TESTING AND EXPERIMENTATION ON BUILDING ENVELOPE UNDER CLIMATE CHANGE

Martino Milardi[1]
Mariateresa Mandaglio[1]
Evelyn Grillo[1]
Caterina C. Musarella[1]
Sara Sansotta[1]
Nadia Tramonti[1]
Corrado Trombetta[1]

1 University Mediterranea of Reggio Calabria | Italy
Corresponding author: mmilardi@unirc.it

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Abstract

In recent decades, the results of Climate Change effects, such as global warming and the increase in CO_2 emissions, have played an increasingly important role in defining concrete and measurable responses in the transformation of the built environment. The Copernicus Climate Change Service (C3S) report notes that, globally, 2020 was the hottest year on record, along with 2016, even though carbon dioxide emissions from fossil fuels were 7% lower than in 2019. As a result, CO_2 concentration levels reached a record high (413.1 ppm), despite a lower growth rate and compared to 2019. Understanding the interrelationships between these impacts and the built environment drives researchers and the various players in the construction sector to develop innovative technological solutions that raise the quality levels of Building Envelopes. It should be noted that the Building Envelope has radically changed the way stakeholders approach building design, becoming a pivotal element of construction that not only defines performance quality but regulates internal conditions independently of transient external ones. The focus is on the adaptive aspect of the Building Envelope, the operation of which is now delegated to technological control and performance response systems that can manage the complexity of energy flows involved in these relationships. The paper, presented here, is in this context and relates to experimental research, which addresses a design methodology for Building Envelopes, able to react to different contextual conditions according to adaptive dynamics to raise environmental and performance quality. The main goal of the research lies in overcoming the consolidated actions, both theoretical and operational, that underlie the "building-context relationship" through new methods of investigation to measure the effects of microclimatic phenomena on buildings in the Mediterranean area and, where possible, verify the outcomes of their biunivocal relationship. This is made possible through: the development of reliable phenomenological case histories under Climate Change in the Mediterranean environment; new models of urban settings that can be related to microclimatic phenomena; and sets of robust indicators useful for surveying the elements that establish synergies of climate change, both produced and "suffered". In recent years, the Mediterranean areas' climatic conditions, characterised by islands and heat waves, extreme rainfall phenomena such as water bombs, and increasingly frequent micro-typhoons, represent a critical point in the Building Envelope, becoming a specific field of application for research activities. This scenario also reveals that, as the complexity of the envelope increases, there is a need to devise innovative envelopes with 'high fluid-dynamic performance'. However, the behaviour of which is linked to the contextual variables with which it is related often escapes the expected qualities because these have been 'designed' but not tested in a simulated regime. Based on these assumptions, the experimental phases of the research were developed, having the opportunity to have an advanced Testing Laboratory, the TCLab Section of the Building Future Lab (BFL) of the Mediterranea University of Reggio Calabria. The combination of machinery and equipment allows the actual performance responses of Building Envelopes to extreme events to be tested according to standardized protocols. Specifically, the behaviour of a façade system was analysed to evaluate its performance regarding air permeability, water tightness under static pressure, and water tightness under real dynamic conditions. From the analyses carried out, the results took the form of test and retrieval protocols which represented real added value to the research, giving concrete form to applied experimentation actions with highly reliable results.

