From the 3 R's Rule of sustainability to the 4 R's of resilience: an architectural approach.

Lorenza di pilla

Civil Engineer, PhD degree in Architecture

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Abstract:
The reduction of energy consumption in buildings recently became tighter and tighter, as well as the need of shortening the building materials' supply chain. Hence, there is a growing interest in sustainable materials, able to reduce peak energy demand, also mitigating climate change and improving indoor comfort. Indeed, it is also fundamental to design buildings able to sustain their occupants during emergencies modulating and adapting their features to a changing climate, to different boundary conditions and to the progressive loss of biodiversity. It is therefore possible, by applying a wider approach, to conceive resilience as a correlated factor to sustainable design. In this regard, the main goal of the paper is to analyze traditional and innovative building materials, highlighting their key-features in terms of environmental costs, energy efficiency and adaptive capabilities. Starting from the specific definition of resilience, the present work analyzes its own application on buildings, while looking at a wider range of tasks. This, also highlighting the four main pillars of resilience in terms of its "4-Rs" (i.e. robustness, resourcefulness, rapid recovery, redundancy) and picking out the relevant connection with the consolidated "3-Rs" of sustainability (i.e. reduce, reuse, recycle).

1. Introduction

The reduction of energy consumption in buildings recently became tighter and tighter, as well as the need of shortening the building materials' supply chain. Hence, there is a growing interest in sustainable materials, able to reduce peak energy demand, also mitigating climate change and improving indoor comfort. Indeed, it is also fundamental to design buildings able to sustain their occupants during emergencies [1] modulating and adapting their features to a changing climate, to different boundary conditions and to the progressive loss of biodiversity. It is therefore possible, by applying a wider approach, to conceive resilience as a correlated factor to sustainable design. In this regard, the main goal of the paper is to analyze traditional and innovative building materials, highlighting their key-features in terms of environmental costs, energy efficiency and adaptive capabilities. Starting from the specific definition of resilience, the present work analyzes its own application on buildings, while looking at a wider range of tasks. This, also highlighting the four main pillars of resilience in terms of its "4-Rs" (i.e. robustness, resourcefulness, rapid recovery, redundancy) [2] and picking out the relevant connection with the consolidated "3-Rs" of sustainability (i.e. reduce, reuse, recycle).

Nowadays, the global resilient design strategies and the growing interest towards buildings designed for "passive survivability" [1] can be directly linked to the adjective "adaptive", i.e. to the capability of flexibly and proactively respond to a wide range of changes (either environmental and climatic, thermal and meteorological, as well as social, urban, psychological) [2, 3]. The term "resilience" has been employed in a wide range of subjects:

- The scientific definition is the ability of a substance or an object to recover its form after suffering some trauma. In other words, it is quite different from resistance, as it concerns the capability of adapting and recovering.
- In ecology, resilience is about the ability of an ecosystem to respond to a perturbation or disturbance, resisting damage and recovering quickly.
- For psychologists, it is the process of adapting after faced adversity, trauma, tragedy, threats or significant sources of stress.
- For architects and urban planners, resilience prepares cities to face and recover from natural disasters.
- For engineers, is the ability to respond, absorb, and adapt to, as well as recover in a disruptive event.

But today, resilience is becoming a key concept when facing climate emergencies and the progressive loss of biodiversity (two planetary boundaries that allow humanity to continue developing). As traditionally well known, for a building to be resilient, should be guaranteed its capability to continuously operate, in a self-sufficient way and during a minimum time-span, without external energy supplies, neither water inputs, also efficiently surviving storms and floods. Thus, the above definition directly addresses to the close concept of sustainable buildings, thanks to their property of requiring less energy to operate ("reduce") through efficiency features, passive deign strategies implementation and on-site energy production ("reuse and recycle"). Notwithstanding, the above-mentioned similarities should not be erroneously confused and misunderstood. Actually, also recalling the United Nations World Commissions on Environment and Development report entitled "Our Common Future" (1987) [4], on the one hand sustainability can be conceived as the "development that meets the needs of the present, without compromising the ability of future generations to meet their own needs". On the other hand, over the past two and a half decades, sustainability has been largely (mis)used as a "trendy and fashionable" subject and its original, noble features have been turned into a buzzword widely and indistinctly applied either to energy conservation, resources efficacy, biodiversity, climate changes etc... Essentially, nowadays, sustainability is all about protecting nature and the environment from human endeavours. But, at this reference, the key -question is: what is able to protect humans from Mother Nature? This is the core-meaning and the heart of building resilience. According to the Resilient Design Institute [5], resilient design strategies can be defined as "the intentional design of buildings, landscapes, communities, and regions in response to vulnerabilities to disaster and disruption of normal life". As a direct consequence of current human and environmental necessities, building respecting construction codes is no longer enough and neither is able to successfully create energy efficient houses: of course, it is able to design more comfortable buildings, also achieving money savings on energy bills and reducing carbon footprint. But the real challenge the contractors are currently facing is to conceive and create houses, buildings and communities that are resilient in the face of droughts, flooding and a huge series of other natural disasters. A challenging task, indeed, that lead current designers, architects, engineers, building contractors and urban developers to apply traditional sustainability approaches, actualizing them towards even more severe backgrounds and delicate boundary conditions.

