# Off-site prefabricated hybrid façade systems

## A holistic assessment

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**Abstract**

*The residential sector is responsible for the largest share of global energy consumption, while the existing building stock in Europe is relatively old. This issue, in combination with the low rate of new constructions, highlights the necessity for deep renovation of existing buildings to reach NZEB standards. At the same time, in the last decades, off-site prefabricated solutions have gained popularity in the building market, allowing the reliable and effective integration of diverse components and reducing the total renovation cost and occupants' disturbance. The current study describes three all-in-one "Plug & Play" prefab renovation solutions and their assessment in terms of thermal, static, acoustic, and fire performance. The assessing performance is selected depending on their incorporated element as well as the national regulations of the country where the renovation solution is going to be installed. The assessment aims to ensure their characteristics' satisfaction with the European and national requirements. In parallel, the assessment identifies the accurate behaviour of prefab façade systems both in passive and active mode and improves/optimises any possible design drawbacks.*

**Keywords**

*deep renovation, prefabricated façade, structural performance, thermal performance, fire performance*

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# 1 INTRODUCTION

The European Commission established the European Green Deal as a policy initiative for Europe to become a climate-neutral continent by 2050. The Energy Performance of Buildings Directive (EPBD), as part of the EU Green Deal, is key to achieving the EU's goals of reducing energy consumption in buildings, which accounts for 40% of energy consumption and 36% of total greenhouse gas emissions in the EU (European Commission, In focus: Energy efficiency in buildings, 2020). Since 85-95% of the existing buildings will be standing in 2050 (Maduta, Melica, D'Agostino, & Bertoldi, 2022) and roughly 75% of the European building stock is estimated to be energy-inefficient (European Commission, In focus: Energy efficiency in buildings, 2020), the renovation of buildings with energy efficient solutions is a viable and feasible measure for achieving the European energy goals.

The required annual renovation rate has to be 3%, with deep renovations accounting for 70% of the total, to achieve climate neutrality by 2050 (BPIE, On the way to a Climate-Neutral Europe: Contributions from the building sector to a strengthened 2030 climate target, 2022). However, the annual renovation rate in Europe is below 1%, of which only 0.2% concerns deep renovation (Filippidou, Nieboer, & Visscher, 2017). These low rates are due to the high cost of renovation solutions, the long duration of work, and the occupant disturbance. In this context, the application of prefabricated modular building elements constitutes an innovative way for a deep renovation of existing buildings, reducing the renovation cost and time while at the same time minimising occupant disturbance (Pihelo, Kalamees, & Kuusk, 2017) (Masera, Iannaccone, & Salvalai, 2014). In prefabrication technologies, the design, manufacturing, and assembling of the building components take place in a specialised industrial environment before their installation at the final construction site (Kamali & Hewage, 2016). The concept of prefabricated building elements is fast construction with fewer resources (Naji, Çelik, Alengaram, Jumaat, & Shamshirband, 2017).

Recently, off-site hybrid prefabricated façade systems, which combine highly efficient insulation façade panels integrated with HVAC and renewable harvesting systems, are an upcoming topic for research, innovation development and policymakers (Du, Huang, & Jones, 2019). Combining innovative HVAC components with renewable energy systems constitutes a cost-efficient all-in-one solution for the renovation of a building towards nearly zero energy building (NZEB) status with significant cost, time, material, and waste savings (Torres, et al., 2021). Several such all-in-one deep renovation façade solutions have been explored and developed within EU-funded research projects demonstrating the extended work done to reach NZEB state after the renovation (D'oca, et al., 2018), such as MORE-CONNECT, BERTIM, E2VENT, iNSPiRe, and 4RinEU. In some cases, prefabricated modules combine HVAC units and integrated RES that are designed as a prefabricated box, while in other cases, the HVAC and energy harvesting systems are incorporated into the wall assembly (Katsigiannis, et al., 2022).

It is vital for these underdeveloped off-site hybrid prefabricated façade systems to be in line with the European and national/regional regulatory requirements in order to penetrate the market. The European Union has put in place a comprehensive legislative and regulatory framework for the construction sector. Health and safety in construction and the free movement of engineering/construction services and products are important policy priorities. However, there is a lack of regulatory framework regarding the installation of prefabricated elements/façades and, in general, kits that combine structural parts with electromechanical equipment because this renovation concept is relatively new. The most relevant regulation regarding hybrid prefabricated façade systems is the Construction Products Regulation (CPR). The objective of the CPR is to achieve the proper functioning of the internal market for construction products by establishing harmonised rules on how to express their performance. The key points of the CPR are: a) to set out the conditions for the marketing of construction products, and b) to set out methods and criteria for assessing and expressing the performance of construction products and the conditions for the use of CE marking. CPR establishes seven basic requirements for construction works: a) mechanical resistance and stability, b) safety in case of fire, c) hygiene, health and the environment, d) safety and accessibility in use, e) protection against noise, f) energy economy and heat retention, and g) sustainable use of natural resources.

Despite the large number of EU projects that develop modular and industrialised prefabricated renovation solutions, there are still many barriers that hamper speeding up market uptake, such as performance verification and the mistrust for the performance of innovative components (Oorschot, Maggio, Veld, & Tisov, 2022). The current study presents the methods that are followed to verify the structural, thermal, and fire performance of three off-site hybrid prefabricated deep renovation façade systems that are developed in the frame of the PLURAL EU funding project (PLURAL EU project, 2020-2024). Each façade system is planned to be installed in a different EU country (Greece, Spain, and the Czech Republic). Selected performance assessment methods of façade systems are implemented to identify their accurate behaviour and to ensure and verify the satisfaction of their characteristics with the European and national requirements. The structural performance of façade panels is investigated in terms of the analysis of their anchoring system or the seismic resistance, where necessary, while the fire performance analysis is carried out in terms of reaction to fire tests. The thermal performance is assessed by calculating all incorporated thermal bridges and the equivalent thermal transmittance of façade panels and investigating the impact of the embodied HVAC systems on thermal transmittance when they are in operation (active mode) and stopped (passive mode).

## 2 DESCRIPTION OF PREFABRICATED FAÇADES

The present study assesses three different off-site prefabricated hybrid façade systems developed in the frame of the PLURAL project: the SmartWall, the Denvelops Comfort Wall, and the ConExWall (Adamovský, et al., 2022).

### 2.1 SMARTWALL

SmartWall is a multifunctional façade system that combines active with passive technologies developed by AMS (AMS coatings and advanced materials, 2023). The concept of SmartWall is to integrate various prefabricated elements (such as windows, doors, and balcony doors) and a wide range of HVAC technologies (e.g. fan coils, split units, air ducting systems, radiators, and convectors) in order to reduce installation time and construction faults during installation. It is a compact, versatile prefabricated façade panel which can be installed externally or internally (in case there are space or aesthetic restrictions) in existing building envelopes, introducing an innovative, dynamic, and flexible retrofitting solution (Katsigiannis, et al., 2022). The SmartWall is easily adjustable to any dimension up to 4 m of height per panel and can be decorated with any kind of finishing material.

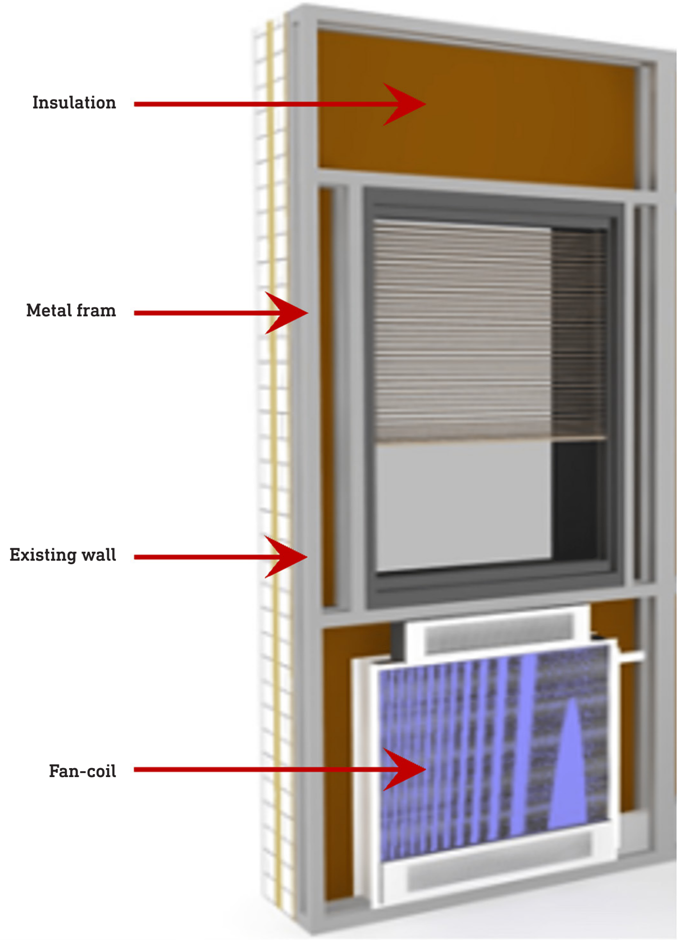


FIG. 1 The concept of SmartWall

The general concept of the SmartWall is presented in FIG. 1 (Katsigiannis, et al., 2022). The basic material for the frame is steel S245, using lightweight 50 x 50 mm members welded in a frame. The concept allows for the design and manufacture of a large variety of panel sizes with various frame strength to accommodate the multitude of materials and technologies that can be integrated into the SmartWall. The basic insulation material is mineral wool, but several alternatives can be used (rockwool, glass wool, EPS, cellulose). Finishing surfaces differ according to the use of the façade system in interior or exterior position, while a large variety of boards containing cement, gypsum, fibre, timber, etalbond®, etc. can also be utilised. The SmartWall is constructed containing flexible piping and electrical wiring connections that can accommodate either the existing or a new heating/cooling system and electrical services (switches, plugs, etc.), which significantly reduces on-site installation time. Photovoltaics can be part of the external SmartWall or can be installed on the roof of the building if the geometry includes balconies or volumes that shade the vertical external surfaces. FIG. 2 illustrates the four different configurations of SmartWall:

