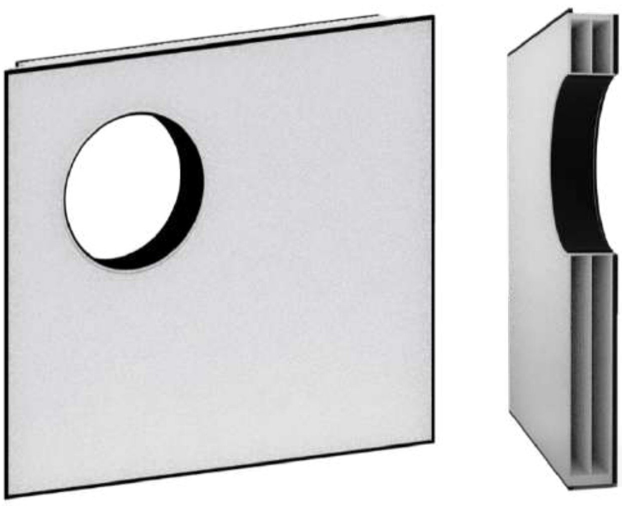

Figure 25 - Panel module with a hole connection to a renovated building's opening.

The modules can also be designed to have a hole that goes through the end of the panel module. These features were planned as cuts in the panel module design. Similarly to the holes, the cuts can have two finishes, as shown in Figure 26.

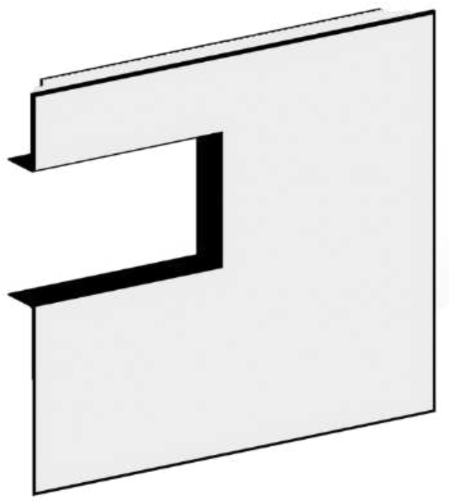

Figure 26 - Panel module with a cut connection to the renovated building's opening.

Corner

The ZeroSkin+ building renovation solution should adapt to every building. Hence, the panel module should accommodate the building's corners. Two possible corner variations were expected in the ZeroSkin+ design - corner and inverted corner. A corner module was defined as a curved module with an angle on its outermost face greater than 180º, while an inverted corner is defined as an outer façade angle lower than 180º. Figure 27 shows some examples of the corners and inverted corner panel module design.

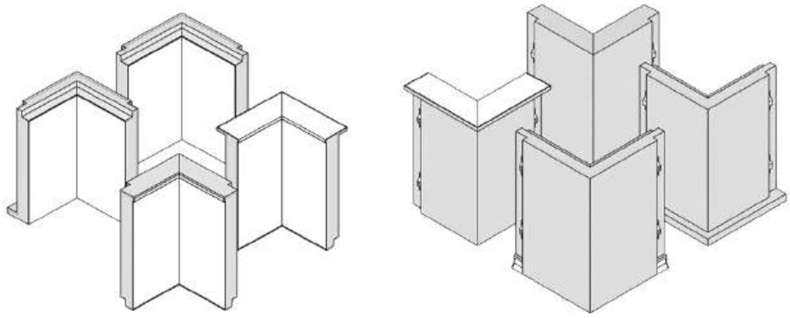

Figure 27 – Corner and Inverted-corner modules.

A reinforced connection between the angled links was designed to compensate for the vulnerability expected in the angled connection between the panel modules. Therefore, a rigid 20 mm section with the corner angle printed in the same 25% infill configuration as the external elements of the panel was added to the design, as shown in Figure 28. A triangular tip was added to the design to reinforce the corner and minimise damage during transport and assembly.

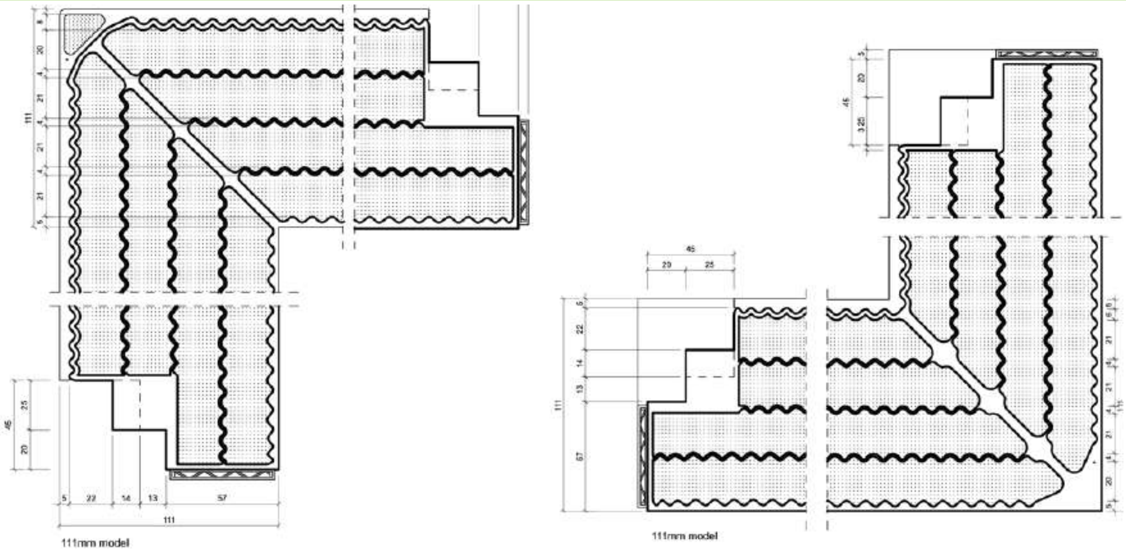

Figure 28 - Corner and inverted corner modules sections of the 111 mm model.