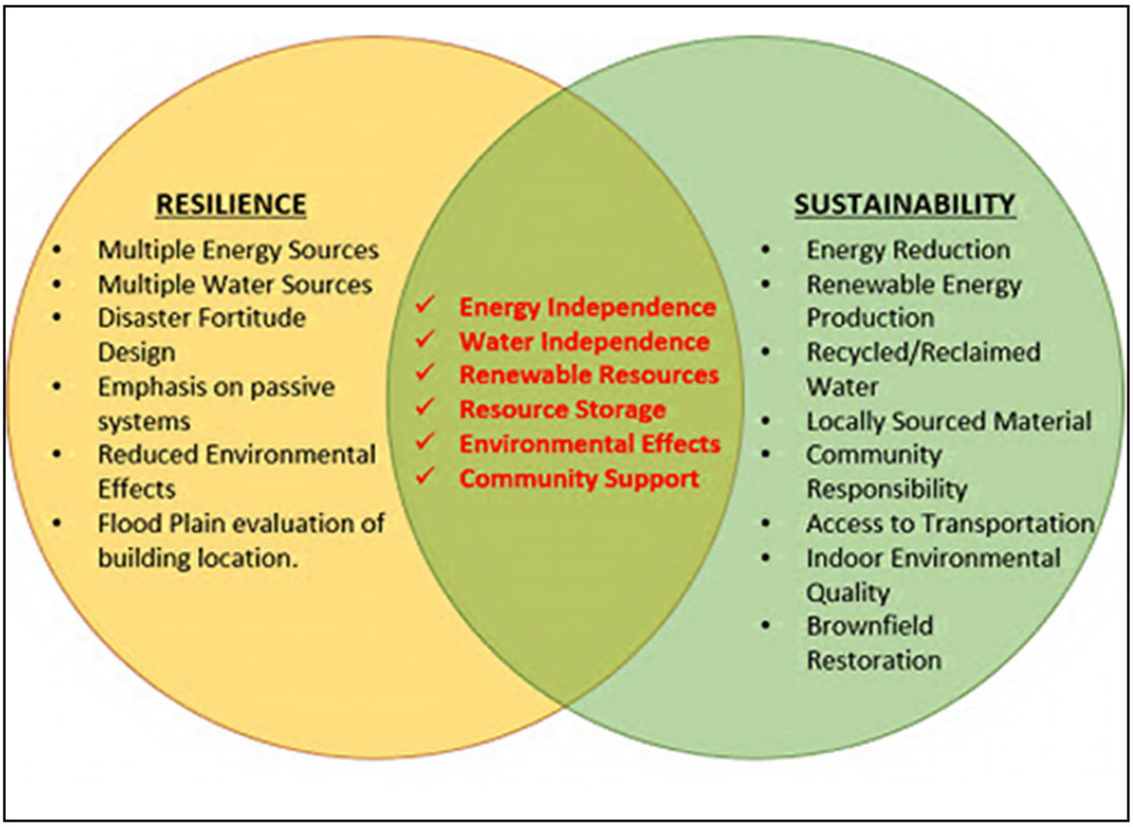

Fig.1. Comparison between the concepts of Resilience and Sustainability: common vs. distinctive features [5]

