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INNOVATION AND EXPERIMENTATION OF ADAPTIVE MODEL FOR CURTAIN WALL

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Abstract. The entire construction sector is the protagonist, in recent years, of continuous research in terms of innovation of strategies and technical solutions leading to the progressive modification in the structure of the systems that make up the building envelopes, also to cope with climate change. Working on the envelopes today means, in fact, correctly adapting their performance reactions to dynamic climatic conditions. In this scenario, lies the current research, whose goal is the development of an adaptive model, using innovative materials based on the biomimetic approach, which can be applied to curtain wall systems. The investigation conducted through experimental evaluations in the laboratory, the TCLab testing section of the BFL of the Mediterranea University of Reggio Calabria, will provide the formulation of solutions to achieve an adaptive envelope that improves overall performance through new technological strategies. The methodological approach has been prepared on sequential phases, organized in thematic sections, related to a study phase and another application phase, which constituted a real added value to the research, realizing actions of applied experimentation with high-reliability results.

Keywords: Climate change, building envelope, testing.

1. Introduction

The current environmental and energy issues that affect the scenario of this time, accentuated by the effects of climate change, such as global warming [1] and the increase in CO_2 emissions, highlight the pressing need to define concrete and measurable responses, moving from a phase considered transitional to one of transformation of the built environment. From many sides of the contemporary cultural debate, it is clear how this urgency causes an acceleration towards a transformative systemic change, with consequences beyond reach. According to the latest report of Working Group 1 of the IPCC, Climate Change 2021 – The Physical and Scientific Basis [2], on average over the next twenty years, the global temperature is expected to reach or exceed 1.5 °C of warming, of which human activities are responsible for about 1.1 °C of warming compared to the period 1850–1900. The construction industry is involved in this process and it is called to define new processes and application methods that can read the dynamic responses of the built environment. Today, building envelopes are understood as a pivotal element of the construction, defining the performance quality and the regulation of internal conditions independently of transient external ones. At the same time, it is becoming increasingly clear that climate change requires a substantial change in approaches to building design to make urban systems more adaptive to climate change. In particular, buildings face the greatest risk of damage caused by the expected impacts of climate change including more frequent strong wind, increased heat, especially in cities (Urban Heat Island effect), floods, and fires that accompany certain extreme weather events. In recent years, the climatic conditions of the Mediterranean areas are characterized by rising temperatures, water bombs, micro-typhoons increasingly frequent and known as Medcane (cyclones formed in the Mediterranean), becoming the new quality requirements that building envelopes must certify. The evolution of construction processes and the use of advanced technologies to raise the performance qualities of buildings have enabled the creation of building envelopes that interact with the external environment and adapt to specific climatic conditions. In view of the above, it follows the importance of the new adaptive functioning of the envelope in the responses to stress phenomena, to limit the impacts and stress conditions on the built environment. Therefore, an envelope can adapt to different needs as a dynamic epidermal layer, emulating from nature the adaptive response strategies [3]. The multidisciplinary approach (inherent in the adaptive requirement of building envelopes), known as Biomimetic, is inspired by the forms present in nature and the mechanisms that govern it to apply them to design solutions and experiments, contributing to an increase in the performance offered to buildings today [4]. Biological systems are seen as the result of complex procedures of refinement and improvement that are proposed to the culture of the project through strategies and design solutions from which to draw inspiration. The research carried out in this field is characterized by a strong scientific component and an interdisciplinary approach [5].