The panel corner angle and connection design were parametrised to accommodate different building's volumetrics.

Curvature

Occasionally, the renovation panel could be applied to buildings with a curvature. For this occasion, the design for curved panel models should be differentiated from the regular models. Hence, this characteristic divides models between straight and curved. Any curved panel model should subsequently be detailed to accommodate different requirements in curvature. Figure 29 shows an example of a section of a curved panel module. The model generation should be done in parametric software that can accommodate the ZeroSkin+ renovation solution to the buildings' curvatures.

Figure 29 - Panel module with curvature.

Sensor Integration

The ZeroSkin+ holistic development also focuses on improving building efficiency by including sensors in the building renovation façade to feed information to IoT devices about the renovation solution requirement for maintenance and environmental data. This information should be used to detect maintenance requirements on the renovation modules, thus decreasing any building pathologies caused by malfunctioning building façade. Additionally, the information transmitted from the sensorised panels could be used to optimise HVAC and lighting efficiency.

The sensorised panel module is a stand-alone panel module which does not require additional building connections. It is equipped with a small PV panel for generating the necessary energy and transmits wirelessly the information gathered by sensors strategically designed to be assembled with the panel. These modules can measure ambient temperature and humidity and detect moisture between the module connections. Figure 30 shows the placement of the sensor box with the PV panel and the four moisture detection sensors.

Figure 30 - Sensor integrated panel module displaying the location of the sensor box with PV panel and opening for ambient sensors (green), connected to four moisture detection sensors.

The heart of this smart module was the sensor box that holds its circuits, batteries, and most sensors. This box is designed to be attached to the renovation panel module and is held in place by four small screws containing a lid attached to the PV panel that generates energy for the module requirements.

The moisture sensors were attached to the top and bottom of the panel towards the connections and the renovated façade. The sensors to measure the temperature, sunlight, and humidity are exposed in the façade in an opening cut above the sensor box. Figure 31 shows the location and assembly of the sensor box to the panel module.

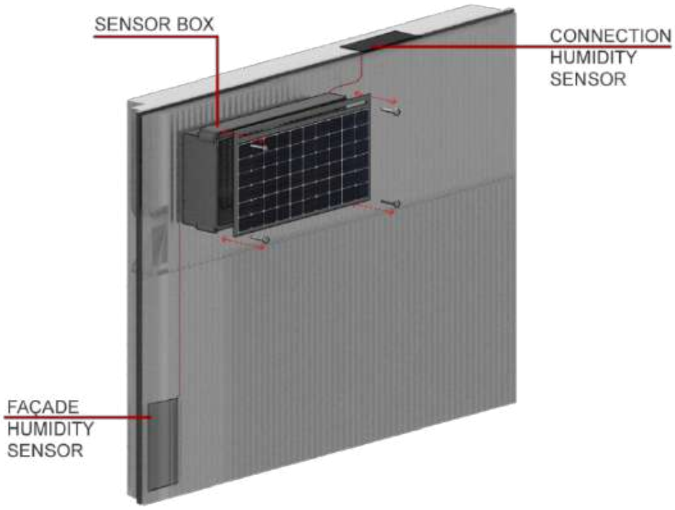

Figure 31 - Sensorized panel module showing its connection to the sensor box and moisture and humidity sensors.

Additionally, this specific module had a slightly different connection on its support connection to allow easy removal for maintenance. The upper panel does not lock this connection and can be removed more easily. This design choice removes the lower panels installed without unmounting a whole building façade.

Figure 32 displays the sensor module connection, and Figure 33 shows the 3D printed module with PV and sensor box integration.

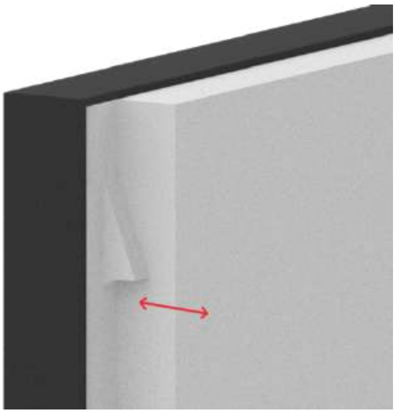

Figure 32 - Fuse-type module connection to the support structure.

Figure 33 - ZeroSkin+ prototype with integration of PV and sensor box.

PV integration

Another aspect of the holistic development of the ZeroSkin+ renovation panel is its integration with renewable energy sources. This integration was done using photovoltaic panels attached to the façade panels. These panels were designed to be placed only on modules with enough light exposure to justify the investment. Figure 34 shows an example of the PV-integrated modules near non-PV-integrated modules.