2. Problem's statement and challenging opportunities

As stated by Alex Wilson, founder of the Resilient Design Institute, resilient design strategies involve the creation of homes, buildings, infrastructures and whole communities able to reveal themselves resilient and reactive in the face of droughts, extreme heat and flooding generated by climate changes: "(....) a resilient building (...) is not built in a floodplain; where we build is a big part of resilience. It has deep roof overhangs to keep water away from the walls and foundation. It is oriented to take advantage of sunlight in passive solar heating. It is designed to minimize overheating and air conditioner use, through simple cooling-load-avoidance strategies; it may have shade trees or a trellis with sun-shading vines on the west. It is highly insulated and has high-performance windows. In drier climates, it isn't surrounded by a lush green lawn in the middle of summer (...)". And actually, by establishing a direct connection between the previous statement and the current relevant task of infrastructure resilience, it is even more evident how these aspects can be fruitfully interrelated. Throughout history, infrastructure resilience has been defined in function of several approaches: indeed, if on the one hand each critical infrastructure sector operates differently, on the other hand a common definition of infrastructure resilience is still needed for public policies and governance to be effective. And the most widely used, as well as the most appropriate, has been provided in 2009 by the National Infrastructure Advisory Council (NIAC) which stated: "Infrastructure resilience is the ability to reduce the magnitude and/or duration of disruptive events. The effectiveness of a resilient infrastructure or enterprise depends upon its ability to anticipate, absorb, adapt to, and/or rapidly recover from a potentially disruptive event" [2].

Table 1. Synoptic table: building resilience key-elements & design process application [2]

THE 4-RS: KEY-COMPONENTS OF BUILDING RESILIENCE DESIGN STRATEGY			
KEY-ASPECT	DEFINITION	MAIN BUILDING’S PARAMETERS INVOLVED	
RESOURCEFULNESS	Is the capability of being effectively prepared to respond and manage a crisis or an extreme event as it unfolds.	It includes the identification of the backup actions to be undertaken in order to preserve the continuity of building’s operation, also mitigating any eventual damage.	Building maintenance.
			Memorandum of understanding (MOUs) between different stakeholders.
			Supply chain management.
			Business continuity planning.
ROBUSTNESS	Is the ability of maintaining critical operation and function levels even in face of a crisis.	It involves the building itself, the infrastructure design, the overall building’s facilities and any building system substitution.	Pillars and columns.
			Structural connections.
			Communication networks.
			Power generation systems.
RAPID RECOVERY	Is the capability of returning and restoring normal operation levels as quickly and efficiently as possible after a destructive event.	It is strictly connected to the capability of working out contingency plans, effective emergency operations and rescue activities.	Roads and access points leading to building.
			Training activities.
			Competent emergency operations.
			Ad-hoc resources relocation.
REDUDANCY	Is the possibility of relying on back-up solutions and alternative resources to support the original building’s configuration in case of failure.	It is directly linked to the planning, design and construction steps addressed to building resilience and original building’s elements’ support.	Main water pipes, sewage systems and building plants.
			Electric and power lines.

Actually, the NIAC recognizes that protection and resilience are not two opposed and discordant concepts, but they represent complementary and necessary elements within an all-involving, complete risk management strategy. The strong foundation developed for infrastructure protection continues to be an essential and vital part of risk management in all critical infrastructure sectors. What is needed now is a strengthening of resilience policies and strategies to build on the successes of the infrastructure protection efforts. In order to conceive and apply resilient design strategies, it is fundamental to consider different aspects of resilience management, to control and help reduce the rapidly increasing costs of manmade and natural hazards and ensure that civil infrastructure exhibits a high degree of resilience. When planning and designing buildings, it is appropriate trying to mitigate the potential of the spiraling cost of operational failures, by opting for more resilient performance through well-thought-out investments in better planning and designs. Resiliency strategies for buildings should be discussed and implemented now, so there is a greater chance of increased performance, not only today but for the future, benefiting all buildings stakeholders. At this reference, a definition of resilience that involve the following four key-components (robustness, resourcefulness, recovery and redundancy) can be meaningful.

3. Design strategies and main choices for achieving resilience at a building scale

For the aforementioned task being effectively and proactively implemented in any design and construction plan, the following best practices can address the most relevant decision-makers, project manager and stakeholders.

