Chapter

Climate Change and Extreme Wind Events: Overview and Perspectives for a Resilient Built Environment

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Abstract

The frequency and intensity of extreme weather events have increased in the last few years. Buildings resiliency against natural hazards (hurricanes, flooding, wildfires, etc.) is fundamental for the adaptation to climate change, however it is hardly included in their design. Buildings exposed to extreme climate conditions may become drivers of vulnerability, rather than providing shelter for users, leading to human and economic losses. The building stock assessment appears to be quite detailed about seismic vulnerability and energy demand related to climate change, but not towards other hazardous events, such as extreme winds. Furthermore, climate data provided by current standards and used for building design need to be seriously reconsidered, since they no longer represent the real weather variables. During windstorms, the main threats are mainly due to the detaching and flying of materials and elements from buildings and urban furniture. The chapter deals with the effects and consequences of strong wind events on the built heritage and calls for an urban transition to create resilient and safe environments for the people. An overview of the current standards related to building design against wind is presented, and mitigation and adaptation strategies are proposed to respond to current and future climate threats.

Keywords: urban sustainable development, built environment, building resilience, climate change, windstorm

1. Introduction

Adaptation to climate change is today recognised as a global issue, as also acknowledged by COP 26 [1] and COP 27 [2]. The number of extreme weather events has increased by more than 250% in the period between 1980 and 2013, and this upward trend is continuing [3, 4].

The world is experiencing huge pressure on living conditions and an increase in damage to assets and asset value due to extreme weather events, most of all in coastal areas, where most of the world's population lives. Moreover, the inertia of the climatic system is such that no matter how great the emissions reductions that may be achieved by 2050, the average temperature will be 1.5–2°C higher compared to the preindustrial era, and there will be a significant increase in the frequency of

Climate hazards	Chronic	Acute
Temperature	Temperature rises Freeze-thaw cycles Permafrost thawing Air quality degradation	Heatwaves Extreme cold Urban heat islands Wildfires
Wind	Wind patterns	Storms Tornadoes
Water	Sea level rise Thunderstorms	Drought Floods Coastal submersion
Land	Coastal erosion	Subsidence Landslides
Biodiversity	Species migration and loss	

Table 1.
Direct and indirect risks due to climate hazards.

extreme climate events [3]. In fact, the expected impacts of climate change, including sea level rise, heat waves, droughts, and storms, will increasingly affect the built environment, economic activities and society itself (**Table 1**). Recent research [4] predicts that, by 2050, 1.6 billion people living in urban environments will be regularly exposed to extremely high temperatures and over 800 million people will be affected by sea level rise and coastal flooding.

Climate change effects call for an urban transition to create safe and resilient urban environments that can face the present environmental challenges, extreme wind events included. In this regard, a comprehensive urban transition should consider adaptation and mitigation strategies for the built environment.

Climate risks affect all aspects of a building: the structure, use, accessibility, provision of services and the safety, health and well-being of its occupants. Buildings strongly exposed to extreme climate conditions may become drivers of vulnerability, rather than providing shelter, leading to both human and economic losses [3–5]. Poor, ill-planned and over-crowded settlements face the highest risk from climate change. During the past two decades, almost 90% of deaths due to storms took place in lower-income countries, though they endured only a quarter of total storms [6]. Climate-related hazards, such as windstorms, forest fires, heavy rain and floods lead to the growing necessity for buildings to be resilient to extreme and unpredictable weather conditions. Therefore, the increased frequency, intensity and impact of extreme weather events call for resilient buildings and urban environments, designed for protection against physical damages and failures. This leads to the need for an accurate analysis of the characteristics and vulnerabilities of the built heritage as well.

Resilient buildings need to face many challenges in many combinations (hurricanes and high wind resistance, wildfire events, etc.) but today their design hardly includes these aspects. Also, for what concerns the building stock assessment generally appears to be quite detailed about seismic vulnerability and energy demands related to climate change, but not towards other hazardous events, such as extreme wind events. Furthermore, climate data provided by the standards and used for building design need to be seriously reconsidered, since they no longer represent the real weather variables [7]. The adaptation of buildings to climate change requires the development of a culture of risk management and the improvement of resilience, beyond the requirements provided by regulations [3].