- Type A – The module contains no fan coil or window (Blank Type).
- Type B - The module contains a slim type fan coil, but it does not contain any windows.
- Type C - The module contains a window, but it does not contain any fan coils.
- Type D - The module contains both a fan coil and a window.


FIG. 2 Four different SmartWall configurations

In the present study, the materials of the SmartWall are anchored on two frames made by Hollow Rectangular Section (HRS) structural steel members with sections of 50x30 mm and 1.8 mm thick. Spacers made by the heat breaker structure are placed in the fixing points to ensure movement treatment, except on the bottom side, where the spacers are made from the HRS frame for structural reasons. The space between the frames (160 mm width) is filled with mineral wool. A gypsum board layer (12.5 mm thick) covers the internal side of SmartWall, while a mineral wool layer with aluminium foil (30 mm thick) is placed on the opposite side that rests against the existing envelope. Moreover, in the cases where the fan coil exists, a Vacuum Insulation Panel (VIP) layer, 20 mm thick, is installed at the back side of the fan coil.

## 2.2 DENVELOPS® COMFORT WALL

The Denvelops Comfort Wall is an off-site prefabricated ventilated façade system composed of vertical stainless-steel guidelines and connectors that allow to attach and bear toads of the cladding (Denvelops, 2022). The cladding system (FIG. 2a) is made of 1 mm thick painted aluminium cladding tiles with resistant powder coating. PV panels are integrated into the façade, locally replacing the final cladding. The thermal insulation is made of mineral wool and is protected by a weathering layer. Both are attached to the system's vertical guidelines in order to achieve the required thermal and water-tightness performance. The mineral wool is covered by a glass-fibre layer that can protect against mechanical damage. Thermal resistance equal to 2.90($m^2{\cdot}K$)/W is achieved with a 100 mm thick Denvelops Comfort Wall façade, considered the optimum passive measure.

The Denvelops Comfort Wall contains an innovative HVAC system called Air Handling Unit (AHU) developed by Czech Technical University (Zavřel, Zelenský, Macia, Mylonas, & Pascual, 2022), located in a vertical position. As presented in FIG. 2b, the AHU incorporates two stages of heat recovery: the first is a passive heat exchanger (plate), and the second is an active heat exchanger with thermoelectric modules that provides supply air temperature control. The unit is connected to the interior space via supply and extract channels. The electric power for the thermoelectric modules is derived from the PVs or the grid.

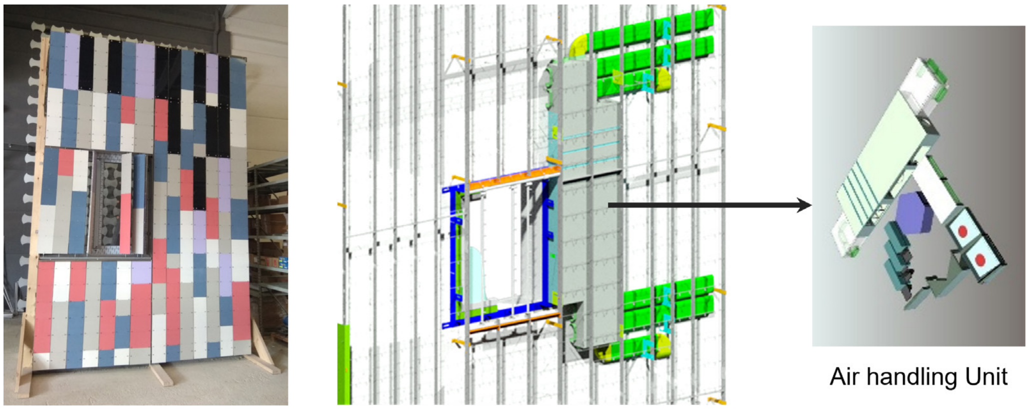


FIG. 3 The Denvelops Comfort Wall façade system

## 2.3 CONEXWALL

The ConExWall is a façade system that integrates a heating/cooling piping system, and it is specifically designed to be used in colder climatic zones, such as alpine and continental locations. The basic configuration of the ConExWall is illustrated in FIG. 4. The fundamental material for the frame is timber because of its low carbon footprint, thermal conductivity avoiding thermal bridges, high flexibility in shape dimensions, and the variety of connection techniques available. The outer layers serve as load-bearing timber and include the main thermal insulation. Its purpose is to ensure the best and maximum contact of the heating/cooling pipes with the existing façade wall accounting for wall irregularities. This enables the element to adapt to uneven sections of the wall (Material: wood fibre, sheep wool, hemp wool, glass and rock wool). The internal side of the ConExWall is a 20 mm layer of wood board with embodied heating pipes and a 60 mm thick flexible layer (Isover Orsik insulation). Next, a layer of 50 mm thick gypsum board is anchored on a timber frame with vertical studs with sections of 180 x 80 mm and stud spacing equal to 750-650 mm. The gap inside the frame is filled with insulation (180 mm thick), while a layer of hard wood insulation (STEICOprotect H) 50 mm thick is anchored on the external side of the frame. A 40 mm thick ventilated timber frame is placed at the external side of the STEICOprotect layer, while a layer of 20 mm thick timber cladding is placed on the finishing layer of the façade panel. The anchoring system of the ConExWall consists of L-shaped (200 x 190 mm and 15 mm thick) metal profiles with a spacing of 1.19 m that penetrates the façade panel and anchors on the existing wall.

The advantage of this heating concept is the thermal activation of the whole existing façade, which allows for using the existing wall as thermal storage. In the case of a heating system with a heat pump and PV, this enables running of the heat pump longer and to higher temperatures during times of excess electricity gains from the PV system, and on the other hand, to run it for shorter times during periods when electricity must be purchased from the electricity grid. Additionally, such an operational mode overcomes the energy shortage delivered to a room, which strongly depends on the opaque external wall area. An integrated control system, utilising an advanced monitoring system, measures weather data, the supply temperature of the heating system, room temperature, and $CO_2$ concentration and will control the thermal comfort as well as the indoor air quality.

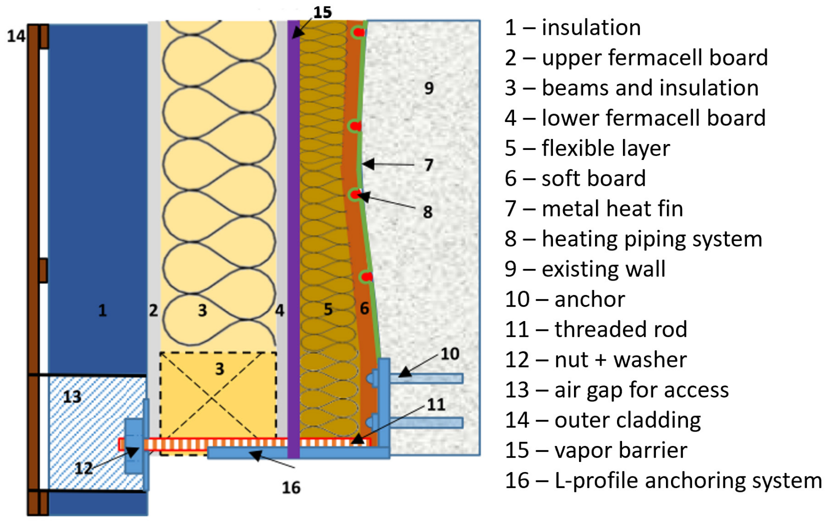


FIG. 4 The ConExWall façade system and its incorporated building elements.

# 3 METHODOLOGY

Each of the previously described prefabricated hybrid façade systems is applied for the renovation of an existing residential building located in a different country with different climate conditions and national building requirements. The SmartWall is implemented in a Greek (Athens), the Denvelops ComfortWall in a Spanish (Terrassa), and the ConExWall in a Czech (Kasava) residential building. The performance in terms of structural, fire and thermal behaviour of each façade system is verified using standardised methods. Each method was selected taking into account the national requirements and the incorporated components. Table 1 summarises the country and the performance assessment method that was carried out for each façade system.