Table 2. Synoptic table: resilient Design principles [1], [6-7], [8-10]

ACHIEVING RESILIENCE ON A BUILDING SCALE: TIPS AND BEST PRACTICES	
ACTION STRATEGY	STRATEGY IMPLEMENTATION
Use low carbon-input building materials and systems, as well as for low energy input constructability	Use of natural materials (even better if locally available, renewable and/or reclaimed); *i.e.* wood, cork, reeds, sheep wool, low-energy input masonry (e.g. adobe) *etc.*. Provide building systems and devices resting on local suppliers of products and skilled labours.
Design, plan, work out and perform buildings with low external energy inputs for ongoing building's operations.	Building designed and realized to be highly energy efficient, also including highly insulated building envelopes, energy efficient glazing, passive solar heating/cooling solutions combined with effective thermal mass storage systems.
Design buildings for maximum day-lighting.	This will allow natural light to be the primary source of light for buildings, thanks to the use of narrower floor plates, internal courtyards, atrium spaces and analogous daylight effective strategies.
"Generic design" of buildings for achieving maximum flexibility levels (also for future uses).	The most effective design strategies for enhancing future flexibility consist in the use of modularity and standardization in program spaces planning. Actually, modularity provides for building's spaces and internal articulation able to identify common denominator areas that can be used for multiple, yet simultaneous uses.
Choice of diverse and redundant systems that are inherently more resilient.	Indeed, more diverse communities, ecosystems, economies and social systems are better able to responds to interruptions or changes, making them inherently more resilient.
Prioritize simple, passive and flexible systems.	Actually, passive and/or manual-override systems are more resilient than complex solutions that can break down and require high levels of ongoing maintenance. Moreover, flexible solutions are able to easily adapt to changing conditions both in the short and long-term.
Prefer building strategies that implement durability.	Good levels of durability increase and enhance resilience: overall durability involves not only building practices, but also building design, infrastructure and ecosystems.
Realize and face the fact that resilience is not absolute	Recognize that incremental steps should be taken and that reaching a "total, complete resilient *status*" in the face of all situations is not possible. This shall drive to conscious and feasible choices in the short term, also working to achieve greater levels of resilience through progressive stages (ref. Fig. 4)

What stated until now can be also usefully described as follows, recalling a recent report issued by the World Resources Institute in 2019 [11], [12].

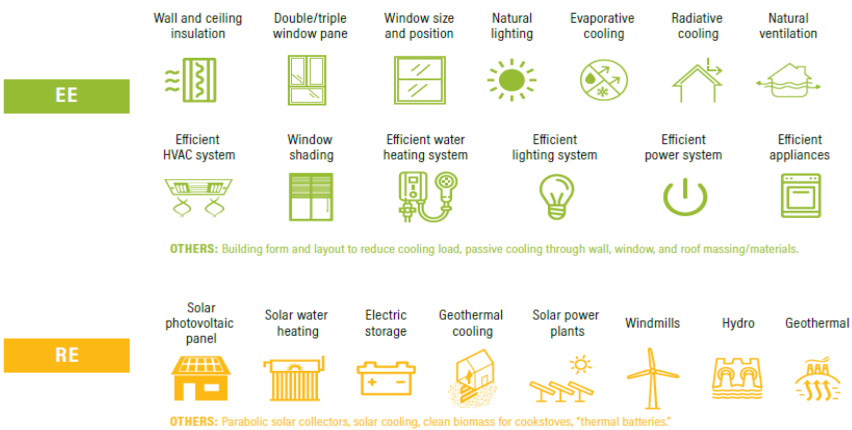

Fig. 2. Widely available Energy Efficiency (EE) and Renewable Energy (RE) technologies that support resilient building design strategies [11],[12]

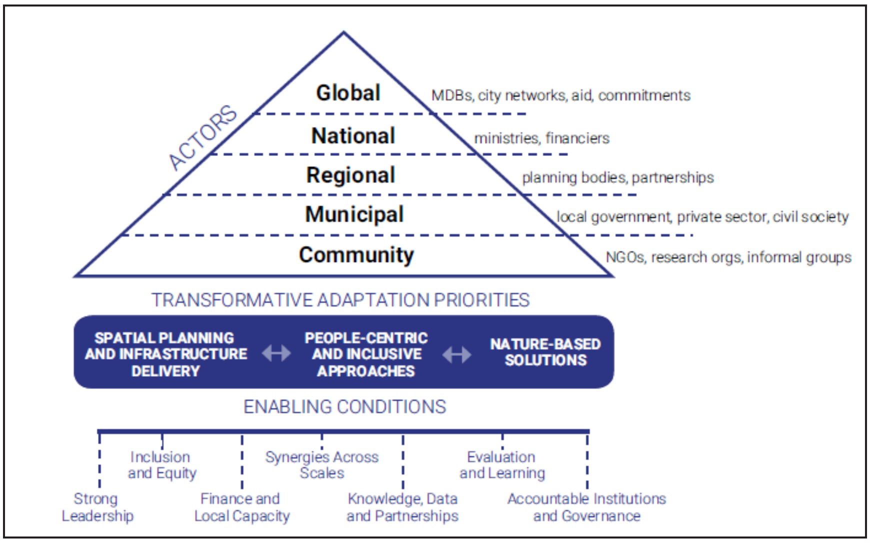

Fig. 3. Transformative adaptation priorities for enabling conditions and scales of decision making building design strategies [11],[12]