The contribution is placed in this scenario and is related to research in progress, financed by funds POR Calabria FESR/FSE 2014-2020 (Axis 12, Action 10.5.6), with the ultimate aim of addressing a design methodology related to the concept of adaptivity of the building envelope. The research activities aim at defining scenarios/models for simulation and application experimentation; the objective is the development of an adaptive model for curtain wall systems through innovative materials, elements, and components based on the biomimetic approach. Recent applications of curtain walling in the building sector show that these technologies are favoured by architects and system manufacturers, especially for tall buildings, due to their advantages in terms of ease of construction, lightweight, weather tightness, quality of detailing, and thermal performance. These systems allow easy processing through mass production and pre-assembly of individual façade units [6]. The deductive methodological approach of the research allows to structure the investigation work by sequential and iterative moments: passing from a study and design phase to finally reach the application phase of implementation and subsequent testing of the adaptive model, through testing activities at the TCLab section of the Building Future Lab[1] (BFL) of the Mediterranea University of Reggio Calabria. The instruments and machines of the TCLab Section reproduce on mock-up, extreme climatic stresses to study the performance responses and to measure their resilient characteristics. In this paper, the authors present parts of the research results, in which a necessary step was the recognition of adaptive materials of biomimetic approach for the development of the adaptive model and the testing of the dynamic behaviour of two curtain walls for future application.

2. Biomimetic approach for adaptive model

The interest in understanding the behaviours of nature as well as the ability to adapt a species within a given ecosystem, become the necessary prerequisite for interventions capable of maintaining a balance between the ability to react, which opposes the change, and the ability to maintain functionality after the change. For this reason, it is useful to adopt biomimetic concepts in architecture, as it allows to identify direct solutions and strategies that respond to external stresses organically and passively. Most organisms have evolved morphological, physiological, and behavioural adaptations to survive in their habitats. For example, plants exchange water vapour to decrease their internal temperature internal temperatures during hot periods through their stomata [7]. In line with these assumptions, the research wants to investigate the complex concept of adaptivity of biomimetic matrix of building envelopes, leading to the creation of a model that can be used as a serial component for curtain wall systems and aimed at achieving high-performance standards. From a review of the state of the art, it highlights how adaptive materials can be divided into two macro-categories: those whose variability is linked to the intrinsic properties of the material of which they are made and those whose variability is linked to the variability of the shape and configuration, using sensors and handling mechanisms classifiable in pneumatic actuators, hydraulic actuators, and drives based on electric motors. These devices can read external variations and send commands to allow parts of the structure to be moved without adversely affecting the stability of the entire building [8]. The study activities focused on the first macro-category, to identify systems that can respond to external stresses, such as rising temperatures and the resulting heat island effect. Within this category, belong Electro-Active Polymers (EAP), whose molecular compositions control and produce performance at the level of the material's shape capable of stretching, bending or folding, depending on the environmental stimulus, without the need for complex electromechanical systems or energy supply [9]. The dynamic behaviour of electroactive polymers is activated when an electric current, the stimulus, flows through the laminate, increasing the electrostatic forces that generate a contraction of the elastomer. An example of the application of this material is *Homeostatic Facade* in New York, a glass façade system that self-regulates itself based on light and temperature variations. Both sides of the dielectric material are coated with silver electrodes: this layer reflects light and also distributes the electric charge through the material, causing it to deform. When environmental conditions change, the charge in the silver layer causes movement using a sensitive actuator, which is created by wrapping the dielectric material around a flexible polymer core. The increased charge causes the elastomer to expand, bending the core and pulling the elastomer material to one side. The effect is that the facade closes, with the opaque construction blocking the light [10]. Another application of Electro-Active Polymers can be found in the *Media TIC Building* in Barcelona. EAP strips help to operate and regulate the outer façade, consisting of ETFE cushions. Protection from external heat is achieved by using the so-called "diaphragm" configuration of the ETFE cladding, whereby three layers of plastic are fixed inside the triangular frame and inflated like a cushion. The resulting bubble contains up to three air chambers that together create a shadow effect and provide thermal insulation for the building [11].