1.1 INTRODUCTION

In recent decades, environmental and energy issues, now accentuated by climate change and global warming [1], have been the main focus of researchers and the various players in the construction sector, including businesses, companies and various stakeholders, to help provide concrete and replicable answers in the construction of increasingly high-performance Building Envelopes. The buildings' role in addressing the consequences of climate change and the energy deficit is becoming increasingly important due to their share in the overall amount of greenhouse gas emissions and the rapid increase in national energy consumption worldwide. According to scientific research that bases its results on real simulations, the change in global surface temperature between 1850 and the end of the 21st century is expected to exceed 1.5 °C. The World Meteorological Organization WMO states that temperatures could rise by 3-5 °C by the end of this century if the current warming trend continues. Thus, limiting warming to 1.5°C [2] above pre-industrial levels would require transformative systemic change integrated with sustainable development. Because of this, the need for a renewed design has now become apparent, highlighting the need to implement new processes and application methods that can read the responses of built systems "dynamically", analysing, on the one hand, the qualitative variations of the components, and on the other, indicating the different levels of risk and vulnerability. The current state of the art on the different dynamics of climate change in the urban environment indicates, in an increasingly rigorous way, that it not only suffers the effects (even catastrophic) but, at the same time, the built environment and buildings. In particular, are themselves the cause - or at least synergistic concomitant - of these changes. It is important to emphasise how the various effects of climate change, classified and grouped into phenomenal categories with clear meanings, such as heatwaves, water bombs, extratropical cyclones and tornadoes, including the so-called Medicanes (cyclones formed in the Mediterranean Sea) [3], unequivocally trace their influence on the systemic behaviour of cities. In particular, buildings face the most significant risks from these phenomena. It is increasingly evident that the Envelope plays a central role in responding to the growing criticality of the environment. The study, presented here, refers to experimental research, whose ultimate goal is to address a design methodology for Building Envelopes, able to react and manage the different contextual conditions, in the Mediterranean area, according to adaptive dynamics to raise the environmental and performance quality. The research, therefore, aims to investigate the issues related to the concept of adaptability of the Building Envelope, in which each layer contributes to satisfying different thermal, visual and acoustic aspects according to internal requirements to be verified and external climatic conditions that are constantly changing.

1.2 BACKGROUND

It seems well established that strong innovations in strategies and techniques are required to raise the quality performance of Building Envelopes in the face of environmental risks due to climate change. This approach has led to a systematic review of design approaches, moving performance issues away from the traditional physical and static properties of Building Envelopes to a broader discussion of how they really perform. An Envelope, or more precisely the skin of the building (without any distinction between vertical surfaces - walls - and horizontal surfaces - roofs), should be designed by adopting those technological strategies necessary to anticipate external environmental variations and able to regulate the behaviour avoiding harmful outcomes, with the lowest energy consumption. For this reason, innovative concepts such as Adaptive Building Façades could play a role in the near future, as their dynamic behaviour could optimise the performance of a building in its complex system of internal and external relationships. Therefore, the development of Adaptive Facades is between Innovation and implementation of reactive and multifunctional materials, also developed in other fields. They can repeatedly and reversibly change some of their functions, characteristics or behaviours over time in response to environmental conditions. According to recent research, in the context of Building Facades, the word "adaptive" is often associated, in literature and within the discipline of architecture and engineering, with words such as smart, intelligent, interactive or reactive. These words are used interchangeably and describe technological systems, which interact with the environment and the user by reacting to external influences and adapting their behaviour and functionality [4]. Today's society is faced with challenging environmental and energy efficiency targets and, therefore, the development of efficient and adaptive façade systems is essential. This scenario of intentions should also be read with reference to the main measures adopted by the European Commission and envisaged by the European Green Deal through the approval of a 'European Climate Act' that binds the EU to the goal of climate neutrality with zero net greenhouse gas emissions by 2050[1]. At the same time as this amendment, 'A more ambitious 2030 climate target for Europe' is presented, including the update of the

[1] This law, explains a Europarliamentary note, transforms the political commitment contained in the Green Deal, aimed at achieving climate neutrality in 2050 with zero net carbon dioxide emissions, into a binding target. The most important points of the climate law: to reduce CO2 emissions by at least 55% (compared to 1990 levels) by 2030; the EU Commission will have to submit a proposal for an emission reduction target by 2040 based on several criteria, including a CO2 budget compatible with achieving climate neutrality by mid-century; by 30 September 2023, and every five years after that, the EU Commission will assess the progress made collectively by member states, as well as the effectiveness of national measures; a scientific advisory body on climate change will be set up to monitor the implementation of the climate law.

2030 Climate and Energy Framework and the revision of the existing renewable energy and energy efficiency targets, as well as climate and energy legislation and actions in all sectors of the economy, starting with the energy and building sectors[2].