The present article deals with the effects and consequences of strong wind events on the built environment. The risks related to such climatic hazards regarding the urban environment, the existing standards and the buildings' vulnerability assessment are discussed. Furthermore, a design methodology and examples of resilient buildings are presented.

The research included a first phase consisting in the state of the art analysis and review of actual standards, considering those areas already affected by strong wind events. This allowed us to define a methodology for resilient building envelope design, involving risk analysis and the definition of design guidelines.

2. The rise of extreme wind events

In the last few years, both intensity and frequency of extreme natural hazards have been increasing [8]. These events cause relevant damage to the environment, buildings and people, especially when they occur in countries not used to them, such as Europe. In 2019, strong winds caused 38% of the recorded injuries and 16% of the recorded fatalities caused by extreme weather in Europe [9].

During powerful storms and cyclones, the major risks are not only related to the high wind pressures but mainly to the impact at high speed of flying debris on buildings [10]. The flying objects can damage the building envelope and its content, eventually causing wind-driven water infiltration, producing potential significant losses of people and goods [11, 12].

The increasing risk of wind-induced damages should raise the awareness of designers, constructors, building managers, building owners and authorities on the importance of a careful building envelope design to resist the rising wind loads due to climate change. The increased frequency and severity of extreme weather events are causing more and more damage and even higher repair costs.

Storm speeds are projected to increase due to climate change in the second half of the 21st century, accompanied by an increase in frequency [13]. However accurate predictions on future storm intensity and frequency are not easy, since the forecast models used have many issues related to the lack of accurate observational data set against which to validate them [14].

Not only wind intensity but also frequency may negatively affect the built environment, subjecting building envelopes and urban elements to cyclic stress.

Despite the relevance of the topic, very few investigations have been conducted [15]. Wind has been investigated extensively to prevent the failure of the major building elements, therefore, several Codes and standards have been developed. Besides this, attention must be paid to building components and urban furniture, which can be vulnerable elements when subjected to strong wind.

Several measures to mitigate the wind effects on the built environment have been already implemented in areas prone to hurricanes, typhoons and tornadoes (i.e.: Florida, Hong Kong, Japan, Australia, etc.). Their major goal is to prevent damage to people and properties due to windborne flying debris, by adopting two sets of actions:

- mitigation, reducing the flying debris phenomenon by improving the resistance of urban and building elements to wind;

- adaptation, setting design guidelines and testing methodologies to ensure the resistance of the building envelope against possible impacts.

In Europe, instead, there are still no requirements concerning the consequences of windborne flying debris, since in the past such events were considered so exceptional to not represent a recurrent threat. However, several European countries experienced an increased number of tornadoes and extra-tropical cyclones in the

Figure 1.
Medicane on South Italy and Greece (left) and tornado in Venice (right) [16].

last years, including multiple so-called medicanes (Mediterranean hurricanes) in southern European countries (**Figure 1**).

Different levels of performance must be required by the standards depending on the building function: lower performances for common buildings and more demanding ones for strategic structures (hospitals, emergency services, schools, etc.), which must act as shelters and/or operational buildings in case of need.

3. Existing standards for building design under wind action

Although climate projections can be used to understand the extreme events that are expected to occur in the future, the legislation on urban planning does not currently consider future climate risks [3].

In Europe, the design of the envelope under wind actions follows Eurocode 1 [17], but extreme load configurations, including natural events, are considered only marginally. For some extraordinary meteorological phenomena that happened in the past, it was noticed that the maximum design values were lower than the actual wind speeds. Anyway, building envelopes may show a critical behaviour already under wind speed below the maximum values predicted by the Eurocode, due to an inaccurate design of technical details.

Currently, the country with the widest and most developed legislation in this regard are the United States. US Building Code ASCE 7-16 [18] provides a map of different areas according to the usual wind speed and the probability of developing hurricanes. The standard also recognises the protocols established by ASTM E 1886 [19] and ASTM E 1996 [20] as reference tests on glazed building elements hit by hurricanes or tornadoes. These standards involve the execution of two different tests on full-scale mock-ups to analyse the combined action of wind pressure and flying debris impact on the construction systems. During the impact tests, the missiles are shot by a compressed air cannon against the specimens (**Figure 2**). The mass and velocity of the test missiles vary according to the building's level of importance and its geographical location. Three missile types are allowed:

- small missile, a solid steel sphere with a mass of 2 g, a nominal diameter of 8 mm and an impact speed between 40% and 85% of the base wind speed (provided by the ASCE/SIX 7);

- large missile, a wooden element with a mass between 910 and 6800 g, a length between 525 and 4000 mm and an impact speed between 10% and 55% of the base wind speed (provided by the ASCE/SIX 7);

Figure 2.
Impact test on a glazed façade mock-up using a large wooden missile, according to ASTM E 1886 and ASTM E 1996.