However, the biomimetic projects are linked to individual cases of architectural design, with large-scale limitations of innovative envelope systems contribut-

[1] Large infrastructure of advanced testing, which bases its activities on a set of standardised and experimental tests (UNI-EN, ASTM, AAMA), having as its object the envelope in its technological and material assets. Source: `https://www.unirc.it/ricerca/laboratori.php?lab=69`

ing significantly to climate change control. Indeed, the technologies currently on the market are scarcely applicable or used only in buildings of particular use or of size or value such as to justify the adoption and the cost of those systems [12]. In addition, there are gaps of knowledge in terms of market share of adaptive facades, including the main concepts, technologies plus more promising technologies, their categorization, their best use, and the distinction between short-term and long-term structural trends of adaptive facades [13].

This activity was necessary for the acquisition of knowledge about innovation and experimentation of materials and the identification of the most congruent material of the adaptive model. The direct impact that is examined in this research concerns the solar radiation reflected directly from the surface of the curtain walls towards the urban microclimate. An adaptive improvement of the facade could, therefore, reduce the environmental temperature and the impact of the building and, consequently, decrease the magnitude of the phenomenon. Given the complex characteristics of innovation, unified testing protocols also require new methods and equipment capable of offering investigation spectra in line with the aspects traced by innovation [14] to test the levels of adaptability of the model by performing simulations of climatic conditions in the urban environment and the effects related to them.

3. Methodology and instruments

In accordance with the illustrated scenario, the research and its activities are organized in theoretical-operational sections: from the identification and study of advanced technologies and materials for the adaptive management of curtain walls to an idea of a model and the verification of its technical feasibility, through laboratory experimentation. The first phase relates to the in-depth analysis of the movement and variability systems of the closing-opening system, the study of innovative materials, the analysis of project technologies already underway, the investigation of process innovation and industrial production, the performance aspects and quality controls necessary both to assess the critical nodes of the state of the art and to propose new solutions for the architectural integration of adaptive components.

The aim is to define the modalities of possible transfers of adaptivity of biomimetic origin to curtain wall systems, through the use of Electro-Active Polymers. We would like to underline how the complexity of the factors underlying the development of a component in the construction sector is also characterized by long testing times and trials in specialized laboratories, in order to test the real conditions of use, so it often happens that new materials are used but born from other industrial sectors and already tested in other production contexts [15]. According to the subsequent steps, the focus is on the performance of the curtain walls compared to extreme events, choosing representative mock-ups to be tested (provided by partner companies of the laboratory for experimental purposes). The comparison and overlapping of the results obtained from laboratory tests on continuous facade systems, without and with the adaptive model have the ultimate aim of developing and updating test protocols, both for subsequent experimental activities and for regulatory certifications. The testing phase starts thanks to the support of the TCLab section, with the possibility of simulating the climatic conditions in urban environments and the effects related to them in order to test the levels of adaptability of the model applied on mock-continuous facade up. For this reason, compared to the phenomena of climate change in the Mediterranean area to be examined, the following procedure has been identified for the experimental activities:

- **heatwave**: the experiment is carried out by reproducing a flow of wind, through a fan AAMA/ASTM, able to verify the performance behavior of the materials of the outer facade of the mock-up under high pressure and in accordance with ASTM E 283-04 (2012);
- **pluvial flooding**: the experiment is carried out by reproducing a constant rain directly on the outside of the mock-up, through a sprinkler system, compared to three water jet simulations, through a sprinkler network with calibrated nozzles: in the absence of wind, wind and extreme wind conditions (hurricane power) and following ASTM E 331-00 (2009), AAMA 501.1-05-00 (2007) and ASTM E 330-02 (2010).