In line with these assumptions, the research focused on controlling performance related to building-context interactions that significantly influence the climate change vulnerability of urban space and the resulting resilient response. However, in order to mitigate the problems encountered within an urban context and implement energy efficiency actions, as required by European directives, there is a need to make a major step-change in scale and analyse in more detail the buildings that make up the urban space, not individually, but by relating them to the context in which they are located [5]. This is where the research comes in, identifying the need to develop Envelopes and façade systems that provide flexible energy performance adapted to external climatic conditions. All these studies and elaborations have provided reliable databases that have allowed the implementation intervention strategies, criteria and techniques. In the same way, both hierarchies and elements ascribable to the different thematic fields were clarified, allowing the topic to be approached with the necessary approaches of inter-scalarity and transdisciplinarity. These approaches are proving to be appropriate keys to highlighting and subsequently networking the different critical nodes that shape the complex scenario of change and extreme phenomena in the urban environment.\

1.3 GOALS AND RESULTS

The approach on which the research activities were developed is part of the current and fertile scenario of studies on climate change in the urban environment. It represents an emblematic example of the cultural and operational challenge that today is posed by the areas of human action, where technological innovation and experimentation represent possible tools able to understand the behaviour. This operational and applicative approach is closely related to the need for measurable control in terms of flow exchanges (material and energy) between heterogeneous environments. These flows influence an interdependent and dynamic way phenomena, effects and quality of the microclimate of the urban environment and, in particular, that which is defined between the building and its context. The studies' general objective was to identify some critical nodes that are established between buildings and their contexts and the consequent evaluation of the stresses of climatic phenomena that affect the Building Envelopes. From this assumption, the need to verify the technical feasibility of the interventions, oriented and supported by experimentation and validation of the results obtained. Specifically, the first part of the research study materialises in the choice of three districts, subject of the study, identified in the Mediterranean environment with morpho-typological and environmental characteristics, such as to outline different microclimatic scenarios. In order to analyse the performance behaviour of these compartments, simulations were carried out with specific software that provided reliable information through greater detail in the representation of the input data (both climatic and regarding the urbanised space) but generating outputs that were more complex to read, especially in the ratios between horizontal and vertical surfaces.

Therefore, there is an urgent need to understand the evolving climate change scenario in the Mediterranean area, which is largely due to islands and heatwaves, heavy rainfall phenomena such as water bombs and micro-typhoons, the so-called Medicanes. These phenomena can cause direct damage to the Building Envelope, with particular attention to its façades, and identify the building elements that need to be reinforced in order to avoid serious damage to the affected properties and the safety of people, avoiding the creation of cascading effects, where one defective piece causes several other pieces to fail, leading to disproportionate consequences. This is to configure possible strategies and technical solutions to direct experimentation towards creating increasingly efficient and adaptive enclosures, in their ability to recover after extreme wind and verified through advanced testing procedures carried out in specialised laboratories. For this reason, as a specific field of application, the activities focused on performance analysis and on the complex role of the Building Envelope, which acquires new specificities dictated by the need to configure itself as an osmotic membrane, capable of changing its dynamic-material behaviour as external stresses change. These new methods of investigation have allowed the identification and development of a set of robust criteria-indicators, given by the critical reading of the compartment simulations and constructing matrices of recurring environmental assets, in order to analyse the effects of climate change on the Envelope and verify, at the same time, how the Envelope can trigger and aggravate climate phenomena. Generally speaking, the results obtained from the indicators of climatic-environmental extraction are intended to act as tools and constitute a new way of interpreting the interdependent relationships between the problems investigated and the range of possible adaptive solutions they must confront. From which, it is hoped, the most suitable choice for the contextual conditions will derive. Therefore, the opportunity to have a Testing Laboratory for Building Envelopes has been a real added value to research, realising actions of applied experimentation with highly reliable results. In addition, the contribution of the testing laboratory has allowed a continuous validation phase of the results obtained and the activation of feedback processes in order to implement a new methodological apparatus and orientate new evaluation standards.

[2] These intentions are within the Horizon 2020 Programme, in continuity with the Horizon Europe Programme, covering 2021-2027. Research and Innovation are key elements in achieving a resource-efficient and climate-resilient economy and society to meet the needs of a growing world population within the sustainable limits of the planet's natural resources and ecosystems.