TABLE 1 Application of hybrid system in different countries and the assessment performant tests

| Hybrid façade system | Country | Performance Assessment | | |
|---|---|---|---|---|
| | | Structural | Fire | Thermal |
| **SmartWall** | Greece | Seismic resistance | Reaction to fire test | Equivalent U-value ($U_{eq}$) – Thermal bridges – Impact of HVAC systems |
| **Denvelops Comfort Wall** | Spain | Anchoring | No need | |
| **ConExWall** | Czechia | Anchoring | No need | |

## 3.1 STRUCTURAL PERFORMANCE ASSESSMENT

FIG. 5 illustrates the European seismic hazard map displaying the ground motion expected to be reached or exceeded with a 10% probability in 50 years, according to Eurocode 8 (Eurocode 8). As indicated on the map, the Spanish and the Czech buildings are located in low-hazard areas, while the Greek building is located in a high-hazard area. For this reason, the verification of the structural performance of the SmartWall façade system in terms of seismic resistance is mandatory. So, the SmartWall that is planned to be installed in Greece is assessed using the Floor Response Spectrum (FRS) method by conducting seismic shaking table testing (Panoutsopoulou, Meimaroglou, & Mouzakis, 2023).

On the other hand, according to national legislation, ČSN EN 1998-1 for the Czech case and NSCE-02 (NSCE-02) and CTE DB-SE (CTE DB-SE) for the Spanish case, it is not necessary to conduct structural assessment of façade systems in terms of seismic resistance. The structural performance of these façade systems is investigated in terms of the mechanical properties of connections and anchoring systems, self-weight, wind and snow loads, using the Eurocode methods (Eurocode 1, Action on structures – Part 1-1: General actions – Densities, self-weight, imposed loads for buildings).

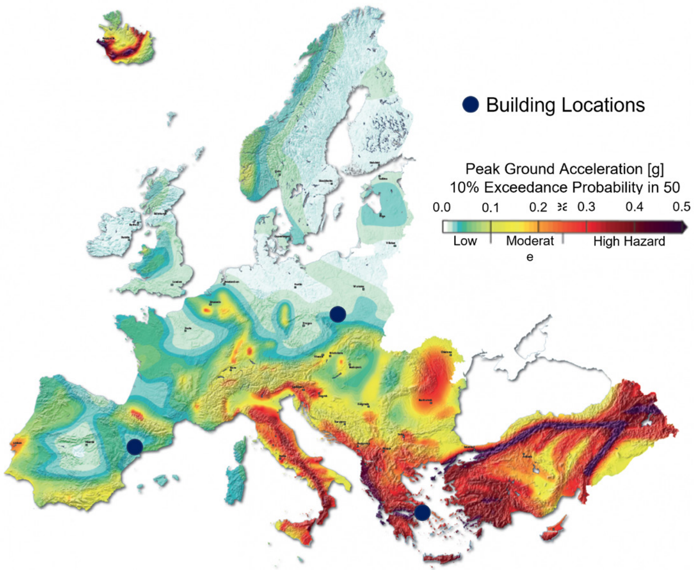


FIG. 5 The European Seismic Hazard Map (European Commission, Mapping Europe's earthquake risk, 2014).

## 3.2 FIRE PERFORMANCE ASSESSMENT

The fire requirements are also dealt with in different approaches for each case, depending on the national requirements, the incorporated materials, and their certifications. The SmartWall façade system, applied in a Greek building, is investigated by performing standard "reaction to fire" tests, following the EN 13823 standard (EN 13823:2020+A1:2022). The results of these tests are used for the classification of the innovative façade system based on EN 13501-1.

This test requires either a corner specimen or two specimens of the examined walls to be joined as a corner. The height of the tested specimen was 1.5 m, while the width was 0.5 m for the short wing and 1 m for the long wing. During the first part of the test procedure, an auxiliary burner is ignited in order to precisely calculate the fire-power level and smoke production of the burner itself. After that, the auxiliary burner is turned off, and the main burner is ignited. The main burner is located at the internal corner of the specimen, providing a steady fire-power level of 30 kW. The duration of the test is 20 minutes, and during this period, the combustion gas products (used to calculate the heat release rate), the smoke production, and the potential creation of burning droplets are measured. Based on the heat release rate, two main parameters are calculated: the fire growth rate (FIGRA), which is an indication of how fast the maximum heat release rate is achieved and the total heat release 600 s after the fire test initiation ($THR_{600s}$). Equations 4 and 5 are used to estimate the aforementioned parameters.

$$FIGRA = 1000 \times max\left(\frac{HRR_{av}(t)}{t}\right) \quad 1$$

$$THR_{600s} = \frac{\sum_0^{600}(max[HRR(t),0])}{1000} \quad 2$$

In addition, two smoke production parameters are calculated with the smoke growth rate (SMOGRA) and the total smoke production 600 s after the fire test initiation ($TSP_{600s}$), according to the following equations:

$$SMOGRA = 10000 \times max\left(\frac{SPR_{av}(t)}{t}\right) \quad 3$$

$$TSP_{600s} = \sum_0^{600}(max[SPR(t),0]) \quad 4$$

The criteria for the "reaction to fire" classification are according to the EN 13501-1: 2019 standard (EN 13501-1 : 2019). For the classification of a specimen in a certain category (heat release rate, smoke production, and droplets), both the involved parameters must be within the range; otherwise, it is classified as the worst category.

TABLE 2 EN 13501-1 Classification criteria

| | | A2/B | C | D | E | s1 | s2 | s3 | d0 | d1 | d2 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Heat release rate** | FIGRA | <120 | <250 | <750 | >750 | - | - | - | - | - | - |
| | $THR_{600s}$ | <7.5 | <15 | >15 | >15 | - | - | - | - | - | - |
| **Smoke production** | SMOGRA | - | - | - | - | <30 | <180 | >180 | - | - | - |
| | TSP | - | - | - | - | <50 | <200 | >200 | - | - | - |
| **Dropplets** | d < 10s | - | - | - | - | - | - | - | 0 | >0 | >0 |
| | d > 10s | - | - | - | - | - | - | - | 0 | 0 | >0 |

The applicable Spanish regulation CTE DB-SI (CTE DB-SI ) establishes requirements on reaction to fire and resistance to fire for external walls. As for reaction to fire, the applicable requirement (class D-s3, d0 for façades up to 10 m height) is met by the individual Denvelops Comfort Wall integrated components and their relevant certification (metallic cladding elements and substructure, mineral wool insulation, etc.). Therefore, it is unnecessary to carry out any additional investigation according to EN 13501-1. As for resistance to fire, the applicable requirement (Integrity & Insulation (EI) - 60 for the external wall as a whole) is already met by the existing wall. The addition of the Denvelops Comfort Wall system does not adversely affect the performance, except for the penetration of the ventilation pipework. In such points, the resistance to fire of the existing external wall is reinstated by the installation of an intumescent fire sealing collar. The resistance to fire performance of the intumescent collar is addressed by its product certification or, at least, by the relevant test according to EN 1366-3 and classification according to EN 13501-2. Therefore, it is unnecessary to carry out any additional test of the Denvelops Comfort Wall system or its components. Finally, the CTE DB-SI does not establish any requirement for large-scale testing for façade elements.

The ConExWall, composed of a commercial basic structure, does not include materials without fire certification (e.g. gypsum boards, insulation) or materials not classified in fire codes (e.g. wood). The ConExWall façade can be installed at an existing wall in two different ways: the basic type and the load-bearing external walls. The basic type is the installation of a façade system as an external insulation complex on an existing external wall. In this case, external walls are constructed from non-flammable materials – typical concrete, bricks, and stones. Fire regulations require load-bearing structures from materials with certain fire resistance, but the ConExWall façade is not a load-bearing structure. The ConExWall only influences fire risk areas, which limit neighbouring buildings. The dimensions of the fire risk area, calculated according to fire protection codes for each specific case, depend on specific layer composition, surface layer (e.g. plaster, wood cladding) and window dimensions. The installation of ConExWall as load-bearing external walls, placed on the uppermost floor, requires specific fire resistance. Fire resistance is achieved by using gypsum board/fiberboard plates from the interior with existing fire. The impact of the façade system on the fire risk area is individually calculated, as in the previous case.

## 3.3 THERMAL PERFORMANCE ASSESSMENT

The thermal performance analysis of the façade systems is carried out following the ISO 10211 (ISO 10211, 2017) methodology, which is a steady-state approach aiming to calculate the equivalent thermal transmittance (U-value) or equivalent thermal resistance (R-value) taking into account all incorporated thermal bridges. The presence of the frame (metal or wooden), the anchoring system, the window or the incorporated heating system into the façade systems creates non-negligible thermal bridges.