4. Innovative building materials: smart and resilient features for modern architecture.

For a long time the term "smart materials" has been (mis)used without precisely clarifying what do they mean [13]. Notwithstanding, the formulation of a clear and precise definition is very difficult: this adjective is already in wide use, but there is no formal agreement about what it actually means. According to the main key-definitions detected through a literature review approach, the terms "smart", "intelligent" and "resilient" have been used almost indistinctly and interchangeably in many relations between materials and building systems. Other lines of thought have drawn sharp distinctions regarding the multifaceted qualities, properties and capabilities herein implied. NASA defines "smart" those "materials that remember configurations and can conform to them when given a specific stimulus". Another definition, highlighted in the Encyclopedia of Chemical Smart Materials and New Technologies reports that "smart materials and structures are those objects that sense environmental events, process that sensory information, and then act on the environment" [14].

Even though these two definitions seem to be referred to the same type of behaviour, they are consistently different: actually, the first one refers to materials as substances, i.e. as elements, alloys or even compounds, all identifiable and quantifiable by their molecular structure; the second definition instead conceive materials as a series of actions. For the purpose of a strategic use in resilient architecture of the so-called "smart materials", the latter definition can be therefore usefully applied. Even more if the below smart material properties are highlighted:

- Immediacy: they respond in real-time to a wide range of stimuli.
- Transiency: they respond to more than one environmental state.
- Self-actuation: their intelligence is internal, rather than external to the material.
- Selectivity: their response is discrete, predictable and easy to be handled.
- Directness: their response is local to the activating event.

4.1. Innovative building materials and resilient architectural solutions

In the light of the above remarks, and in particular in terms of architectural building solutions, designing and conceptualizing resilient materials and construction strategies can lead to a wide range of approaches and innovative strategies. Resilient designs are usually "site specific" and predicting the potential scenarios for a typical building use (and even potential disasters that could challenge the integrity of the project and its occupants) is a fundamental starting point. Moreover, it is possible to address adaptive structures and materials that can ''learn" from their environment, also continuously "reinventing" themselves [15].

At this regard it is possible to mention, as some of the most innovative examples and concrete application of resilient, smart materials (even though still under analysis and development), the following solutions [16-18].

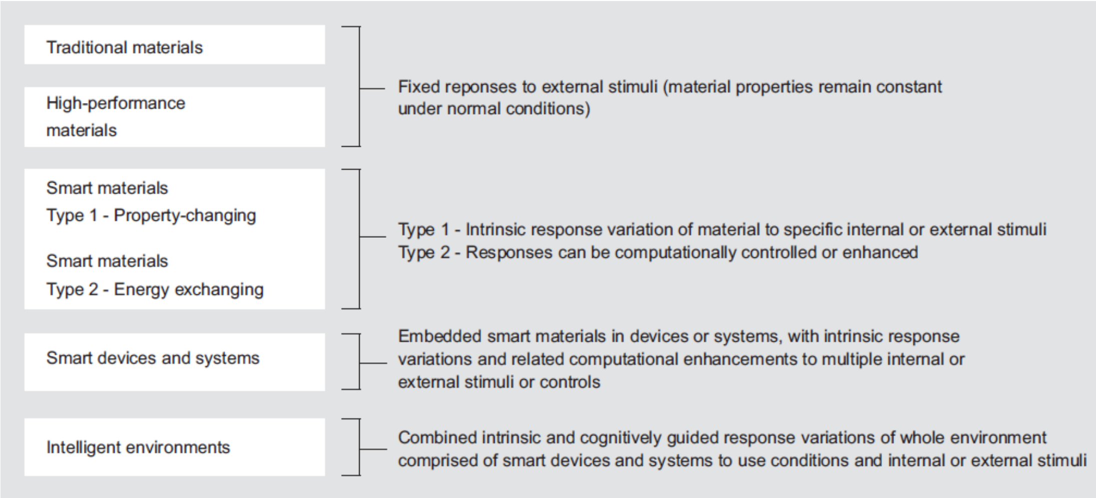

Fig. 4. Distinction between smart and intelligent systems and environments [13]