1.4 METHODS AND TOOLS

Within the broader theme of climate change, understood as a structural phenomenon, the focus of the research is to provide innovative strategies and tools in order to improve the quality and environmental performance of urban and peri-urban districts through the construction of a pattern of intervention that, in line with the general guiding strategies, is configured as a basis for the drafting of good practices and guidelines. The difficulties lie in the issues of measurability: the complexity of the technological and material elements, which make up the Building Envelope, makes it difficult to correctly read-evaluate their behaviour, given the sum of the different performances of the components of which they are made up and which, indirectly, influence the climatic-environmental conditions of the area in which it is located. For these reasons, research activities are set up to have the possibility to detect, through simulation tools, specific climatic data and to quantify the material aspects of the urban context and describe the related synergies through the development of reliable indicators. This framework led to the structuring of the research methodology into three sections and reported below, useful to guide the consecutive steps of the research activities:

1. Knowledge/Taxonomy;
2. Measurement/Evaluation;
3. Experimentation/Comparison.

As previously mentioned, the application context of the research consists of three urban districts in the Mediterranean area, on which simulations of climate change conditions were developed. In addition to the purely urban parameters, parameters relating to geomorphological, microclimatic, planovolumetric, typological and material requirements were considered and analysed and qualitative requirements linked to the panorama of values indicating thermophysical performance to be measured both statically and dynamically to obtain tangible results.

Through the algorithmic interpolation of data on surface materials, urban settings, climatic factors and elements, using modelling software, it was possible to simulate the dynamics of climatic phenomenology and operation in order to understand the interdependencies of the different actions of 'triggering' and 'passivity'. The activity's result allowed the identification of indicators defining the degree of climate-responsiveness of the different districts through the analysis of sets of specific qualitative and quantitative indicators present in the literature and the subsequent identification of new indicators. Each indicator is specific and often reductive concerning the globality of the phenomenon it is intended to represent. In order to describe the latter as reliably as possible, it is necessary to select a plurality of indicators, which are then grouped into indices through statistical aggregation procedures in order to summarise the information that can be inferred from the individual indicator. The indicators were analysed by filing, selecting the most recurrent ones and identifying the relationships between climatic phenomena and the urban environment. Subsequently, the categories of phenomena were extended to identify new sets of indicators. The aim was to identify the technical solutions that really responded to a selected indicator and link the indicators to a specific category of technical solutions in a two-way relationship. The indicators' analysis allowed the simulation of new urban scenarios and the drafting of a "model" sheet to construct a synoptic framework for applying the selected criteria to new and/or existing buildings. In a vision of application in the context of national and European strategic guidelines, climate change adaptation actions are an essential factor for a renewed design of the urban environment. By identifying indicators, it is also possible to develop a dynamic protocol that can be applied in different urban and environmental context situations, constituting a new way of reading the relationships between the problems investigated and the adaptive and resilient solutions proposed. The advances produced in these first phases represent the basis for the subsequent activities of simulations from life through the use of the equipment of the Building Future Lab section of the Mediterranea University of Reggio Calabria [6].

The complex operation of data collection, processing and systematisation led to the drafting of test reports due to comparison and verification of the experimentation actions carried out. The experimentation activities are described in the next paragraph.