The equivalent U-value, $U_{eq}$, taking into account the impact of thermal bridges, is calculated by the equation:

$$U_{eq} = U_{clear} + \frac{\sum_k (\Psi_k \cdot l_k)}{A} + \frac{\sum_n \chi_n}{A} \qquad 5$$

Where $U_{clear}$ is the thermal transmittance without the effect of thermal bridges, calculated according to ISO 6946 standard, $\Psi_k$ expressed in [W/(m·K)] is the linear thermal transmittance of the linear thermal bridges, $l_k$ [m] is the length over the which the $\Psi_k$ value applies, $\chi_n$ expressed in [W/K] is the point thermal transmittance of the point thermal bridges and A [m$^2$] is the total surface of the façade system.

The window frame, if present in a façade panel, is assumed to be made of aluminium, with $U_f$=1.4W/(m$^2$K), while the glazing system is assumed to be double pane Argon filled with $U_g$=1.2W/(m$^2$K).

TABLE 3 Boundary conditions for the thermal performance analysis

| Boundary Condition | SmartWall | Denvelops Comfort Wall | ConExWall |
|---|---|---|---|
| Outdoor temperature | 0° C | -2° C | -15° C |
| Indoor temperature | 20° C | 22° C | 20° C |
| External heat transfer coefficient, $h_{out}$ | | 25 W/(m$^2$K) | |
| Internal heat transfer coefficient, $h_{in}$ | | 7.69 W/(m$^2$K) | |
| Temperature of medium | 28° C | 22° C | 25° C |

For the calculation of the equivalent thermal transmittance/resistance, each façade system is simulated by means of the commercial CFD package (COMSOL and ANSYS) in steady-state conditions. The boundary conditions are summarised in Table 3.

The total heat flow, Q, which passes through each façade configuration, is obtained by the simulation results. Hence, the equivalent U-value, $U_{eq}$, is calculated by the following equation:

$$U_{eq} = \frac{Q}{A(T_{in} - T_{out})} \qquad 6$$

When the HVAC system is active in heating mode, an equivalent thermal transmittance is also calculated following the methodology described in (Kisilewicz, Fedorczak-Cisak, & Barkanyi, 2019). This method takes into account the temperature of the medium fluid, but in the current study, a constant temperature for each system is assumed, as presented in Table 3.

For the geometries, which include window or glass door, the equivalent U-value is calculated by the equation:

$$U_{eq} \cdot A = U_{eq,opWall} \cdot A_{opWall} + U_{Win} \cdot A_{Win} \qquad 7$$

Where $U_{opWall}$ is the equivalent thermal transmittance of the opaque area of the façade, including the effect of all thermal bridges, $A_{opWall}$ is the opaque area of the façade panel (area without the window opening), $U_{Win}$ and $A_{win}$ are the U-value and the window area (including the glass and the frame), respectively.

# 4 RESULTS / DISCUSSION

## 4.1 SMARTWALL

### 4.1.1 Structural performance

The structural performance of the SmartWall façade system is investigated with the shaking table test, allowing for proper validation of the structural response under different earthquake tests. A real-scale steel frame structure with a brick masonry infill wall (supporting structure) fitted with SmartWall was tested at the Laboratory for Earthquake Engineering (LEE) of the National University of Athens (NTUA), using the shaking table facility. The SmartWall (FIG. 6a) was fixed to the brick wall using Z-shape steel plates (hanging brackets) at three positions through its height. Additionally, it was anchored to the brick wall with two chemical anchors at the top to ensure no vertical and in-plane movements of the module independent of the infill wall during an earthquake. Thus, the SmartWall is considered an acceleration-sensitive non-structural component, and damage could occur from inertial forces.

The Floor Response Spectrum (FRS) method is used for the analysis of the SmartWall façade. The FRS was calculated for Peak Ground Acceleration (PGA) equal to 0.36 g (highest seismic zone for Greece) and EC8 soil category B for the two horizontal directions, resulting in a 0.86 g peak floor acceleration. The vertical component spectrum was set equal to 0.80 of the horizontal ones. Compatible floor acceleration time histories were generated and used as the input motion.

The characteristic periods of the FRS were chosen to cover floor spectra for buildings with 1 to 10 storeys, and the non-structural component was assumed to be located on the upper floor (roof). This spectrum is considered the Required Floor Response Spectrum (RFRS) for the present study. The acceleration time histories used as base motion were modified from the Landers earthquake that occurred on June 28, 1992, near the town of Landers, California, in order to be compatible with the RFRS.

The specimen was subjected to triaxial ground motion time history with base acceleration increased stepwise corresponding to the different limit states to investigate the response of SmartWall. Prior to and after the execution of the shaking table tests, the dynamic properties of the specimen were measured through logarithmic sine sweep excitation along the X, Y, and Z main axes.


FIG. 6 Structural performance test of SmartWall: a) the experimental set-up and b) the anchoring system

The main conclusions that can be derived from the structural performance test:

- No visible damage is observed in steel members, brick walls, and the SmartWall panel during triaxial shaking table tests.
- For the SmartWall façade system, frequencies and corresponding damping ratios are close to the dynamic characteristics before testing in both horizontal and vertical directions.
- For the brick wall, a reduction of frequency and an increase in damping ratio is found in the X direction. This may be attributed to very light, invisible damages, such as sliding along the bed and head mortar joints, as well as sliding between the brick wall and surrounding steel frame.
- The two chemical anchors (FIG. 6b) used at the top of the SmartWall could withstand the imposed inertial forces for the tested level of base acceleration.
- The selected method of fixing the SmartWall onto the brick wall with Z-shape plates is found to be adequate for the tested level of base motion.

### 4.1.2 Fire performance

The fire performance of SmartWall is carried out by standard “reaction to fire” tests, following the EN 13823 standard (EN 13823:2020+A1:2022) , also known as Single Burning Item (SBI) test. Two different SmartWall types are examined: a) Type A, serving as a “blank type”, was a simple configuration constructed by the metal frame, gypsum plasterboards, and mineral wool (FIG. 7a) and b) Type B corresponded to a SmartWall panel with the fan coil unit (FIG. 7b).

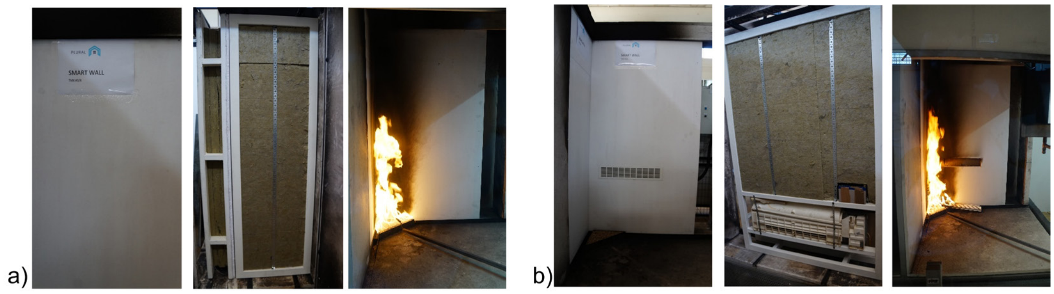


FIG. 7 The examined SmartWall samples (front side, back side and during the test): a) Type A and b) Type B.

Table 4. summarises the results of the standard EN 13823 test. Based on these results and the classification according to EN 13501 (EN 13501-1 : 2019) both the SmartWall Types are classified as B-s1, d0 and have similar behaviour as far as the test is concerned. The presence of a fan coil results in a heat release reduction of 45% in comparison with the blank type of SmartWall, while the smoke production is almost the same.

TABLE 4 EN 13823 results for the examined SmartWall types

| Parameter | SmartWall - Type A | SmartWall - Type B | Classification |
|---|---|---|---|
| **FIGRA** | 0.00 | 0.00 | B |
| **$THR_{600s}$** | 0.79 | 0.44 | B |
| **SMOGRA** | 0.00 | 0.00 | s1 |
| **TSP** | 43.34 | 44.85 | s1 |
| **d < 10s** | No | No | d0 |
| **d > 10s** | No | No | d0 |

In the frame of the fire performance tests, a number of additional thermocouples (Type K, 1.5 mm diameter) were added to the specimens in order to achieve a better understanding of their fire behaviour. The thermocouples were added at the gypsum plasterboard at the unexposed side, at heights of 100 mm, 400 mm (fan coil height for the SmartWall Type B) and 800 mm and at the metal frame at the height of 400 mm. In the SmartWall with the fan coil (Type B), an extra thermocouple was added at the centre of the fan coil unit.