- other missiles, another item with mass, size, shape and impact velocity determined as a function of the base wind speed, calculated by engineering analysis.

The standard impact points include the centre and the edges of the specimen. In case of successful impact tests, the specimens are subjected to pressure cycles according to the design wind speed, provided by the building codes. A total of 4500 positive and 4500 negative pressure cycles are performed and the duration of each cycle is 1–3 seconds. Also, the voluntary standard AAMA 506-16 [21] is based on ASTM E 1886 and ASTM E 1996, and it requires the control of other parameters, such as temperature, during the test. Instead, no standard tests are defined for the opaque envelope.

The Australian and New Zealand design Code AS/NZS 1170.2 [22] requires doors, windows and façade cladding systems to withstand the impact produced by:

- a wooden element with a mass of 4 kg and a cross-section of 100x50 mm, launched at a speed equal to 40% of the base wind speed for horizontal trajectories and 10% for vertical ones;
- a steel sphere with an 8 mm diameter and a mass of 2 g, launched at a speed equal to 40% of the base wind speed for horizontal trajectories and 30% for vertical ones.

The test methodology and acceptance criteria for the effects produced by windborne debris on opaque and transparent building envelopes are provided by the technical Note N.4 [23]. AS/NZS 1170 is the most stringent standard with respect to impact velocities. However, it does not require façade testing under positive/negative pressure cycles. Furthermore, it prescribes that the building envelope must resist flying debris impacts only up to 25 m of height from the ground.

At the international level, tests for certifying the resistance of glazed products to tornadoes are regulated by ISO 16932 [24], which is based on ASTM. As for the United States, there are no protocols for testing opaque envelope elements.

Finally, in Asian countries, only few standards provide prescriptions for the construction of resilient building envelopes, despite the high frequency of extreme phenomena. In Japan, for example, the standard JIS R 3109 [25] refers to the international Standard ISO 16932.

4. Assessment of the environmental vulnerability

Flying debris during wind events is mainly due to the detaching of materials and pieces from buildings, structures, and urban furniture, such as roof tiles, façade elements, antennas, etc. Therefore, wind can cause direct damages (i.e. failure or detachment from the 'source building' of elements under wind load actions) and indirect damages (i.e. impact of windborne flying debris on other buildings). Hence, each building can be both source and target for flying debris **(Figure 3)**.

The risks related to the environmental context are highly variable according to the levels of vulnerability that characterise the environment [26]. For this reason, the assessment of the local vulnerability level is fundamental [27]. First, the urban heat island contributes to creating a microclimate, which can worsen the consequences of local weather events [28, 29]. Then, the presence of old/historical buildings, but also buildings refurbished using new technologies, which are weak with respect to strong wind loads, could affect the vulnerability of the area.

In order to improve the resilience of the built environment, it is fundamental to strengthen the resistance against wind not only considering the already completed building but also its behaviour during the construction/renovation process, when the elements' resistance usually does not meet the final design performance.

The damage caused by windborne debris is a complex function of the wind conditions, the aerodynamic characteristics of the debris, the point of release, the type of impact and the strength of the structure impacted. The dispersion of windborne debris is related to several factors, including the variability of the wind speed, the turbulent flow field created by buildings and other structures, the fixing type and quality of the elements on the structure [30]. For example, a roofing tile securely fixed may stay in place during a hurricane until the wind reaches its maximum speed, when it will be carried away for a considerable distance and, consequently, hit a target building. On the other hand, if it had been less securely fastened, it may

Figure 3.
The environment assessment is essential to identify the possible risks and the elements that can fail in case of strong winds, becoming flying debris.

have detached from the roof during a weaker wind gust and it would have fallen to ground more quickly and closer to the source building.