1.5 THE IMPORTANCE OF TESTING ACTIVITIES FOR 'NEW' ENVELOPES

Nowadays, design, especially in critical or sensitive environmental areas such as the Mediterranean, seems to be increasingly adding phases that seek to anticipate the executive ones; these phases consist of actions aimed at understanding the dynamics and verifying the applicability of the solutions. This instrumental opportunity of research, in its different scalar aspects, offers the project the strategic possibility to support the prediction of expected results - or to better calibrate their configuration - through particular conditions able to read in advance future outcomes, thus enriching the process with a new ability to control performance dynamics. In accordance with the research objectives, it is intended to relate the above to the routines of field experiments. Field experimentation is commonly understood as the real-life study of the behaviour of buildings - stressed by the reproduction of climate change phenomena - through experimental activities and testing on full-scale test models, known as mock-ups. Starting from the simulation of the three compartments and the results obtained, the boundary conditions generated between the building and its context were recreated in the TCLab section of the Building Future Lab (BFL) [7]. A series of tests were carried out on two 1:1 scale mock-up of Facades, one transparent and the other opaque, made available for experimental research by TCLab partner companies. The objective was to study and compare the behaviour of the different Facades in situations of climate change, specifically heat islands, heatwave and pluvial flooding. According to standardised protocols, the laboratory aims to respond to this through the modelled simulation of environmental flows. It is designed as a continuous instrumentation upgrade to carry out activities linked to the innovation trends of processes that create adaptive, integrated and environmentally

interactive enclosures [8]. From the methodological point of view, the urban layout to be reproduced in the laboratory was identified, which can be traced back to a building with an external space similar to a courtyard. The test chamber (dimensions 17 x 12 x 4.50 m) is closed on three sides, while the fourth side contains mock-ups to be tested. The test chamber is located externally, giving the possibility to interact directly with the external climatic conditions and offering the opportunity to model them to specific needs. In addition, the test chamber is equipped with three seismic beams for carrying out displacement and elastic balance tests. Other main machines are a large fan that simulates winds of up to 200 km/h, a thermal chamber (dimensions 7 x 5 x 1.50 m) and a retractable rain simulator, the latter of which has been the subject of an international patent [9].
With respect to the phenomena to be analysed, the following procedure was identified for the experimentation activities:
1. heat-wave, the experimentation was carried out by reproducing a wind flow through an AAMA/ASTM fan-which reaches to simulate the power of a hurricane-which allowed the verification of the performance behaviour of the external façade of the two mock-ups subjected to strong pressure.
2. pluvial flooding, the experiment was carried out by reproducing a constant rain directly on the external Facade of the two mock-ups. Three simulations of the water jet were carried out through a network of sprinklers with calibrated nozzles: in the absence of wind, in the presence of wind and extreme wind conditions (hurricane power).
3. heat island, experimentation was possible through the use of the thermal chamber, through which it was possible to identify the maximum temperature to which the two mock-ups could be subjected.
The transparent Facade mock-up [fig. 1], consisting of aluminium mullions and transoms with two openings, was supplied by the company Aluk, while the opaque Facade mock-up [fig. 2] was supplied by the company TCK and consisted of a frame system to which calcium silicate "nano-modified" plasterboard sandwich panels are bolted, coated internally and externally with a fireproof layer.
For both mock-ups, the following test methods were planned and carried out:
1. Water tightness performance under static pressure was performed in accordance with ASTM E 331-00 (2009), by applying a constant flow of water to the external façade and exposed edges simultaneously with a uniform static pressure of 15 lbf/ft² (pounds per square foot), 720 Pa for a time of 15 minutes.
2. Water tightness performance under dynamic conditions was performed in accordance with AAMA 501.1-05-00 (2007), applying a dynamic pressure of 31.5 lbf/ft² (pounds per square foot), 1508 Pa and 5 U.S. gallons per square foot in an hour (= 3.4 l/min m2) of water to the mock-ups for 15 minutes through a series of nozzles placed on bars placed horizontally and at a standard distance from the external face of the mock-ups.
3. The structural performance was carried out in accordance with ASTM E 330-02 (2010), applying a positive and negative test pressure of 50% and 100% of the design wind load, for which measurements and checks are carried out to verify that, under these effects, the two mock-ups present an allowable deformation and retain their stability characteristics.
4. The thermal performance was carried out in accordance with AAMA 501.5-07, subjecting the mock-ups to 3 cycles of 8 hours of temperature varying between 176°F and 5°F (80°C, - 15°C), therefore with a positive/negative differential with respect to the environmental one.
From the experiments carried out, a framework was constructed for reading and comparing the performance data in order to highlight the potential, criticality and malfunctioning of the technological systems that characterise the typological and geometrical structure of the samples analysed. In general, no negative façade behaviour was found when simulating the heat island and pluvial flooding in the absence of wind, resulting in a positive and flexible reaction behaviour of the façades. The verification of the performance in pluvial flooding conditions in the presence of wind, for the transparent type of façade, has shown some water infiltration, thus requiring more attention in the production, installation of rainwater runoff systems for this type of façade. In extreme wind conditions, however, the two mock-ups reacted positively as the pressure generated by the fan disperses the flow of water across the façade; thus, no water accumulates, and infiltration into the Building Envelope is prevented. About the simulation of the heat islands, reproducing an external temperature up to 89° C, through the thermal chamber, negative behaviours have been identified referred to the gaskets of the two mock-ups, highlighting the need to pay attention to the choice of sealing materials, especially those of plastic derivation. These experimentation activities have allowed to configure the various scenarios of adaptability of the Building Envelopes, directing the design decisions towards the most congruent options to the different contexts of reference and relationship. From this brief overview, it can be seen that the experiments, carried out at the macro and microclimatic level in specialised test laboratories, play a pivotal role in the implementation of an architectural design integrated with environmental issues [10]. In this sense, for the actors of the construction sector, the testing process is configured as an adaptive control tool for climate change, based on measurements and performance evaluations with respect to specific and real environmental contexts.