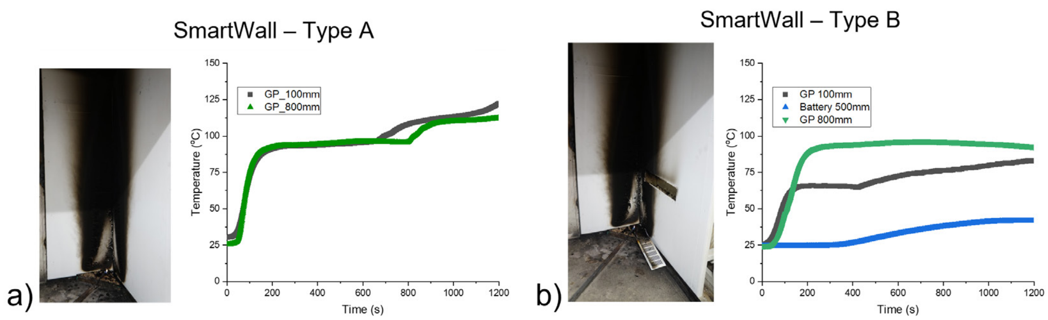


FIG. 8 The SmartWall after the test procedure and the measured temperatures for Type A (a) and Type B (b)

FIG. 8 depicts the temporal variation of the temperature at the aforementioned measuring locations. In both test cases, the temperature in the back of the specimen did not exceed 100°C. There was no major difference in the fire performance of the two specimens, judging by both the EN 13823 results and the additional thermocouples. As a result, the existence of the fan coil unit and the incorporated battery does not seem to have a significant effect on the fire performance of the specimen (the rise of the temperature at the height of 400 mm was due to a crack in the gypsum board).

### 4.1.3 Thermal performance

The thermal performance investigation of the SmartWall façade panel is carried out for the four different types of the façade system, depending on the presence of a fan coil and/or window on the façade panel (Types A - D). The thermal transmittance of the blank type SmartWall (Type A), without considering any thermal bridge, $U_{clear}$, is calculated according to ISO 6946 equal to $U_{clear}$ =0.176 W/(m$^2$K). Table 5 summarises the equivalent U-values of the whole SmartWall, including ($U_{eq}$) and excluding ($U_{eq,op}$) the window. It is observed that the presence of the metal frame increased the U-value of the opaque wall by 0.05 W/(m$^2$K), the presence of the window by a further 0.05 W/(m$^2$K) and the fan coil by a further 0.03 W/(m$^2$K).

For the types with a fan coil, two alternatives are assumed depending on the operation of the fan coil: passive and active. In passive mode, the temperature of the fan coil depends on the temperature of the adjacent materials, but in active mode, a constant temperature of ca. 25$^0$ C (low-temperature system) is assumed. When the fan coil is stopped, it acts as a thermal bridge, increasing the U-value by 43% compared with $U_{clear}$. However, when the fan coil is in operation (active), it acts as a heat source, reducing the equivalent U-value of the whole façade area by 13%. The change of the U-value depending on the operation of the incorporated fan coil seems to be significant for the overall thermal performance assessment of the system.

TABLE 5 Thermal transmittance (U-values) of all types of SmartWall, including the effect of thermal bridges

| SmartWall type | $U_{eq}$ | $U_{eq,op}$ | U-value difference | |
|---|---|---|---|---|
| | W/(m$^2$K) | W/(m$^2$K) | [W/(m$^2$K)] | [ % ] |
| **Type A** | 0.23 | 0.23 | 0.05 | +29% |
| **Type B – fan coil passive** | 0.25 | 0.25 | 0.08 | +43% |
| **Type B – fan coil active** | 0.12 | 0.12 | -0.06 | -32% |
| **Type C** | 0.46 | 0.28 | 0.10 | +58% |
| **Type D– fan coil passive** | 0.48 | 0.31 | 0.13 | +74% |
| **Type D – fan coil active** | 0.35 | 0.15 | -0.02 | -13% |

FIG. 9 illustrates the U-values for the four investigated SmartWall types, as provided by the COMSOL environment. It is obvious that the most severe thermal bridges occurred at the window and the bottom side of the metal frame. The last is due to the presence of HRS spacers at the bottom side for structural reasons instead of heat breakers. The fan coil does not create significant thermal bridges due to the use of VIP behind it, creating a relatively homogenous thermal resistance at the central part of SmartWall. All thermal bridges (window, metal frame, and fan coil) increase the opaque wall U-value by 74% (from $U_{clear}$=0.18 W/(m$^2$K) to $U_{eq}$=0.31 W/(m$^2$K)).

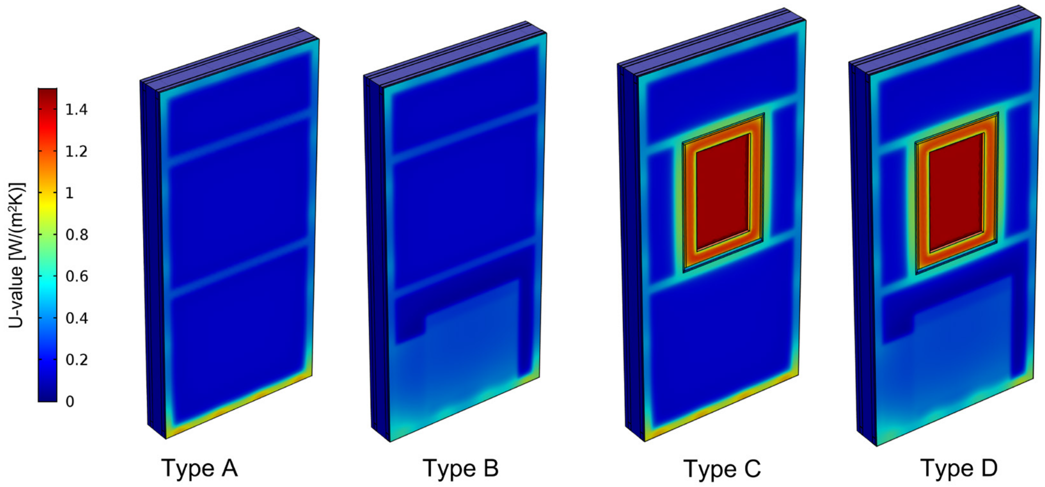


FIG. 9 U-value contour for the four types of SmartWall system in COMSOL software

## 4.2 DENVELOPS COMFORT WALL

### 4.2.1 Structural performance

The Denvelops Comfort Wall is considered, according to the Spanish Resistance Construction Standard, as an add-on constructive element and, therefore, not part of the building structure (NSCE-02). For such cladding systems, only the mechanical resistance of the connections between the add-on element and the building structure must be verified. For this reason, the present study only investigates the structural performance of the anchoring system of the Denvelops Comfort Wall for the Spanish building.

The structural performance and anchoring system analysis is carried out in accordance with Eurocodes and Spanish adjustment "Documento Básico de Seguridad Estructural" (CTE DB-SE). The structure is considered a main façade, and the loads are divided into permanent, variable, and accidental loads. Specific weights for permanent and variable loads are assumed according to Eurocode 0, while the accidental loads have not been taken into account. For the design of steel structures, the parameters and criteria described in the Eurocode 3 and the DB-SE-EA are used, assuming stainless steel 79 $kN/m^3$, for self-weights and wind load, $q_e$, for wind pressure, expressed by the equation:

$$q_e = q_b \cdot c_e \cdot c_p \qquad 8$$

where $q_b$ is the wind dynamic pressure, $c_e$ is the exposure's factor, and $c_p$ is the pressure's factor. Two possible wind pressures are investigated: at the centre of the mesh, applying the values of $c_e$=1.9 and $c_p$=0.8 ($q_{e,m}$=1.20kPa) and on the side of the mesh, applying the values of $c_e$=1.9 and $c_p$=1.2, ($q_{e,s}$=0.80kPa).

The obtained criteria for the structural performance of Denvelops Comfort Wall are summarised in Table 6.

TABLE 6 Criteria for the structural performance of Denvelops Comfort Wall

| | Criterion | Explanation |
|---|---|---|
| Cross section | When the section is subjected to an axial force, $N_{t,Rd}$, must be less than design plastic resistance, $N_{pl,Rd}$: $N_{t,Rd} \le N_{Pl,Rd} = A \cdot f_{yd}$ | $f_{yd}$: Design resistance determined by: $f_{yd} = {f_y}/{\gamma_M}$ $f_y$: Characteristic value of the particular resistance determined with characteristic or nominal values for material properties and dimensions $\gamma M$: the global partial factor for the particular resistance |
| | For sections subjected to the combination of $N_{Ed}$, $M_{y,Ed}$ and $M_{z,Ed}$ , the following criteria should be met: $\frac{N_{Ed}}{N_{Rd}} + \frac{M_{y,Ed}}{M_{y,Rdy}} + \frac{M_{zEd}}{M_{y,Rdz}} \le 1$ | $N_{Rd}$: Design value of the resistance depending on the cross-sectional classification. $M_{y,Rd}$: Design value of the resistance depending on the elastic resistance. $M_{z,Rd}$: Design values of the resistance depending on the plastic resistance. |
| | The design value of the shear force, $V_{Ed}$, at each cross section shall satisfy: $V_{y,Ed} \le V_{pl,Rd} = A_v \cdot \frac{f_{yd}}{\sqrt{3}}$ | $V_{Ed}$: Design value of the shear force $V_{pl,Rd}$: Design plastic resistance |
| Buckling | A laterally unrestrained member subject to major axis bending should be verified against lateral-torsional buckling as follow: | $M_{Ed}$: Design value of moment and $M_{b,Rd}$: Design buckling resistance moment |

The structural performance analysis of wind and load anchors was carried out by means of finite element simulation in ANSYS software. The wind anchor, consisting of two parts (FIG. 10), is the part of the mesh in which the wind strength is applied to the façade. The maximum wind force applied to the wall is 3.046 N perpendicular to the façade, applied to both parts of the anchor. The results of the analysis are presented in FIG. 10b. The maximum force applied in the load anchor is 1.334 N perpendicular and 1.512 N parallel to the façade (FIG. 11). The results of both anchors show that the von Mises tensions satisfy the criteria.