As noted by Baker [31] in his theoretical analysis, small changes in initial conditions can completely change the whole character of a flight path. The removal of one roof tile can start to lift a neighbour one or can expose a neighbouring tile to higher wind loads. Hence, if one tile breaks free, those around it are likely to follow. If the first tile is immediately carried clear of the structure, then the subsequent path will primarily depend on the wind speed and direction at that time, which could easily be different from that which prevails when the next tile breaks free. Therefore, even if the tiles originate from a similar location, they may be dispersed by the variability in wind speed and direction (**Figure 4**).

Wind pressure acting on a building envelope depends on wind speed, characteristics of the surrounding environment and shape of the building itself. In particular, the parameters to be considered are:

- ground characteristics, since the smoother the terrain, the greater the wind speed;
- orography, which considers the presence of surface reliefs (hills, cliffs, etc.). Abrupt changes in topography cause wind to speed up;
- height and proximity of the surrounding buildings, which influence the pressure distribution. A building located in a densely populated city is shielded from the surrounding structures, while a building located near the sea or in open countryside is totally exposed to the surrounding weather conditions;
- base wind speed, defined by the standards as a function of the geographical area and the altitude above sea level. As the speed increases, the pressures grow exponentially;
- wind direction, which determines the arrangement of positive and negative pressure areas;
- building height, since the wind speed increases with the height above the ground. Therefore, the taller the building, the higher the speed and the wind load;

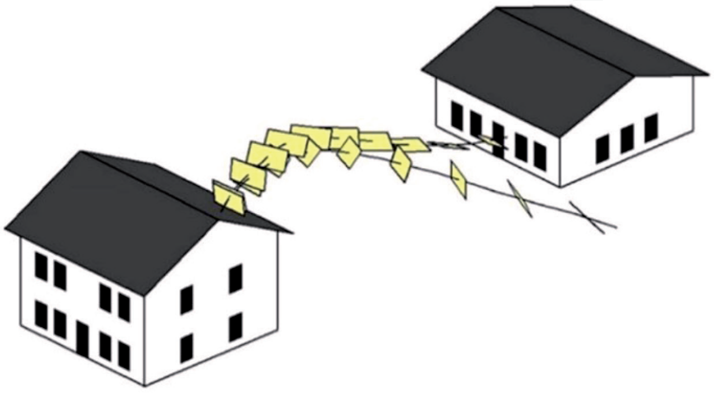

Figure 4.
Example of probabilistic wind-borne debris trajectories of a typical roof-sheathing panel with identical initial conditions [32].

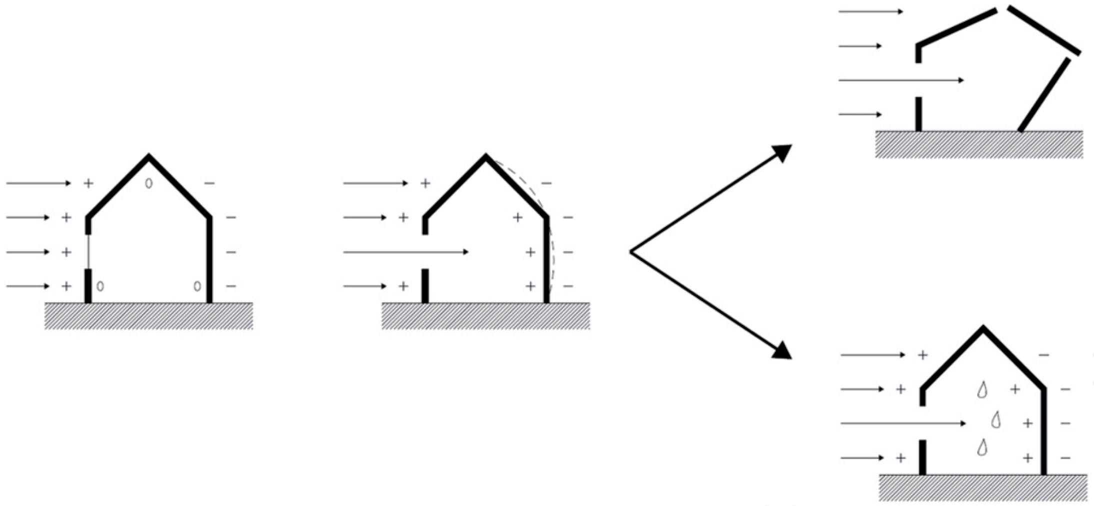

Figure 5.
Schematic of internal pressure condition in case of wind infiltration inside a building [10].