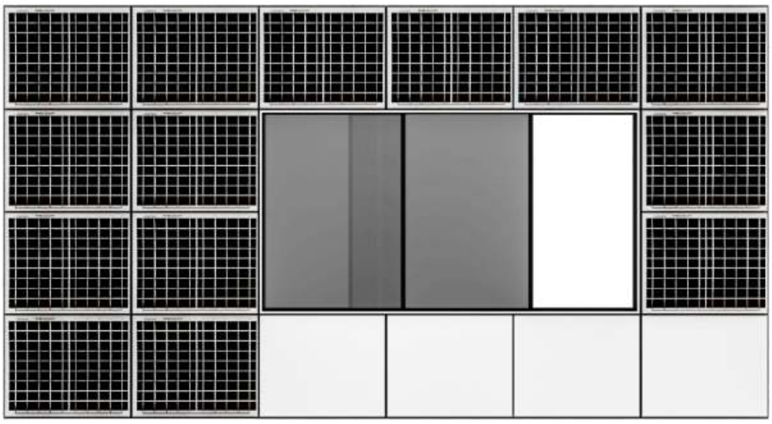

Figure 34 - PV integrated panels modules example on a façade.

The rigid plastic element in the PV integrated modules has a circular opening that is 20 mm in diameter that serves as a passage of the energy cables to the renovated building. The wires were installed through the omega steel profiles used in the seismic reinforcement structure. The PV panel was fixed in the renovation panel through nylon screws fixed to the PETG façade supported in the fixture of the aluminium casing provided with the PV panel. Figure 35 shows a section of a PV-integrated module with space for the passage of the energy cables.

Figure 35 - Section of PV integrated module.

Nonetheless, the ZeroSkin PV integrated modules were limited to the size of the PV panel modules. Currently, the panel is limited to multiples of 540 mm by 680 mm since this is the panel considered for the prototype development. Figure 36 shows the PV integrated panel module. Figure 37 shows the prototype of the model with PV panel integration.

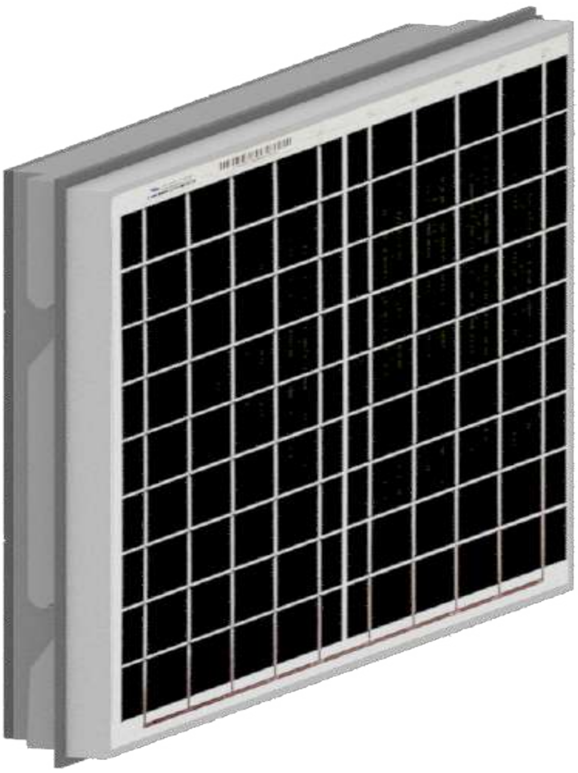

Figure 36 - PV integrated building renovation module.

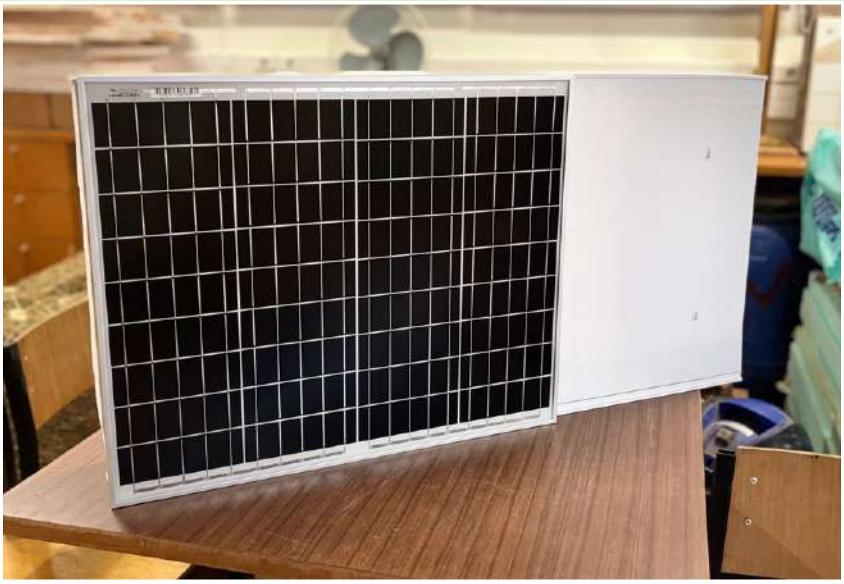

Figure 37 - Internal panel prototype 3D printed in PETG with the insulation layer of agglomerated cork.