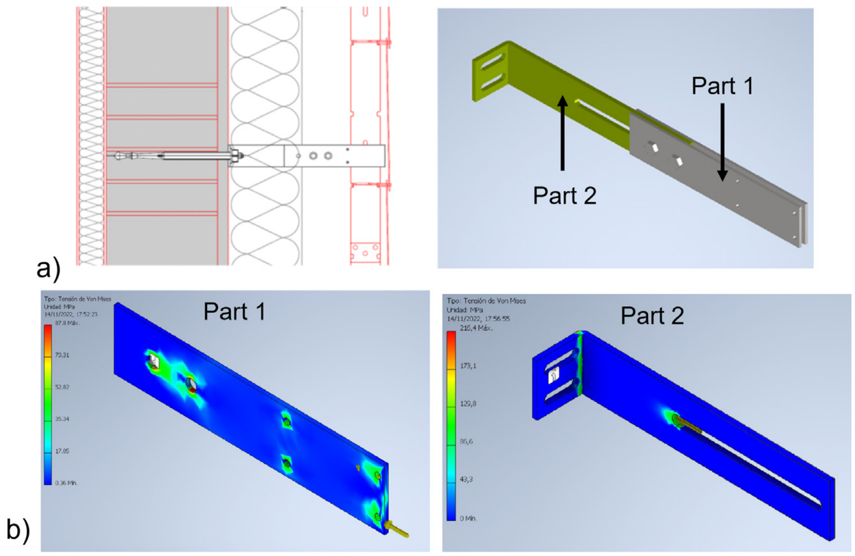


FIG. 10 The wind anchor of Denvelops Comfort Wall: a) Geometry and b) Von Mises Strength study in ANSYS software.

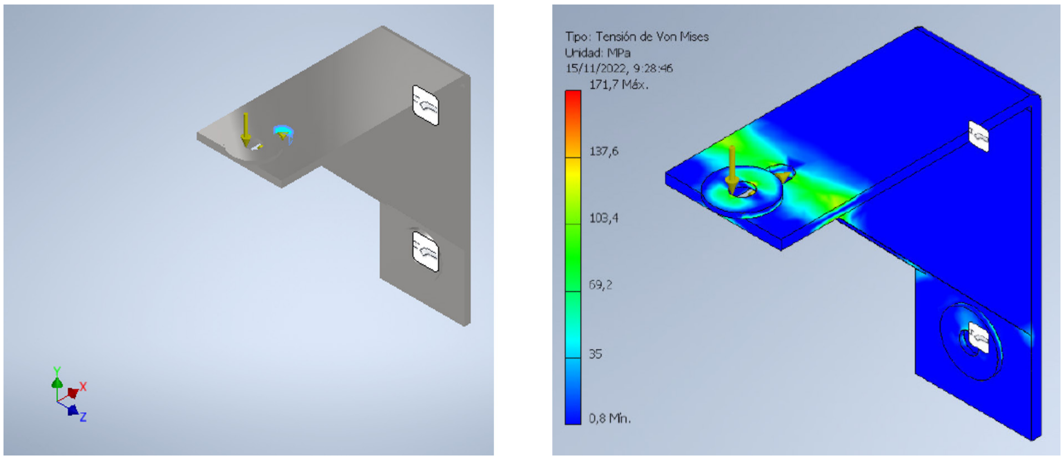


FIG. 11 The load anchor of Denvelops Comfort Wall: a) Geometry and b) Von Mises Strength study in ANSYS software.

## 4.2.2 Thermal performance

The thermal performance of the Denvelops Comfort Wall is carried out by means of the ANSYS Fluent software, following the methodology described in section 3.3. The analysis focuses on the calculation of all incorporated thermal bridges on the façade system, especially the thermal bridges created by the presence of the air handling unit (AHU). A 3D façade panel is modelled, including the different layers of the structure (wall, thermal insulation layers, closed air cavity, and the AHU). Since the Denvelops Comfort Wall is a ventilated insulation system with an air gap in front of the thermal insulation, the external cladding was not considered in the model. The AHU model is also simplified, excluding fans, control system, and heat exchangers. The geometry of the model is illustrated in FIG. 12, indicating the air handling unit and the vertical plane for the calculation of thermal bridges.

The analysis is performed for three different cases:

- For the façade panel without the AHU (reference case)
- For the façade panel with the AHU unit off
- For the façade panel with AHU in operation

The dimensions of the wall model are 2 m (width) and 2.7 m (height), while the dimensions of the AHU are 0.6 m (width) and 1.5 m (height). The simulations were performed for an interior temperature of 22°C and an exterior temperature of 2°C (Table 3). The anchoring system of the building envelope is not modelled but is taken into account in the calculation by a surcharge U-value of 0.02 W/m$^2$K. Thermal resistance in AHU channels $R_{AHU}$ is assumed to equal 0.01 (m$^2$K)/W.

Table 7 summarises the simulated results of the Denvelops Comfort Wall for the three examined cases. The results show that the façade panel with switched off AHU has a higher U-value (0.231 W/m$^2$K) by 18.5% than the façade without the AHU (0.195 W/m$^2$K), indicating the high thermal bridge created by AHU. However, when the AHU is in operation, the thermal transmittance decreases by 3.6% (0.188 W/m$^2$K) in relation to the panel without AHU due to the circulation of warmer air and creating an active insulation area.

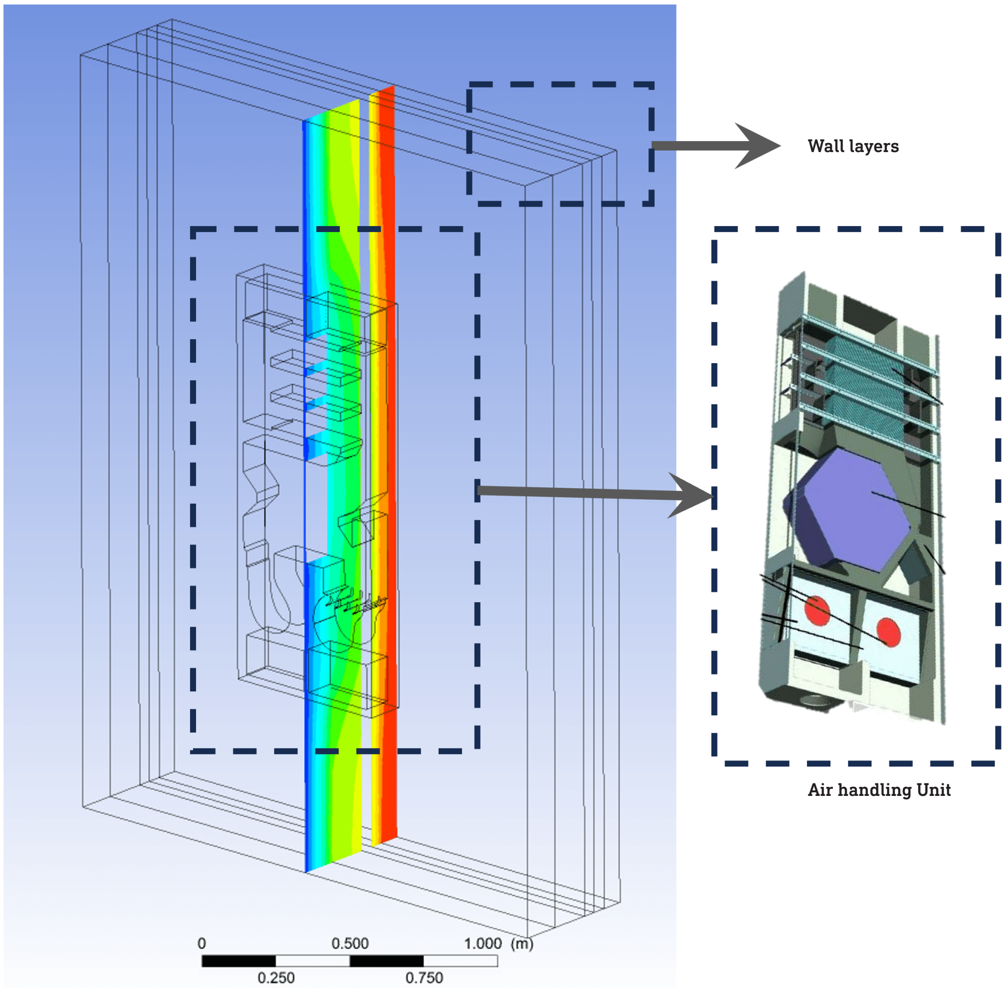


FIG. 12 Geometry of Denvelop Comfort Wall in ANSYS Fluent

TABLE 7 Equivalent thermal transmittance ($U_{eq}$) for the three cases of Denvelops Comfort Wall

| | $U_{eq}$ | Increase of U-value |
|---|---|---|
| | W/(m²K) | % |
| **Façade panel without the AHU** | 0.195 | |
| **Façade panel with AHU stopped** | 0.231 | 18.5% |
| **Façade panel with AHU in operation** | 0.188 | -3.6% |

FIG. 13 presents the temperature contour for a section of the simulated façade in the three examined cases. In the case without AHU, the total heat flux value equals 18.9 W, while the calculated U-value equals 0.175 W/m$^2$K (without anchoring system). The temperatures in the wall layers are homogenous, indicating that there is not any severe thermal bridge. The presence of AHU (when it is stopped) creates a severe thermal bridge at the middle height of the façade panel, changing the temperature homogeneity of the insulation layers. However, when the AHU is in operation, the insulation layer behind the AHU is warmer due to the air circulation and the operation of the heat exchanger.