4.1.1. SPONG3D

Spong3D is a façade system that integrates multiple functions to optimize thermal performances according to the different environmental conditions occurring throughout the entire year. The idea is linked to the possibility of monitoring and modulating the heat transfer between the internal and external parts of the building during a controlled time-span. The proposed system incorporates air cavities to provide thermal insulation and a liquid variable in volume (water mixed with other additives) to provide heat storage, where and whenever needed. The liquid is able to provide additional heat storage as it flows through channels located along the outer surfaces of the system (on the indoor and outdoor faces of the façade). Furthermore, when needed, the liquid can be transferred from one side to the other side of the building façade in order to absorb and release heat. The composition of the channels and the cavities are able to form a complex structure, integrating multiple functions into a singular component.

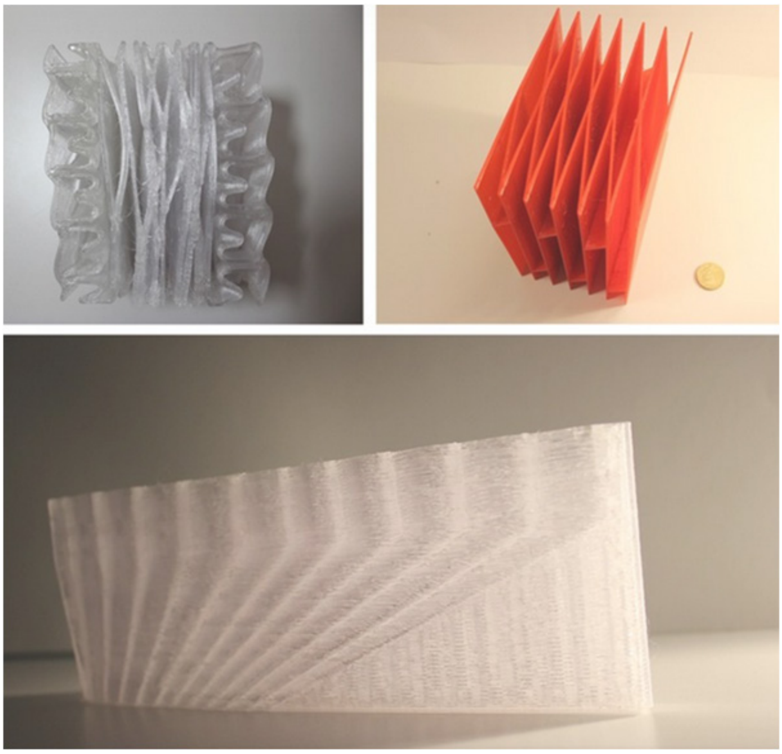

Fig.5. Spong3D: application [15]

4.1.2. GEOtube

GEOtube is an innovative solution worked out by Berkeley-based Faulders Studio that uses saltwater to grow a façade. The proposed envelope solution for a tower in Dubai (United Arab Emirates) is to suck up water from the Persian Gulf (the source of the world's saltiest ocean water) through a 4,62 km long underground pipeline, and then spray it over its mesh façade. The building's skin is therefore going to be entirely 'cultivated' rather than built: actually, instead of being fully finished, it is in continuous development. As the water evaporates and salt deposits aggregate over time, the tower's appearance transforms itself from a transparent skin into a solid, highly visible white surface.