Naming system

The design variations and factors discussed in the previous topics could be used to determine a naming system for module model identification besides its identification number. This identification system could automate the panel modules' application to a designed building or facilitate on-site assembly of the ZeroSkin+ prefabricated renovation solution. Therefore, a naming system considering the panel variations options was developed, as shown in Figure 38. This naming system comprises the panel thickness followed by a 7 to 8-digit code to define the combination selected. This code is designed to be separated by commas and slashes to facilitate the readability of the module design. When auto-generated, each panel module should include in its 3D printed parts its identification code and number.

Thickness	Location		Opening Type	Addtional Opening		Corner	Curvature		Sensor Integration	PV integration
61mm	C	.	N	N	.	B	S	/	0	0
Options	Options		Options	Options		Options	Options		Options	Options
61mm	C Centre		C Complete	O Open Corner		B Basic	S Straight		1 Yes	e Yes
86mm	B Bottom		P Partial	H Hole		C Corner	C Curved		0 No	0 No
110mm	T Top		N None	N None		IC Inverted Corner				
	L Left									
	R Right									
	TR Top Right									
	TL Top Left									
	BR Bottom Right									
	BL Bottom Left									

Figure 38 - Renovation panel nomenclature system.

Five thousand eight hundred thirty-two combinations of characteristics might define a renovation model design precisely, including aspects such as size, curvature, opening locations, shapes, and sizes. Hence, these characteristics were determined individually through automated parametric design, where each model was attributed a number that identified its plan and location, helping with the on-site assembly process.

Overall, the broad quantity of panel module models and variations demonstrate the exploitation of additive manufacturing technology to develop the ZeroSkin+ building renovation solution. This number of models would be unviable in another manufacturing system.

Thermal Performance

Experimental data from Hotbox experiments reveals an R-value of the panel of 1.14 ºC.m²/W for the 61mm panel, 1.63 ºC.m²/W for the 86mm panel, and 2.13 ºC.m²/W for the 111mm panel. When added to a typical building façade in Portugal, these values surpass the minimum requirements outlined in the Portuguese thermal regulation. According to this regulation, the external wall's U-value should be below 0.35 – 0.50 W/m².ºC, depending on the climatic region. Furthermore, when considering a standard 22 cm brick wall, the U-value of the solution (panel + wall) decreases to 0.25 W/m².ºC. As an example and for comparison purposes, the panel performance was simulated as an addition to a 0.84 W/m².ºC U-value, corresponding to a typical Portuguese building façade (11+15 cm hollow brick wall) [1].

Table 3 – ZeroSkin+ module thermal performance.

Panel Model	R-Value (ºC.m²/W) ZeroSkin+ panel alone	U-Value (W/m².ºC) ZeroSkin+ panel + (11+15) cm building façade
61mm	1.14	0.43
86mm	1.63	0.35
111mm	2.13	0.30

The panels integrated with PV panels for the sustainable generation of electricity were able to provide 1 kWp in a simulated solar photovoltaic installation at the University of Minho's Campus de Azurém. The simulations were conducted using the Photovoltaic Geographical Information System (PVGIS) from the European Commission. A simulation with optimal azimuth and slope (4° south orientation and 35° slope angle) showed a total annual energy production of 1434.7 kWh, which are promising results for the integration of renewable energy sources in the renovation of building façades.

It was also simulated photovoltaic modules integrated into prefabricated panels on different facades. The results showed energy production percentages relative to the optimal orientation: south-facing facade (64%), west-facing facade (60%), east-facing facade (33%), and north-facing facade (23%). The simulations revealed that energy production is highly dependent on orientation. Hence, the solar module integration should be made on a case-by-case basis, considering cost-effectiveness.

Therefore, despite installing the PV at a 90° slope angle not being the most efficient, its integration into the ZeroSkin+ building renovation panel is promising, and its installation could be cost-effective depending on the façade orientation and solar exposition.

[1] P. dos Santos and L. Matias, ITE50. ICT Informação Técnica, 2006.

Life Cycle Assessment

The Life Cycle Assessment (LCA) is a quantitative analysis where the energy and material consumption and the waste released in the environment are estimated according to a methodology that follows the ISO 14040 standard.

The first approach to a life cycle assessment (Conceptual LCA) of the ZeroSkin+ system was conducted to evaluate the magnitude of its carbon emissions exclusively. The study focuses on the Global Warming Potential (GWP) indicator, which refers to the increase in the average global temperatures as a result of greenhouse gas (GHG) emissions and is the most relevant indicator related to the objectives of this assessment. Detailed information can be found in the Deliverable - 4.2 Life Cycle Performance and Circular Economy Report.

The material quantities were calculated for a ZeroSkin+'s typical module with 1 m^2 (functional unit), a total thickness of 61 mm, printed with an infill of 25%, and filled with agglomerated cork insulation with 40 mm thickness.

A cradle-to-gate life cycle model was chosen to determine the magnitude of ZeroSkin+ carbon emissions. It corresponds to the Production Stage of the panel and is limited to the assessment of ZeroSkin+ primary materials and the 3D printing process.

The quantification of the PETG filament was provided by PrusaSlicer software, which was used to generate the 3D printing g-code of the panel. The amounts of the other materials were calculated based on the technical information provided by the manufacturers and technical publications.

The GWP indicator for PETG and rPETG is presented as a range of values because it was impossible to obtain enough sources to consider using a single valid value, e.g., the average. Variations of values were found for the corkboard's GWP, and a revision may be necessary in the future. Table 4 lists the primary data used for the analysis performed.