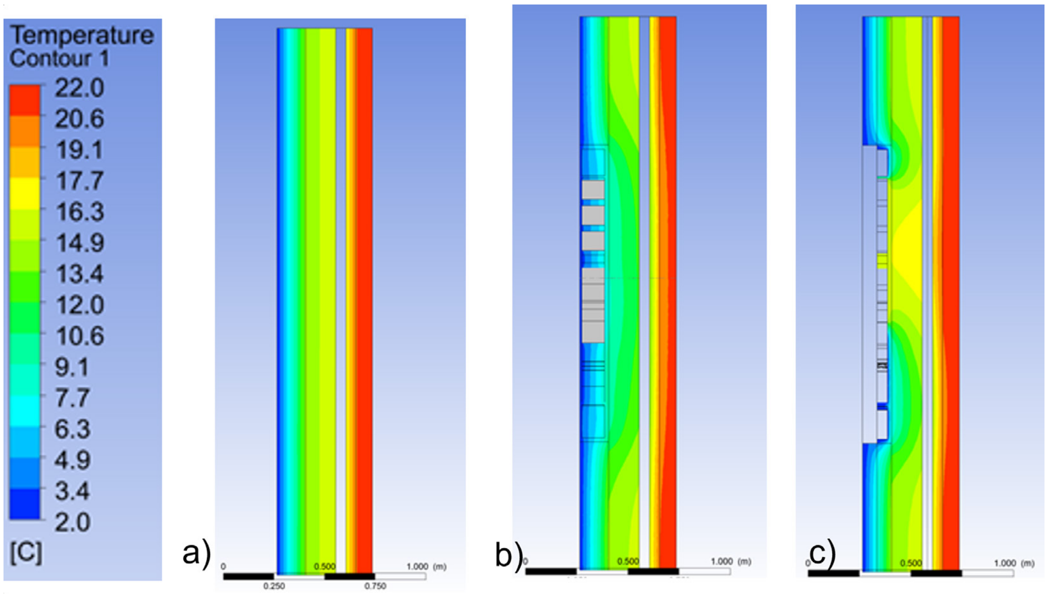


FIG. 13 Temperature contour of the Denvelops Comfort Wall for the three examined cases: a) without AHU, b) AHU stopped and c) AHU in operation

## 4.3 CONEXWALL

### 4.3.1 Structural performance

The structural performance of the ConExWall façade system is carried out by investigating the mechanical performance of the anchoring system. The ConExWall panels are anchored on the existing load-bearing walls using point steel anchors. Each anchor consists of a steel element and chemical anchors for masonry or concrete. The following basic parameters need to be taken into account for the design of panel anchors:

- The material of the main construction of panels and joints
- The material of the existing structure of the building into which it will be anchored

The ConExWall, planned to be installed in a Czech residential building, is designed as large-format wood-based panels. So, pressed structural joints of timber panel elements are structurally more advantageous than tensile joints. The existing load-bearing walls of the building are made of solid ceramic bricks, while there are sandwich walls underground (inside solid bricks and outside stones). The inner part is made of ceramic solid bricks on lime cement mortar, with a total thickness of 150-300 mm. The outer part is faced with hack-lite stone masonry (sandstone).

The general rules and the methodology for the structural performance analysis follow the standard of the Eurocodes (Eurocode 1, Action on structures – Part 1-1: General actions – Densities, self-weight, imposed loads for buildings) and Czech adjustment ČSN EN 1991-1-1, 03/2004 (incl. National Annexes – ČSN EN 1990 NA, ed.A, 02/2021). The requirements for mechanical resistance and stability take into consideration: a) the existing structures of the building, b) the anchoring of panels, and c) the panel construction. The loads are divided into permanent, variable, and accidental loads. The expected load derived from:

- self-weight of the panel: $g_k$=1.0 kN/m$^2$, $g_d$=1.350 kN/m$^2$
- wind load: for $v_{b,0}$ =25.0 m/s, $w_{e,k}$=-0.490 kN/m$^2$; $w_{e,d}$= 0,735 kN/m$^2$ (Eurocode 1, Actions on structures - Part 1-4: General actions - Wind loads)
- snow load (irrelevant for this case)
- pre-stress axial load: set by experiment: $P_{Sk}$ 0.9 kN/m$^2$, $P_{Sd}$=1.215 kN/m$^2$

The steel part of the anchor depends on the geometry of the panel. The size is chosen so that the panel can be supported, and the steel part of the anchor is designed with a large margin from a structural point of view. The anchor must be able to withstand vertical $V_{Sd}$=3.645 kN and horizontal loads (tension), $N_{Sd}$=3.316 kN. The estimated scheme of anchors is illustrated in FIG. 14, while the design values of the most loaded row of anchors are summarised in Table 8.

TABLE 8 Design values of the most loaded row of anchors in ConExWall

| Design value | Value |
|---|---|
| **Vertical loading** | $V_{Sd}$ = 3.645kN/m |
| **Horizontal load** | $N_{Sd}$ = 3,316kN/m |
| **Number of chemical anchors per meter (Fischer anchors M10)** | $N_1 = V_{Sd}/V_{Rd} + N_{Sd}/N_{Rd}$ = 7,5<br>$V_{Rd}$ = 1.00, $N_{Rd}$=0.86 |
| **Number of chemical anchors per meter (Hilti HIT-HY 270 anchors M10)** | $N_2 = V_{Sd}/V_{Rd} + N_{Sd}/N_{Rd}$ = 7.062<br>$V_{Rd}$ = 0.50, $N_{Rd}$=2.80 |

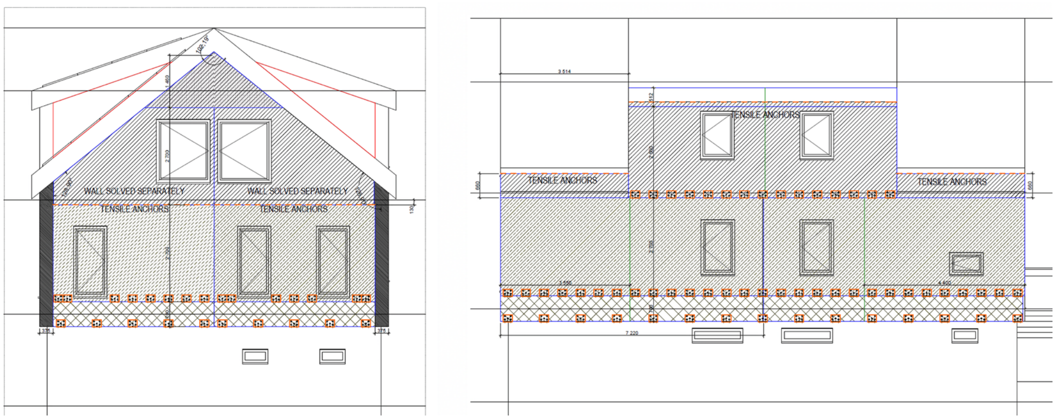


FIG. 14 The scheme of anchors for the Czech building

## 4.3.2 Thermal performance

The thermal performance of the ConExWall façade panel is investigated using COMSOL software and the methodology described in section 3.3 for a representative geometry in accordance with the panel that is planned to be installed in the Czech building. The simulated geometry (FIG. 15) has dimensions of 7.035 m length and 3.400 m height, and it is considered to be installed on the external side of an existing wall. The under-investigation façade panel contains two windows (3.95 m$^2$ area for each window) and two ventilation systems. The window frame is assumed to be wood-aluminum, with $U_f$=1.4 W/(m$^2$K), while the glazing system is assumed to be triple pane Argon filled with $U_g$=0.58 W/(m$^2$K). The thermal transmittance of the overall window is equal to $U_w$=0.74 W/(m$^2$K).

The ventilated system is assumed to be a box with a metal case and still air, without being operated. For the thermal performance analysis of ConExWall, the vapour barriers are excluded. Based on the above, the thermal transmittance of the ConExWall (for 180 mm insulation thick), without considering any thermal bridge, $U_{clear}$, is calculated according to ISO 6946 equal to $U_{clear,ConExWall}$=0.125 W/(m²K).