The advances produced in these first phases of study, represent the bases for the successive activities of development of the model, of experimentation and simulation from life, through the use of the machinery and the equipment[2] of the section TCLab [16]: a "Chamber of Test" (Test Lab, $15 \times 12 \times 4$ m) and a Climatic Simulation "Cell" for indoor and outdoor accelerated tests (Test Cell, 360 somebody/Lat/β). The test chamber, the Test Lab used for the experimental phase, consists of a steel frame structure $17 \times 12 \times 4.50$ m, closed on three sides, while the fourth side is open to ensure the assembly of mock-ups in scale 1 : 1, of curtain walls (defined by EN 13830:2015 – Curtain Walling), or similar elements, to be tested according to standardized test procedures. The Test Lab consists of an AAV system (air, water and wind, pressure-depression), a thermal chamber (dimensions $7 \times 5 \times 1.50$ m), seismic and mobile beams, for the performance of displacement tests and elastic

[2]Other instruments to support large equipment: UNI fan ($\sim$ 60 km/h), AAMA / ASTM fan ($\gtrsim$ 190 km/h), Fan pressure (+ and -) 6 000 Pa, Mobile sprinkler grid for watertightness tests, 8 Beams for seismic tests of non-structural elements (2 Seismic Beams on x-y-z axes + 6 Mobile Beams), in addition to the normal tests involving the standard "facade-building" connection.

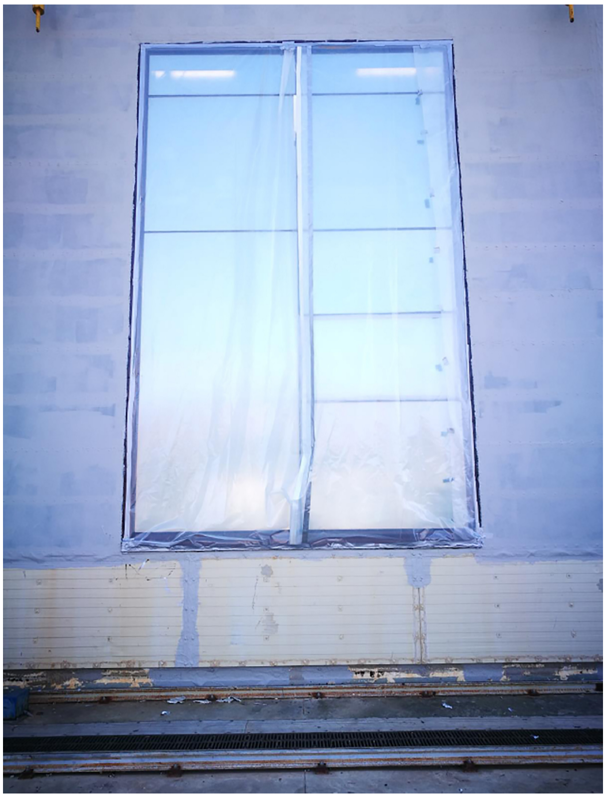

Figure 1. Air permeability test on mock-up 01.

balances. It is also equipped with 50 lasers for measuring front deflections during wind load tests and a sprinkler system (subject to international patent) which aims to generate a uniform film of water on the surface of the specimen with sprays of different intensities, according to the flow rates required by the UNI and ASTM regulations. The Test Cell is a structure for the thermodynamic characterization of building envelope systems in full scale and is equipped with a Hot-Heat flow evaluation box [17]. To carry out the partial results obtained, the first experimental activities are described in the following section.

3.1. The experimental actions of testing

According to the "Report on the Italian Building Envelope Market", the building envelope component production sector, despite the economic downturn, is aiming towards an increasingly advanced innovation that aims at the production of components resulting from modelling, testing, and improved feedback, increasingly configuring the "new role of the envelope" [18]. The instrumental and operational opportunity of the research, in its different scientific implications, is realized in the strategic possibility to support the prediction of the expected results – or to better calibrate the adaptive configuration of the model – through particular conditions able to read in advance future outcomes, thus enriching the process of a new ability to control the performance dynamics. Following the objectives of the research, we wish to refer to the routines of the experiments carried out

Figure 2. Air permeability test on mock-up 02.

in the laboratory in a simulated regime. We report the experimental activities carried out on 2 mock-ups of curtain walls without the adaptive model, to verify the performance behavior to the phenomena of heatwaves and pluvial flooding. This activity was necessary to orientate the technological solutions for the development of the adaptive model.