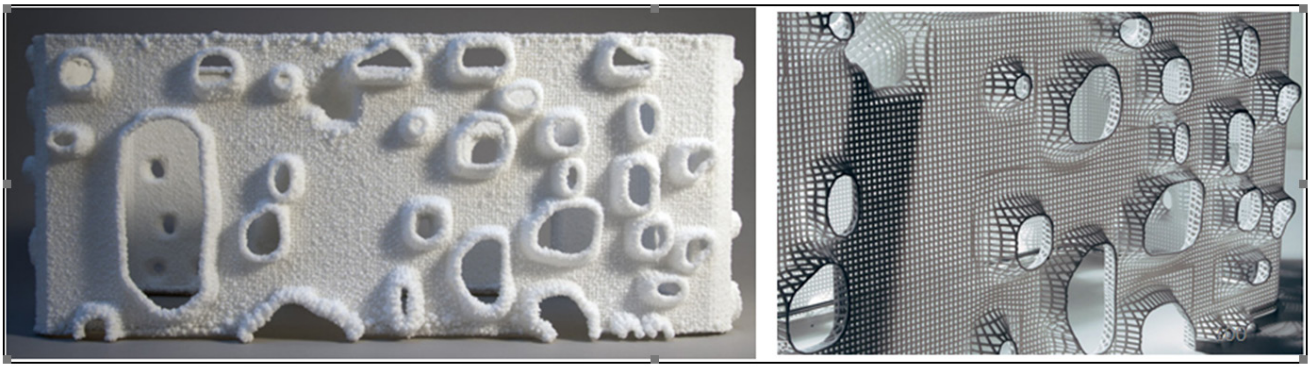

Fig.6. GEOtube mesh [15]

4.1.3. Smart Masharabiya concept material

It is an example of responsive façade designed and worked out by Aedas Architects for the Abu Dhabi's (United Arab Emirates) newest pair of towers (Al Bahar Towers). It consists in an advanced lattice shading device which takes cultural cues from the mashrabiya traditional Islamic pattern. Using a parametric description for the geometry of the actuated façade panels, this architectural solution is able to modulate its operation in response to sun exposure, also changing incidence angles during the different days of the year. The screen operates as a curtain wall, protruded and standing two meters outside the buildings' exterior on an independent frame. Each triangle is coated with fiberglass and is programmed to automatically respond to the movement of the sun as a way to reduce solar gain and glare. In the evening, all the screens are able to completely close.

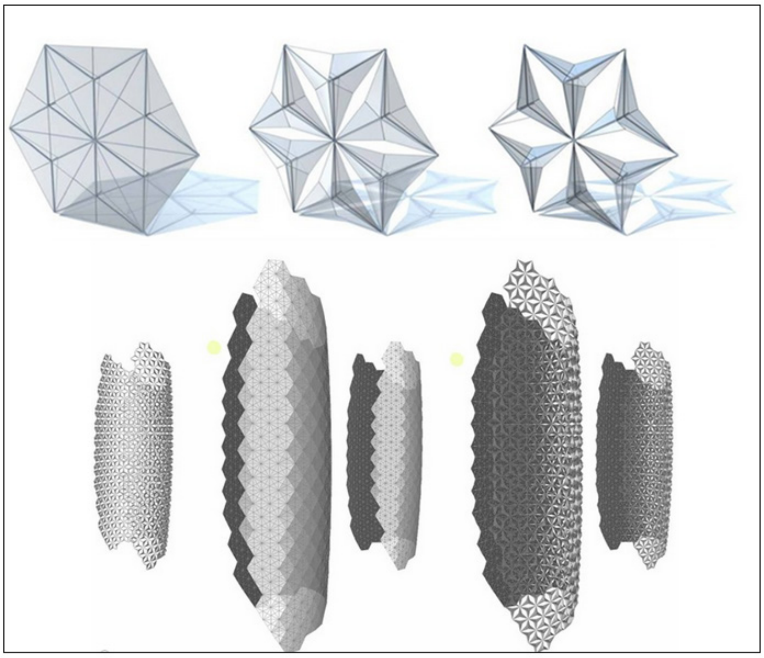

Fig.7. Al Bahar Towers, Abu Dhabi, UAE. Smart Masharabiya concept material panel diagram [15]

Fig.8. Al Bahar Towers, Abu Dhabi, UAE [15]

The above images also propose an example of kinetic façades architecture solutions. They can actually assume a multitude of forms throughout the years, also mediating between aesthetics and utility, pushing stunning visuals alongside environmental protection. The façade's umbrella-like panels open and close in response to the sun's movement, protecting building users from heat and glare, decreasing the need for air-conditioning and making the building more sustainable. Moreover, as above highlighted, the panels themselves are not only aesthetically-pleasing and star-like in design, but are inspired by traditional Islamic shading systems (i.e. masharabiya), respecting cultural heritage as well.

4.1.4. Hygromorphic Materials

Hygromorphic materials are moisture-sensitive materials that can have response driven by wood shrinkage and swelling. These naturally responsive mechanisms employ the inherent properties of available materials, such as the moisture-induced opening and closing of conifer cones.