Table 4 – Material quantities for 1 m^2 of ZeroSkin+ façade and GWP per kg of material.

Material	Quantity kg/m^2	Density kg/m^3	GWP total (A1-A3) kgCO_2eq/kg
Recycled PETG (rPETG)	12.24	1270	2.550 – 4.080
Virgin PETG (as a comparison to rPETG)			5.850 – 6.270
Agglomerated cork board λ = 0.04 W/(m.ºC), thickness 40 mm	4.09	115	1.590
Omega steel profile H = 50 mm, 2 linear meters	78.00	7800	0.553[1]

Other sources:

[1] Average value based on papers related to the EU context

For a typical panel of 1 m^2 and 61 mm of total thickness, a printing time of 4 days, 22 hours, and 10 minutes (equivalent to 118.17 hours) was estimated using the PrusaSlicer software.

The panel prototypes were printed at the University of Minho with a Builder Extreme 1500 Pro printer. As disaggregated energy consumption data according to the stage of the printing process for this 3D printer was not available at the time of this assessment, a reference found in the literature was used instead, relating the following average power demands: idle state (12 W), set-up state (72 W), warm-up state (75 W) and build state (71 W). These values are at the lower end of power demand for a Fused Depositions Modelling printer, as they were measured for a desktop 3D printer. Therefore, the 3D printing calculation considered 5 minutes of set-up state, 5 minutes of warm-up state and 118.17 hours of build state, resulting in a total power demand of 8.40 kWh/m^2. This value was converted to carbon emissions using the Portuguese electricity emission factor, defined as 0.184 tCO_2eq/MWh for 2020. The total carbon emissions produced by a typical panel 3D printing is 1.55 kgCO2eq/m2.

Figure 39 presents the total GWP in tCO_2eq/m^2 for five façade renovation compositions considered:

- ZeroSkin+ using recycled PETG (rPETG), considering the lowest and the highest GWP values found for rPETG.
- ZeroSkin+ using virgin PETG (PETG), considering the lowest and the highest GWP values found for PETG.
- ETICS using a mineral wool panel with similar thermal conductivity to the corkboard.

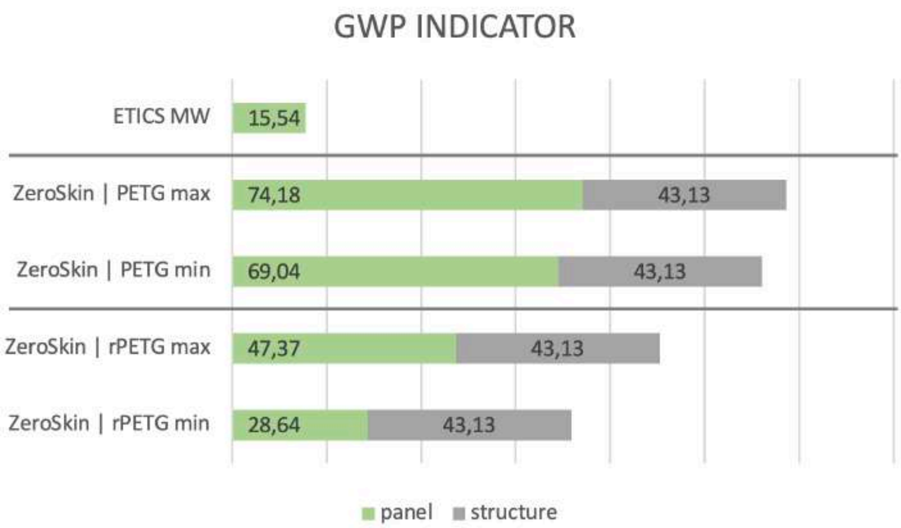

Figure 39 - Comparison of the total GWP impacts of the analysed façade renovation solutions.

The structural frame corresponds to a significant percentage of ZeroSkin+'s total GWP in all the cases. When PETG is used in the panel, the structure's GWP is equivalent to 51 to 54% of the panel's GWP, i.e., the structure and the panel are responsible for almost equal shares in carbon emissions. When rPETG is used, a reduction in the panel's GWP leads to an increase in the proportion between the structure and the panel's GWP, ranging from 74 to 110%. This means that when rPETG is used, the structure represents a greater proportion of the total emissions, surpassing the panel emission. The use of recycled PETG proved valid in this assessment since it reduces carbon emissions up to 51% when compared to virgin correspondent material.

It was verified that the ZeroSkin+ solutions presented higher environmental impacts than the ETICS MW, even if the panel mounting structure is not considered in the comparison.

When the environmental impacts of the panel are disaggregated by material, it is clear that, at this moment, not only the virgin PETG production but also the recycling process still releases high carbon emissions (80 to 90% of the panel emission). The use of recycled PETG compared to virgin PETG represented a carbon reduction in the range of 32 to 51%. On the other hand, it showed that the plastic recycling process is still responsible for relatively high emissions. In this study, it was responsible for between 80 and 90% of the panel impact (not considering the steel structure).

Seismic Performance

The results obtained from the seismic tests are mainly in terms of force values, measured by four load cells placed at the contrasting structure and displacements assessed using the 13 linear variable differential transformers. Another important output is the cracking pattern, which provides valuable information on the effectiveness of the resisting mechanisms of the structure. Visual observations are also important to assess the evolution of the cracking during the test.