- building shape, irregularities in the geometry (such as recesses, overhangs and changes in inclination) can cause localised turbulence. These cause punctual acceleration phenomena with a consequent increase in the intensity of the wind load.

During extreme wind phenomena, the pressures acting on the building envelope can exceed the maximum design values, and the action of flying debris coming from the surrounding environment can be added to these actions. If flying debris reaches high speeds (and consequently high kinetic energy), it can damage and break the components of the building envelope (mainly transparent façades and windows, but also some types of light dry-assembled opaque façades, walls, etc.).

The main consequences deriving from these disruptive actions are:

- increase in internal pressure and new redistribution of loads on internal and external elements. The downwind façade is subjected to higher pressures than the design ones and it can be damaged, or it can even collapse. Also, pressures acting on the internal walls become much higher than that considered for their design;
- water penetration through openings and breaks in the building envelope, pushed by the pressure difference between inside and outside.

The breaking of even a small window due to a flying debris impact is typically sufficient to cause full pressurisation inside a building. When a building becomes fully pressurised, the loads applied to the exterior walls and roof are significantly increased if compared to the designed ones. The build-up of high internal pressure can blow down interior partitions and blow ceiling boards out of their support grid. Furthermore, water penetration can cause further damage to the building's content (**Figure 5**).

5. Design methodology for resilient building envelopes

Wind-induced damages are often related to the buildings' construction quality. Failures can affect building structures; however, the worst consequences are usually concentrated on façades and roofs. Nevertheless, ensuring that the entire building envelope is not damaged during extreme events requires design strategies that could be uneconomical. The sporadic occurrence of these phenomena does not justify the adoption of specific design solutions on a large scale. Therefore, it is necessary to define an analysis methodology that allows designers to collect the necessary information to establish the level of risk related to a specific case study, with respect to exposure to extreme winds and flying debris effects on it. In case of high-risk levels, the buildings that must remain always in operation and subject to higher wind pressures and the impact of more damaging debris must be identified and design strategies must be specifically planned.

An assessment methodology for resilient building envelopes design, for new and existing interventions, is proposed and discussed in this paragraph (**Figure 6**). The first analysis to carry out concerns the wind conditions at the project site, both in terms of average speed and prevailing direction, given by the standards and/or from a climatic database. The data included in the Codes represent an average of historical records, they do not provide information on the wind characteristics during exceptional events that occurred in the past. For this reason, it is also necessary to analyse the wind values recorded in the last decades to evaluate whether these are in line with the values given by the standards.

The second analysis involves the collection of information regarding buildings and urban spaces located within a radius of 200 m from the considered building. It is necessary to evaluate:

- the geometric characteristics and the construction technologies;
- the conditions and level of maintenance of the nearby buildings;
- the urban furniture located in the surrounding areas, such as in parks, streets and uncultivated and abandoned spaces.

Based on the information collected, it is possible to identify the potential wind-borne debris that might hit the target building in case of extreme wind phenomena, which might be considered in wind engineering analysis for an integrated design.

The assessment of the possible impact effects on the building envelope is then carried out based on the potential debris, the building characteristics and function (which determines its social and economic importance). The results of the analysis should meet the requirements in terms of building safety, serviceability, durability and robustness. Safety is the most important issue during the design, and it shall be strictly guaranteed. Serviceability and durability are fundamental as well. Hence, designers are supposed to minimise the risk of out-of-service and maintenance costs during the service life.

In case the requirements provided by the available construction standards are not considered appropriate, a building design optimization process should be considered. Once obtained, the optimised parameters could be used as a guideline for re-designing the whole building envelope. In this case, the design of the technical details should be defined after specific experimental tests, as well as finite element modelling. Impact tests might also be performed, while data including the impact velocity and impactor characteristics (material, geometry, etc.) are collected. This information plays a significant role in the definition of the necessary equipment to be arranged for the verification of the building envelope's effectiveness against flying debris protection. To perform this kind of impact test on façades, it is necessary to set up specific testing equipment. In fact, compared to existing tests conducted using missiles, the projectile to be shot on the façade might have different sizes, materials, weights, and impact speeds. The test aims to verify the façade solution's effectiveness in withstanding the impact of wind-borne objects, which have been previously identified as a potential danger under extreme wind conditions (**Figure 6**).