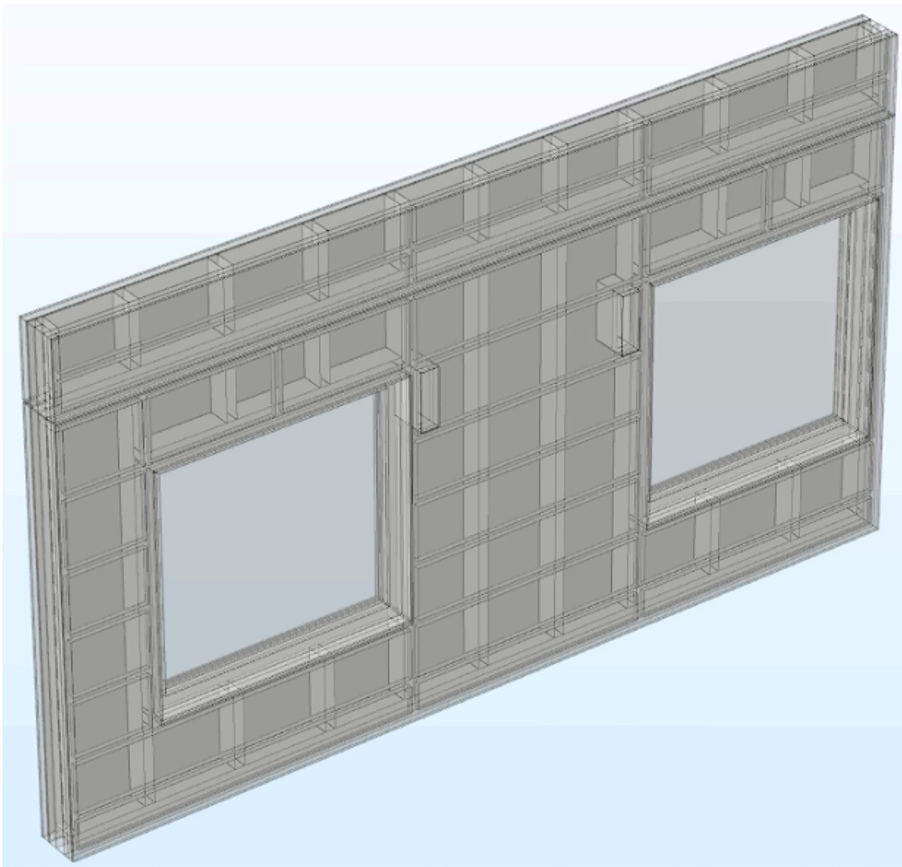

FIG. 15 The simulated geometry of ConExWall in Comsol software.

For the thermal performance analysis of ConExWall, the piping system is considered to be either in passive mode, meaning that the water temperature is changed depending on the boundary conditions, or in active mode, meaning that the water temperature is stable and around 30° C. Due to the complexity of the geometry, the heating pipes are impossible to simulate along with the whole ConExWall geometry. For this reason, the contribution of heating pipes is calculated in the layer of wood fibre board. The layer is simulated with the heating pipes, and an equivalent thermal conductivity is calculated, taking into account the effect of the water and piping system, according to the following equation:

$$k_{eq} = \frac{d_{layer}}{\frac{A \cdot (T_{in} - T_{out})}{Q} - \frac{1}{h_{in}} - \frac{1}{h_{out}}} \qquad 9$$

where $d_{layer}$ is equal to the layer of the soft heating board (20 mm), Q is the heat that penetrates the soft heating layer in [W], A is the total area of the equivalent layer in [m²], and $T_{in}$, $T_{out}$, $h_{in}$ and $h_{out}$ are the internal/external temperatures and heat transfer coefficients, respectively, according to the Table 3.

The wood fibre board (the layer that incorporates the piping system) is simulated without and with the embodied heating pipes. In the case without the piping system, the average heat flow of the layer is 58.78 W/m$^2$, while in the second case (with the piping system), the average heat flow is increased by 4.83 W/m$^2$ (Table 9). This increase can be achieved if, in the first case (layer without the heating pipes), the thermal conductivity is 0.053 W/(m·K) instead of 0.047 W/(m·K). So, the complex geometry of the wood fibre board (k=0.047 W/m·K) with the water heating pipes can be replaced by another layer with thermal conductivity equal to 0.053 W/(m·K) without heating pipes.

TABLE 9 Results of the analysis of wood fibre board with and without the piping system

| | Heat | Thermal conductivity |
|---|---|---|
| | W/m$^2$ | W/(m·K) |
| **Wood fibre board without heating pipes** | 58.75 | 0.047 |
| **Wood fibre board with heating pipes** | 63.61 | 0.053 (equivalent) |

Table 10 summarises the equivalent thermal transmittance ($U_{eq}$) of the whole ConExWall (including the window, $U_{eq,ConExWall}$) and the opaque wall (excluding the window, $U_{eq,opConExWall}$) for passive and active heating system and for two different insulation thicknesses (120 mm and 180 mm). For the passive systems, it is observed that the presence of ventilation units, anchoring systems, windows, and wooden frames almost double the U-value of the opaque wall. The wooden frame, the anchoring system, the ventilation unit, and the window further increase the U-value by 0.11 W/(m$^2$K). The increase of insulation thickness by 60 mm reduces the U-value by only 7%. When the heating system is active in heating mode, the whole wall surface acts as a heat source, resulting in a very low thermal transmittance of the opaque wall equal to 0.05 W/(m$^2$K). This value is similar to values found in the literature (Kisilewicz, Fedorczak-Cisak, & Barkanyi, 2019).

TABLE 10 Equivalent thermal transmittance of the ConExWall for two insulation thicknesses

| Insulation thickness | $U_{clear}$ | Piping heating system | $U_{eq,opConExWall}$ Excluding windows | $U_{eq,ConExWall}$ Including windows |
|---|---|---|---|---|
| mm | W/(m$^2$K) | | W/(m$^2$K) | W/(m$^2$K) |
| **120** | 0.153 | Passive | 0.27 | 0.40 |
| | | Active | 0.05 | 0.24 |
| **180** | 0.125 | Passive | 0.25 | 0.38 |
| | | Active | 0.05 | 0.23 |

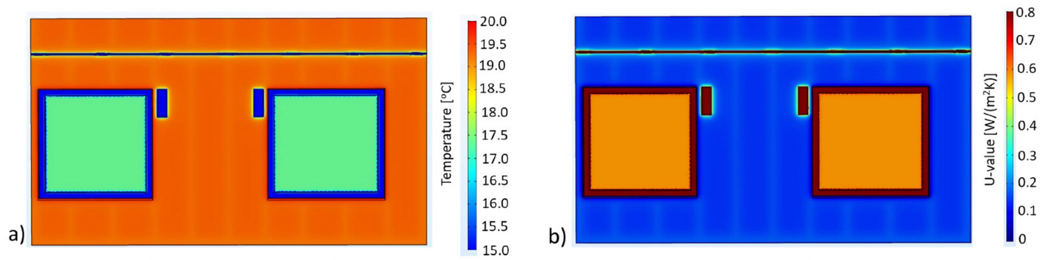


FIG. 16 Temperature and U-value contour of the simulated geometry at the internal side

FIG. 16 presents the temperature and the U-value contours of the internal side (the surface contacting the existing wall) of the ConExWall façade panel for 180 mm insulation thickness in the case that the heating system is passive mode. Except for the window area, whose U-value is much higher than the opaque wall, the ventilation units and the air gap in the height of the anchoring system (L-profiles) create significant thermal bridges providing temperatures lower than 15°C.

## 5 CONCLUSIONS

This study presents a holistic assessment of three innovative hybrid prefabricated façade systems (SmartWall, Denvelops Comfort Wall, and ConExWall) in terms of structural, fire, and thermal performance. These systems, developed in the frame of the PLURAL project, are planned to be installed in existing residential buildings in three countries (Greece, Spain, and the Czech Republic). The methodology applied for the investigation of their assessment takes into account the European and national codes that must be met for the implementation of the façade systems as a deep renovation solution in the proposed existing buildings. The structural performance of the façade system that will be installed in a building in Greece was assessed in terms of its seismic resistance due to the high-risk seismic location, while the other systems are not required to be stimulated in such seismic tests. The study presented a part of the pathway that must be followed for the certification of such façade systems for the renovation of existing buildings in order to penetrate the market, highlighting the importance of being in line with the Construction Products Regulation (CPR).

The special challenge of the three hybrid façade systems is that they incorporate HVAC systems: fan coil for the SmartWall, air handling unit for the Denvelops Comfort Wall, and heating piping system for the ConExWall. This study investigates their thermal performance, calculating the equivalent thermal transmittance using the most accurate method (ISO 10211) both in the case where their systems are stopped (passive mode) and in operation (active mode). The results showed that in passive mode, the presence of these systems creates significant thermal bridges, but in active mode, part of the wall or even the whole wall acts as a heat source, drastically reducing the equivalent wall thermal transmittance.

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