The mock-up of façade 01, consisting of aluminum mullions and transoms (stick wall system) with one opening to the outside, is by the Aluk Group, instead of the mock-up of façade 02, consisting of aluminum mullions and transoms (stick wall system) with a curved corner and three opening windows (one window and two doors), including a balcony (not considered for the overall performance of the façade system), is by Glasbilt LLC. In accordance with the test protocols and for these types of façade, the following test methods were planned and carried out:

- Air permeability, ASTM E 283-04 (2012), consists of the application of incremental and decremental, positive or negative (6.24 psf, 300 pascal) pressure steps, with airflow measurements at each test pressure, to determine the air permeability of curtain walls, both fixed and opening portions expressed in (m^3/h). The test is divided into three different phases: measurement of the air permeability of the test chamber, measurement of the permeability of fixed sample and test chamber joints and measurement of the overall of the sample and test chamber (Figures 1, 2);
- Watertightness performance under static pressure was performed in accordance with ASTM E 331-00 (2009) by applying a constant flow of water to the exterior façade and exposed edges simultaneously with a uniform static pressure of 15 lbf/ft^2 (pounds per square foot), 720 Pa for a time equal to 15 minutes (Figure 3]);
- Watertightness performance under dynamic conditions was performed in accordance with AAMA 501.1-05-00 (2007), by applying a dynamic pressure

FIGURE 3. Watertightness performance under static pressure on mock-up 01.

FIGURE 4. Hurricane test on mock-up 02.

of $31.5\,\mathrm{lbf/ft^2}$ (pounds per square foot), 1508 Pa and an amount of water equal to 5 U.S. gallons per square foot in an hour ($= 3.4\,\mathrm{l/min\,m^2}$) to the specimens for 15 minutes through a series of nozzles placed on bars placed horizontally and at a normed distance from the exterior face of the specimens (Figure 4);

- Structural performance was performed in accordance with ASTM E 330-02 (2010), applying positive and negative test pressures of 50 % and 100 % of the design wind load, for which measurements and checks are made to verify that, under these effects, the two specimens exhibit allowable deformation and retain their stability characteristics.

After conducting the tests, a synthetic comparison framework was developed to highlight the potentialities and criticalities of the technological system of the mock-ups. In summary, no disadvantageous behaviour was identified, to the simulation of the heatwaves and pluvial flooding in the absence of wind, revealing a positive and flexible response behaviour of the facades.

The results of the air infiltration tests for mock-up 01 (Table 1), and mock-up 02 (Table 2) are reported.

It should be noted that the acceptance limit for fixed modules is $0.06\,\mathrm{cfm} \times \mathrm{ft}^2$ and the acceptance limit for the openable module is $0.10\,\mathrm{cfm} \times \mathrm{ft}^2$.

Test is validated for positive pressure values of fixed modules with the value $0.0116\,\mathrm{cfm} \times \mathrm{ft}^2 < 0{,}06\,\mathrm{cfm} \times \mathrm{ft}^2$ and openable modules with the value $0{,}0121\,\mathrm{cfm} \times \mathrm{ft}^2 < 0{,}10\,\mathrm{cfm} \times \mathrm{ft}^2$. Test is validated for negative pressure values of fixed modules with the value $0{,}0211\,\mathrm{cfm} \times \mathrm{ft}^2 < 0{,}06\,\mathrm{cfm} \times \mathrm{ft}^2$ and openable modules with the value $0{,}0442\,\mathrm{cfm} \times \mathrm{ft}^2 < 0{,}10\,\mathrm{cfm} \times \mathrm{ft}^2$.