Fig 1. Mock-up of transparent façade tested

Fig. 2 Mock-up of opaque façade tested

1.6 CONCLUSION

The analysis emerged that environmental issues [11] have complex and extremely important implications for the Building Envelope and its design. The research objectives aim to respond to the challenges indicated by different sides of the scientific debate in recent decades. There is an increasing need to develop innovative Building Envelopes whose performance response is undeniably linked to the variables related to the environmental conditions with which they relate. The concept of high building performance is not just about energy issues, nor can it be attributed solely to the Envelope but its systematisation. The Building Envelope becomes a pivotal element for the continuation of innovative research developments. In this perspective, the Envelope represents the physical element of mediation between the external and internal environment: it responds to the signals that qualify the external environment, contributing to become an element of transformation and control. In order to understand what kind of climate change could take place, it is necessary to know and monitor the elements that make up the context and the relations that are produced between them through the identification of reliable parameters and indicators.

In particular, constructing a core set of new indicators useful for the detection of synergies and effects of climate change in the urban environment constitutes an innovative and interrelated way of reading the technological-environmental characteristics of Building Envelopes. However, although concluded in its main objectives, the research could be considered to be in progress, as it opens up promising fields of investigation. In fact, it would seem interesting to develop actions to detect the dynamic trend of the thermal values on the two mock-up, both with a thermometer and a thermal camera at regular, pre-established intervals, also to verify the propagation of heat, visible through the thermal camera, trying to calculate the cost of the energy used. In addition, a point of strong relevance of testing activities is to offer designers and technicians in the sector guarantees on the reliability and conformity of data and results, with important repercussions on experimental and industrial research.

These operations are a fertile opportunity for integrated research and experimentation for activities and skills aimed at controlling the overall quality of the building and the urban context of reference. The focus shifts to the performance of the Building Envelope, choosing a representative model to be tested with the ultimate aim of developing test protocols, both for subsequent experimental activities and for certification in the regulatory framework.

This is the direction taken by companies that specialise in the production of high-performance components and can enter the international market by supplying highly innovative products and technical-scientific activities aimed at creating new systems for Building Envelopes to be tested in a regulated and controlled manner.

This scenario indicates that as the complexity of Envelope systems increases, there is a need to increase the range of performance investigation criteria that underpin both their adaptive design and operation in use. Criteria that increasingly shift the axis towards evaluation systems must be aligned with the innovative content and complexity of the object to be tested and therefore require an equal level of innovation. For an effective transition to an adaptive response to take place, it is also necessary for the regulatory and decision-making instruments to evolve and adapt to European and national policy guidelines. The gap between ideal and actual visions is often confirmed by the gap between the tools available for research and those provided by the regulatory apparatus. It is in this sense and from this perspective that the key role of design, methodologies, regulations and technical-operational tools supported by testing and modelled and adaptive forecasting criteria is clarified and outlined.

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