The comparison between the load-displacement curves obtained from the two tests is shown in Figure 40. As can be seen, the ZeroSkin+ reinforcement solution considerably improved the infill wall's out-of-plane capacity, achieving a 42% increase compared to the unreinforced masonry (URM) wall. The difference in the initial stiffness was mainly due to residual plasticity effects on the frame from the first test, which did not prevent the following improvement of the wall capacity. The omega profile reinforcement system becomes effective after an initial displacement (i.e. 2.5 mm) where the two curves are almost coincident. After this threshold, there is a clear different trend between the two plots: while the URM wall presents a horizontal plateau with nearly constant force and increasing displacement, the reinforced structure still exhibits an increased applied force in the out-of-plane. It should be mentioned that the boundary conditions change with this reinforcing solution since the steel profiles work as additional constraints to the wall. In the URM wall, there were no constraints to the displacement of the wall except the connection with the RC frame, which resulted in a weak restraint, as can be seen from the displacement profiles in the following.

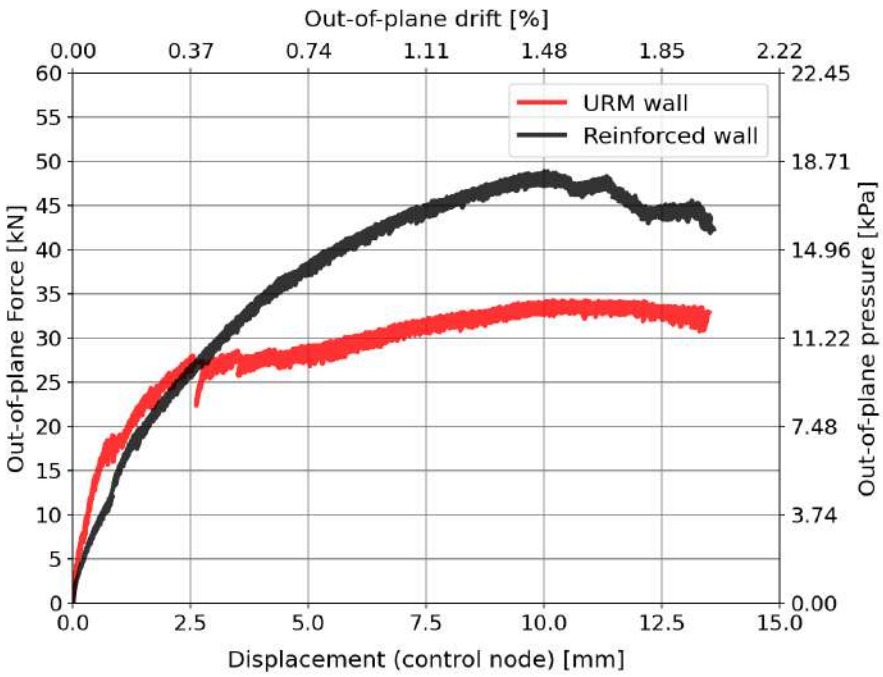

Figure 40 - Load-displacement curve obtained from the two tests on the infill walls.

In the reinforced wall curve, a softening phase was observed after the peak with the maximum applied force, mainly due to generalised masonry cracking and the RC elements' initial damage. On the other side, for the URM wall, such a trend was less visible due to the lower load applied and the response to the failure of the infill masonry, which acted as a rigid body with very dangerous consequences in real practice (e.g. complete expulsion of the infill). This was not observed for the reinforced structure, which not only increased the out-of-plane capacity of the infill but also prevented the masonry's fragile collapse involving the RC failure's ductility in the failure mechanism. The URM wall instead presented a trilinear cracking pattern.

Plots in Figure 41 and Figure 42 show the out-of-plane displacement profiles of the URM and reinforced wall obtained from the experimental tests at increasing load according to the disposition of the LVDTs in the two main alignments, i.e. vertical and horizontal, respectively. It is possible to note that, in both cases, the infill is detached from the surrounding RC elements. This highlights that it is not safe to take into account such a constraint to avoid the out-of-plane collapse of infill walls in RC frames without suitable connecting systems. Such a phenomenon is present with the ZeroSkin+ solution as well.