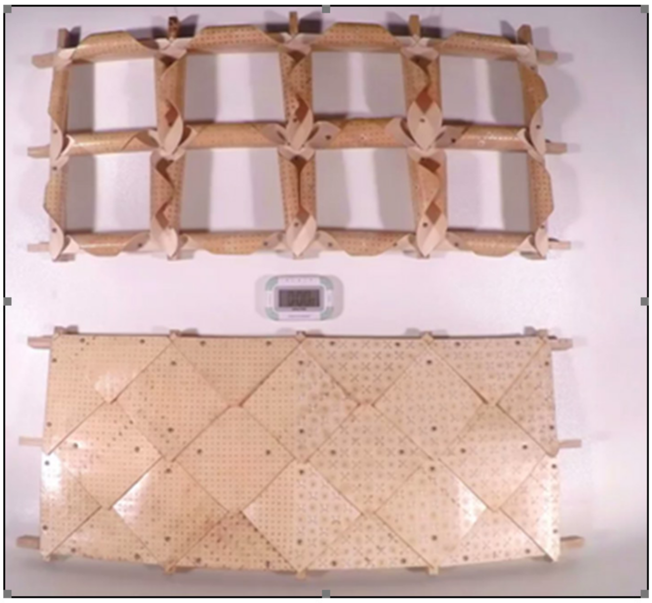

Fig.9. Hygromorphic material's behaving pattern [15]

4.1.5 Pollution-Eating Façade-The prosolve370e

It is a decorative architectural module that can reduce air pollution in cities when installed near traffic ways or if used in the construction of facades. The material contains titanium dioxide, which effectively "cleans" the air from toxins, releasing spongy free radicals that could eliminate the pollutants. Actually, the tiles characterizing this system are able to neutralize air pollutants when installed in heavily polluted conditions. Inspired by fractals in nature, their wavy forms maximize the surface area of the active coating, enhancing its capabilities to diffuse light and air turbulence.

Fig.10. Prosolve370e mesh - Torre de Especialidades, Hospital Manuel Gea Gonzales Mexico City [15]

Fig.11. Prosolve370e application - Torre de Especialidades, Hospital Manuel Gea Gonzales Mexico City [15]

4.1.6 People's Pavilion /bureau SLA + Overtreders

This pavilion is a design statement of the new circular economy: a building entirely worked out by using recycled materials. The astonishing coloured tiles that made up the Pavilion's upper facade are from plastic household waste materials collected by Eindhoven residents [19]

Fig.12. People's Pavilion /bureau SLA + Overtreders, Eindohven, Netherlands [19]

5. Conclusion.

As emerged by the aforementioned remarks, observations and architectural building solution examples, resiliency is not a single solution, concept or perspective. Resiliency is a multifaceted lens which balances proactivity and reactivity to inform solutions to disruptions. Nowadays, resilient design strategies are taking that lens and using it to rethink and reshape the built environment. The term resilience has been employed in a wide range of subjects (the scientific definition is "the ability of a substance or object to recover its form after suffering some trauma") and its core meaning is quite different from resistance, as it concerns the capability of adapting and recovering to a wide range of extreme contexts and destructive events. In ecology, resilience is about the ability of an ecosystem to respond to a perturbation or disturbance, resisting damage and recovering quickly. For psychologists, it is the process of adapting after faced adversity, trauma, tragedy, threats or significant sources of stress. For engineers, "is the ability to respond, absorb, and adapt to, as well as recover in a disruptive event". And finally, for architects and urban planners, resilience prepares cities to face and recover from natural disasters. But today, resilience is becoming a key concept when facing climate emergencies and the progressive loss of biodiversity. Predicting the potential scenarios for a typical building use, and even any disasters that could challenge the integrity of the project and its occupants, is an important starting point for addressing adaptive structures and materials that can ''learn'' from their environment and continuously reinvent themselves.

All the proved effectiveness of the examples displayed in this research, have been timely demonstrated on a scientific basis and thanks to the use of simulation engines and protocols [17, 18, 19].

The innovative examples herein illustrated, not only involve in their own features the key-elements of resiliency, but would also display its concrete application and provide some inspiring solutions that can enable future architects to design and develop more resilient, smart and proactive building structures.

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NOTES

1. The Tables 1 and 2 have been developed both on the basis of the NIAC (2019) and on the basis of the following publications: Allinson and Hall, 2005; Anastaselos et alii, 2009; Asdrubali et alii, 2015; Corscadden et alii, 2014; Eben Saleh, 1990; Lechner, 2015.