It should be noted that the acceptance limit for fixed modules is $0.1 \times \mathrm{ft}^2$ and the acceptance limit for the openable module is $0.30 \times \mathrm{ft}^2$. Test is validated for positive pressure values of fixed modules with the value $0.028 \times \mathrm{ft}^2 < 0.1 \times \mathrm{ft}^2$, openable modules (n.1 window) with the value $0.03 \times \mathrm{ft}^2 < 0.30 \times \mathrm{ft}^2$ and openable modules (n.2 doors) with the value $0.0095 \times \mathrm{ft}^2 < 0.30 \times \mathrm{ft}^2$.

Test is validated for negative pressure values of fixed modules with the value $0.008 \times \mathrm{ft}^2 < 0.1 \times \mathrm{ft}^2$, openable modules (n.1 window) with the value $0.12 \times \mathrm{ft}^2 < 0.30 \times \mathrm{ft}^2$ and openable modules (n.2 doors) with the value $0.098 \times \mathrm{ft}^2 < 0.30 \times \mathrm{ft}^2$. Although the tests are considered successful, it is pointed out that a slight wind pressure on the façade can change the façade behaviour. Therefore, as an adaptation strategy for curtain wall systems, it is necessary to develop adaptive models as components to be applied in the façade to increase the performance quality to external phenomena and stresses.

4. Conclusion

The research has concentrated its efforts on the assumption that the current curtain walls guarantee

	Positive pressure	**Negative pressure**
Air infiltration of facada	3.7 mc/h (0.01 cfm × ft^2)	6.7 mc/h (0.02 cfm × ft^2)
Air infiltration of openable	0.3 mc/h (0.01 cfm × ft^2)	1.1 mc/h (0.04 cfm × ft^2)
Max value of facada	19.07 mc/h (0.06 cfm × ft^2)	19.07 mc/h (0.06 cfm × ft^2)
Max value of openable	2.4 mc/h (0.10 cfm × ft^2)	2.4 mc/h (0.10 cfm × ft^2)

Table 1. Air infiltration test for the mock-up 01 in positive and negative pressure.

	Positive pressure	**Negative pressure**
Air infiltration of facada	8.47 mc/h (0.028 × ft^2)	2.23 mc/h (0.008 × ft^2)
Air infiltration of openable (n.1 window)	0.41 mc/h (0.03 × ft^2)	1.53 mc/h (0.12 × ft^2)
Air infiltration of openable (n.2 doors)	0.29 mc/h (0.0095 × ft^2)	3.06 mc/h (0.098 × ft^2)
Max value of facada	50.00 mc/h (0.06 × ft^2)	50.00 mc/h (0.1 × ft^2)
Max value of openable n.1	6.4 mc/h (0.3 × ft^2)	6.4 mc/h (0.3 × ft^2)
Max value of openable n.2	15.9 mc/h (0.3 × ft^2)	15.9 mc/h (0.3 × ft^2)

Table 2. Air infiltration test for the mock-up 02 in positive and negative pressure.

constant performance thresholds calibrated to the average values required by the regulations, resulting in envelopes that have the same performance even in different contextual conditions. Therefore, this research, even if still in progress, is oriented towards the design of the optimal combination of the adaptive model, through the use of electro-polymer materials aiming at the most appropriate adaptive efficiency, calibrated to specific environmental contexts. The theme intended to fit into the context of studies conducted on the new dynamic performance of the architectural envelope, which is offered not only by mechanical elements or typological, stratigraphic, and material passivity but above all by the panorama of biomimetic strategies. Incorporating these principles into the prototyping of the adaptive model, to be applied and experimented on the mock-ups studied, becomes an essential activity for an architecture that intends to follow the laws that regulate vital processes and cycles. From this point of view, the prototype to be developed represents the physical element of mediation between the external and internal environment, capable of regulating and reacting to the signals that qualify the external environment, contributing to becoming an element of transformation and control. It can be affirmed that the activities and prospects of research and experimentation, can outline concrete solutions, at a theoretical and operational level, referring to the current and future challenges, moving towards an increasingly controlled vision in the relationship between innovation and architectural design.

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