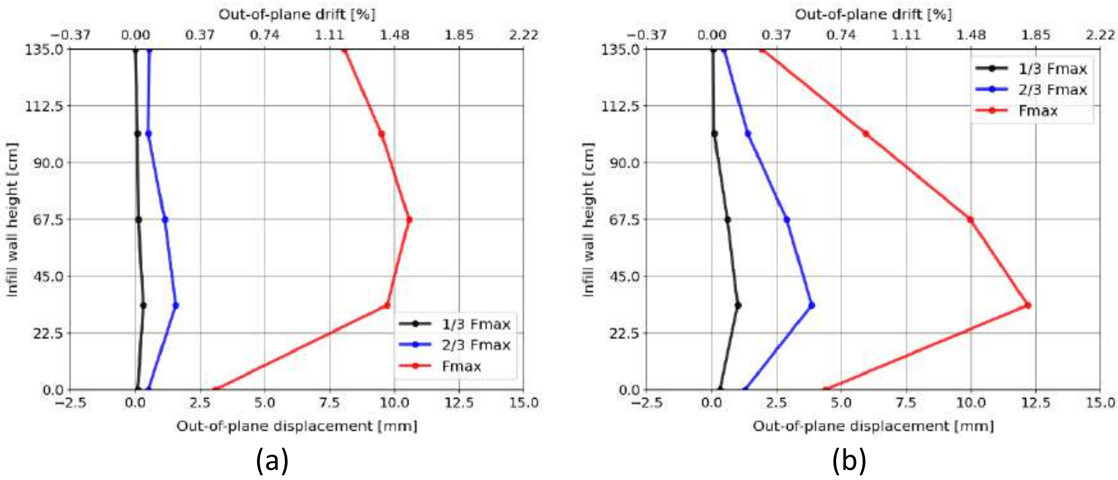

Figure 41 - Out-of-plane displacement profiles of the URM wall: (a) vertical and (b) horizontal alignment.

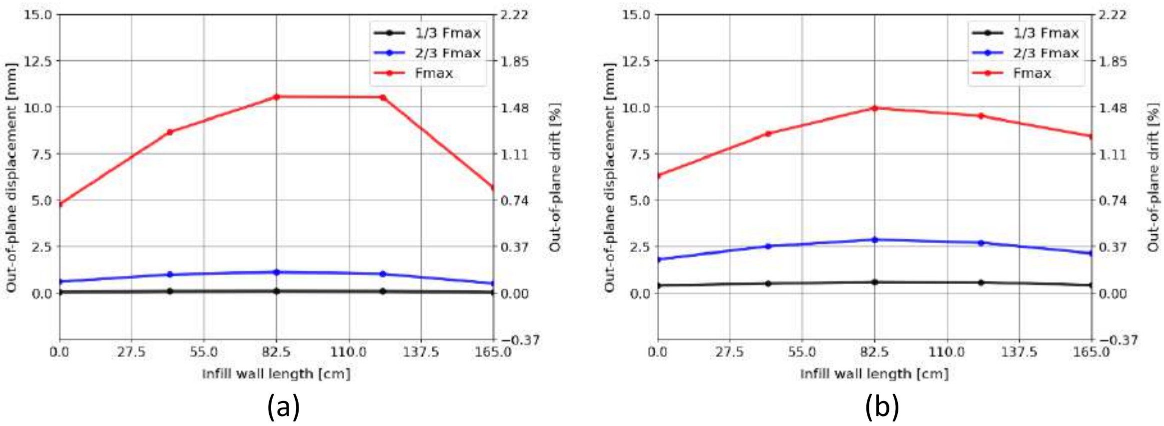

Figure 42 - Out-of-plane displacement profiles of reinforced wall: (a) vertical and (b) horizontal alignment.

In such a comparison in terms of displacement profiles between the URM and reinforced walls, the considered loads are different since the maximum load supported by the infill was much higher in the second test with the strengthening system. However, it is interesting to notice the beneficial effects of the solution, with more concentrated displacement at the highest load levels mainly due to local damages and the masonry disgregation given the higher force values, possibly exceeding the strength of the masonry itself. On the contrary, the URM wall presented a more global response, which may involve high safety risks. The considerable reduction of the top displacement with the reinforcement is mainly due to the steel profiles themselves, which constitute an additional constraint between the wall and the top beam. In contrast, in the URM wall, the connection between the RC element and the masonry wall was only provided by the mortar layer constituting the upper joint.

It is also interesting to assess the damage evolution and the cracking patterns obtained from the two tests. The presence or absence of the ZeroSkin+ solution significantly changes the masonry wall's damage, as seen from the pictures in Figure 43 and Figure 44 for the URM and the reinforced wall, respectively. The URM wall exhibited a trilinear cracking pattern with deformations concentrated in the central point of the wall, as already highlighted by the displacement profiles. A vertical mid-crack in the upper part joined to two diagonal cracks from the bottom corners of the wall, dividing the infill into three main bodies (see Figure 43).

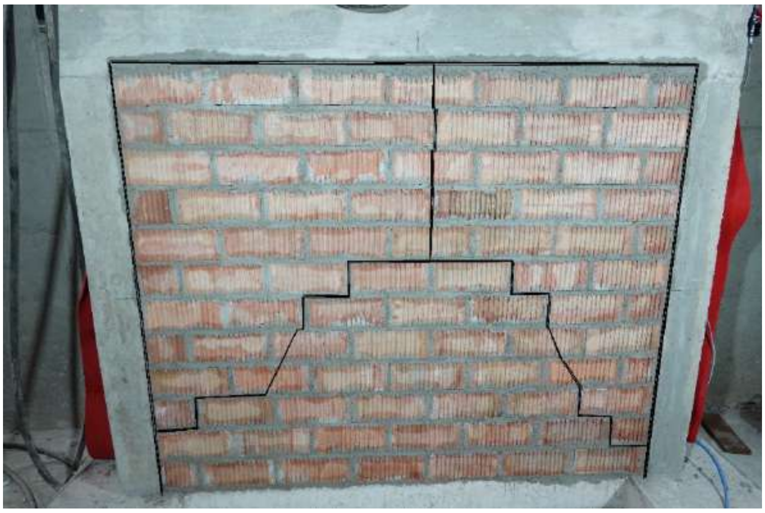

Figure 43 - Observed damage in the URM infill wall: cracking pattern.