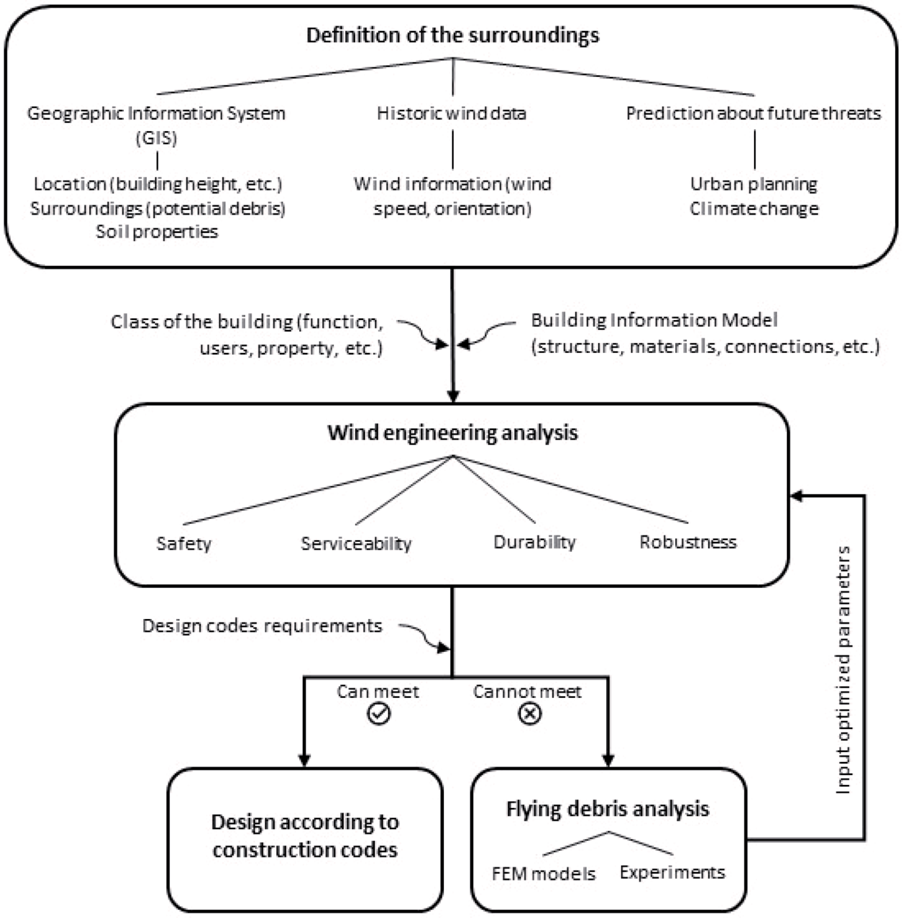

Figure 6.
Proposed methodology for resilient building envelope design.

6. Examples of resilient building and urban environment design

The risks deriving from extreme wind events, such as tornadoes or hurricanes, cannot be eliminated completely, but specific design strategies can be used to mitigate their effects. Adequate building resistance to wind actions can only be achieved with good design, construction and maintenance. A significant deficiency of any of these three elements could compromise the performance of the entire building [33].

When envelope failures occur only in specific areas of the building envelope (i.e., corners, changes in building geometry and inclination, etc.), the causes are usually related to the underestimation of the wind pressure acting on their surface. Otherwise, scattered failures are mainly related to the impact of windborne debris or to the effect of interference due to the presence of other buildings.

In this paragraph, some considerations and recommendations about resilient envelope design are presented and discussed.

For what concerns opaque façades, although some failures of massive brick walls have been observed after cyclones and hurricanes, the construction systems most subject to damage are the dry-assembled ones. In recent years, there has been an increase in the use of dry construction technologies, which allow higher flexibility, lightness, fast installation and waste reduction. Dry cladding systems are composed of the combination of different materials and layers, which allow them to achieve increased or higher energy performance compared to traditional technologies to optimise the thickness, masses and time of installation and to simplify the connection and interfaces among the various components (**Figure 7**).

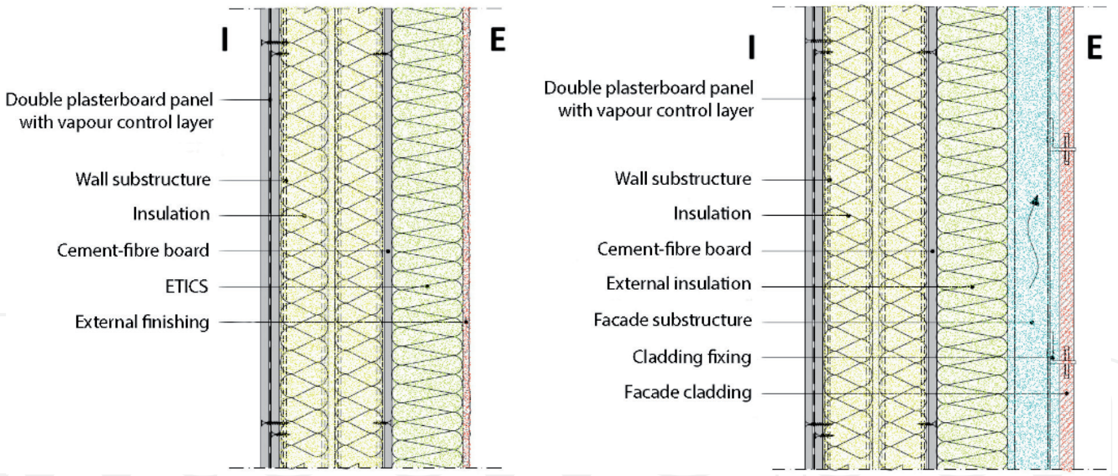

Figure 7.
Example of ETICS and ventilated façade system applied on a dry-technology wall.

Figure 8.
Detachment of the plasterboard panel from the wall substructure in Pensacola (Florida) [34].

Dry stratified vertical walls, although without any structural function, must be able to resist positive and negative wind pressures to avoid their collapse. Therefore, the wall substructure must be adequately fixed to the structural support and adequately stiffened by decreasing the distance between mullions, or by adding intermediate transoms. Finally, it might be useful to integrate a double panel fixed to the external side of the substructure, using concrete-based panels reinforced with a fibreglass mesh instead of classic plasterboard panels.

In case of ETICS (External Thermal Insulation Composite Systems) applied on dry walls, in addition to damage and perforation of the insulation layer by flying debris, common failures concern the detachment of the external coating from the insulation, the separation of the insulation from the rear panel of the dry-wall (e.g., concrete-based or plasterboard panels) and of the latter from the wall substructure. In the worst cases, it is also possible to detect the partial failure of the substructure **(Figure 8)**.

Considering ventilated façades, failures can involve the cladding panels, the substructure, or the connections of the panels to the substructure. The finishing panels are the most vulnerable components since they are the most exposed and stressed by wind actions. The substructure components are calculated according to the expected state of stress and the maximum service limit displacement. Moreover, the substructure should be provided with adequate reinforcements in all the areas that can be subjected to particularly high stresses (for example, the building corners). The impact of flying debris on the façade can cause damage, above all, to the finishing slabs **(Figure 9)**. The most critical points are generally the centre of the slab and the anchoring areas, where failures might be more likely due to the concentration of

Figure 9.
Extensive damage due to wind action and flying debris to the opaque and transparent façade of the Hyatt regency hotel (New Orleans) [8].

stresses. The resistance of the system can be increased in several ways, including the reduction of the size of the slabs, the increase of the slab thickness and of the number of fixings for each slab; the reduction of the distance between the substructure elements and the fixing brackets and the increase of the metal substructure thickness. Also, the use of ductile materials for the finishing slabs (e.g. metal panels) can ensure better behaviour against non-penetrating flying debris than fragile materials. The size and anchor type of the cladding are relevant since the panels might detach from the substructure, causing trouble to the people outside and damage to the buildings.

The fixing typology might allow the substitution of each module independently in case of damage. Attention is to be paid to the action of wind inside the cavity. In fact, the wind can enter through the façade openings, joints or broken panels, stressing the anchors and tearing the cladding away. The anchors of the façade should be tested under cyclic loads, as well as under localised impacts, to evaluate their mechanical resistance.