On the other side, the reinforced wall presented visible horizontal cracks in the mid-span and in the bottom part, which is justified by the higher displacement values obtained from the LVDTs. Moreover, the retrofitted wall showed generalised cracking (see Figure 44), mainly concentrated in correspondence with the omega profiles. This was mostly due to the constraint provided by the steel reinforcement, which does not allow the free deformation of the masonry and, at the same time, was the reason for the localised increase of the applied load. Both the walls presented detachment at the boundaries with the surrounding elements.

Figure 44 - Observed damage in the reinforced infill wall: cracking pattern.

The ZeroSkin+ renovation's main goal was to improve the renovated building's energy performance while addressing holistically other issues such as the reutilization of plastic waste, seismic renovation, integration of RES in building renovation, and the integration of sensors in a building façade. The renovation solution was manufactured primarily with recycled plastic materials. It also must be a functional and feasible renovation solution on an industrial scale to be implemented in a building renovation scenario. The ZeroSkin+ building renovation solution had to comply with the KPIs defined in Table 5.

Table 5 – ZeroSkin+ integrated renovation solution KPIs

KPI	Indicator	Prototype Results	Compliance
Thermal transmittance (U-value) of the ZeroSkin+ panel together with the pre-existing building façade (11+15 hollow brick wall with a U-value of 0.84 W/m².ºC)	0,35 W/m².ºC	The thermal resistance of the panel varied from 1.14 to 2.13 ºC.m²/W, resulting in a global U-value of 0,35 W/m².ºC in the combination of the medium panel with the pre-existing wall	Yes
Thermal resistance (R-value)	1,60 ~C.m²/W	1.14 ºC.m2/W to 2.13 ºC.m2/W	Yes
Resistance to high dry bulb temperature	47.5 °C	Softening point 80 °C	Yes
Resistance to low dry bulb temperatures	-16 °C	-21.8 °C	Yes
Integrate renewable energy sources	Yes	Done	Yes
Achieve toughness and resistance to vandalism according to ISO 179-1:2010	Yes	Specified tests have not been conducted	Untested
Comply with Portuguese regulation for acoustic performance	Yes	Acoustic tests were not conducted due to time limitations	Untested
Resistance to theft and unauthorised removal	Yes	Done	Yes
Watertight connections in heavy rain conditions and pressurised water exposure conditions	Yes	Waterproof tests were not conducted due to time limitations	Untested

Table 6 (continued) - ZeroSkin+ integrated renovation solution KPIs

KPI	Indicator	Prototype Results	Compliance
Resistance to UV radiation according to the expected life cycle and annual average UV radiation in Portugal	2368,8 kWh/m²/year	Selected material and prototype material comply with the UV radiation resistance requirements	Yes
Fire resistance classification according to the Portuguese regulation for opaque envelope elements and European standard EN 13501	Fire resistance classification between B-s2 d0 and C-s2 d0	Selected material and prototype material comply with the fire resistance requirements	Yes
Achieve self-support structural capacity	Yes	Done through the seismic renovation solution	Yes
Cost-effectiveness compared to common opaque envelope renovation solutions in Portugal	Yes	The calculated costs are still above the ETICS average costs, but the costs were calculated based on a laboratory production process and not based on industrial mass production	No
Recycled plastic as a primary material	Yes	Yes	Yes
Optimised to prefabrication process	Yes	Done	Yes
Optimised to the additive manufacturing process	Yes	Done	Yes
Comply with the Watertight connections in heavy rain conditions and seismic Regulation - Decree-Law n.º 95/2019	Yes	It could not be tested within the project's time limit	Untested

The KPIs previously defined positively indicate that the ZeroSkin+ project has met most of the indicators. However, for various reasons, some aspects could not be tested within the project's time limit. Although these aspects could not have been met within the project's time limit, the overall results are still positive, pointing towards a successful outcome for the ZeroSkin+ project's development.

Conclusion

The ZeroSkin+ renovation panel has been conceived as a product intended for additive manufacturing, focusing on using recycled plastic in conjunction with sustainable low-emission materials, such as agglomerated cork. Incorporating this innovative solution within the building façade aims to enhance thermal and seismic performance. The increase in thermal performance seeks to bolster the building's energy efficiency. It is crucial to note that the building façade plays a pivotal role in the context of energy conservation, accounting for approximately 25% of total energy losses in buildings. Furthermore, renewable energy sources have been thoughtfully integrated into the designed solution, most notably by including photovoltaic (PV) panels within the building's façade. This strategic integration of PV panels has the potential to propel the renovated building toward achieving a status as a positive energy building, with a return on investment anticipated to occur throughout the renovation solution's life cycle. Complementing these features, the panels are equipped with sensors designed to assess water infiltration and furnish measurement data pertaining to temperature and light exposure for a specific building component. In summary, the panel contributes to enhancing the quality of life for the inhabitants of older buildings by addressing thermal performance deficiencies, all while utilising recycled plastic in its composition.

ZeroSkin+

The ZeroSkin+ project developed a 3D-printed recycled plastic panel to enhance the buildings' energy and seismic performances. The additive manufacturing of the panel, aligned with the reuse of plastic waste, promotes the development of a circular economy by consuming plastic waste and decreasing the embodied emissions related to transportation, manufacturing and waste management.

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