Concerning flying debris impact, transparent façades are the most critical part of the building envelope. Glass breakage is particularly insidious, since it causes an increase in the internal pressure due to wind infiltration into the building, compromising the envelope's watertightness as well (**Figure 10**). There are mainly two ways to improve glass façades behaviour:

- increase the resistance of the façade components;
- introduce external shielding systems acting as façade protection.

The use of float glass should be avoided, while the use of laminated glass is preferred. In fact, in case of breakage, the plastic interlayer keeps the glass pieces in place, avoiding the formation of openings and damage to people and/or things. The most used interlayer is the PVB, but over the last decade, new solutions have been studied and tested, which guarantee greater resistance to the impact of flying debris in areas exposed to the danger of hurricanes. PVB reduces its elastic module to around 30°C (glass transition), decreasing its mechanical properties. In case of exposition to the sun and for higher resistance to flying debris impact, ionoplast interlayers are recommended. Moreover, for further improvement of the glazing resistance against impacts, laminated glass made by coupling float and toughened glass can be used.

However, acting only on the type of glass is not enough. In fact, it is also necessary to use adequate glass retention systems. The structural bonding technology responds better to the mechanical stresses caused by wind than mechanically retained façades. First, the sealing ensures a good response to wind suction since it is put on the whole glass perimeter. Moreover, the presence of the gaskets prevents direct contact between the glass and the frame, avoiding mechanical stresses in case of wind loads and possible glass or frame breakage. Anyway, a mechanical retention system should be integrated, acting as additional protection in case of adhesion failure. If a solution with mechanical retention is chosen, particular attention must be paid to the connection between the frame and the pressure plate.

The choice of the frame must take place according to the reliability of the system and the methods of breaking (and consequent replacement) of the glazing. From this point of view, a unitized system allows easier maintenance and guarantees a higher quality of the product, since the elements are assembled off-site. An advantage of the unitized façade, compared to stick systems, is that each cell is independent of the others, allowing the substitution of a single unit in case of damage. Moreover, the façade system should integrate fixings that allow the substitution of the broken glazed part without touching the inner frame and layers. Hence, in case of glass breakage during wind events or construction phases, it is possible to change only the glazed part and fix it to the inner frame.

If a stick system is preferred, the length of the mullions must not exceed the distance between two consecutive floors and the connection between the vertical and horizontal elements must be reinforced. Stick systems show lower performance than unitized façades in case of strong wind events. This is especially because, in case of damage to the glazed or framed parts, the substitution of a large façade portion might be required. The cross-section between transoms and mullions is critical from the point of view of wind loads, thus preliminary pull-out laboratory tests should be performed on this connection. The building involves a façade portion with external louvres.

Point-fixed curtain walls are, on the other hand, to be avoided in locations subject to extreme wind events. In fact, all the functions required of a building are entrusted to glass (mechanical resistance, air and water tightness, etc.); therefore, in the event of glass failure, the entire façade fails.

Among the solutions that increase the level of protection, expensive but effective technology is the double skin façade. Normally used for purposes related to internal comfort, this solution, if properly designed, provides good protection of the indoor environment. The internal and external glazing are totally independent of each other, and they are separated by an air cavity. The outer skin must be strong enough to protect the inner one in case of extreme events. Shielding systems (with slats, fixed, adjustable, etc.) can be installed in the air gap, with the aim of regulating solar radiation and indoor daylighting. However, these systems must be able to withstand gusts of wind and the impact of flying debris, and, in case of failure of the outer skin, they should be able to close completely to form a continuous barrier to protect the innermost glazing. If not sufficiently resistant, once exposed to the external environment, the screens could become a potential source of debris.

Other protection systems are represented by external shielding, which can be permanent or can be activated in case of extreme wind events. Some examples are roller shutters, shutters or more innovative systems, such as coiled wire systems (i.e., light metal meshes, used both for decorative purposes and to improve the building's thermal performance). The presence of external sunscreens can be hazardous in case of strong wind since they can break and damage the façade itself or other parts of the building envelope. Thus, they should be fixed to the façade in an appropriate way and their substitution should be guaranteed without touching the façade module behind them.

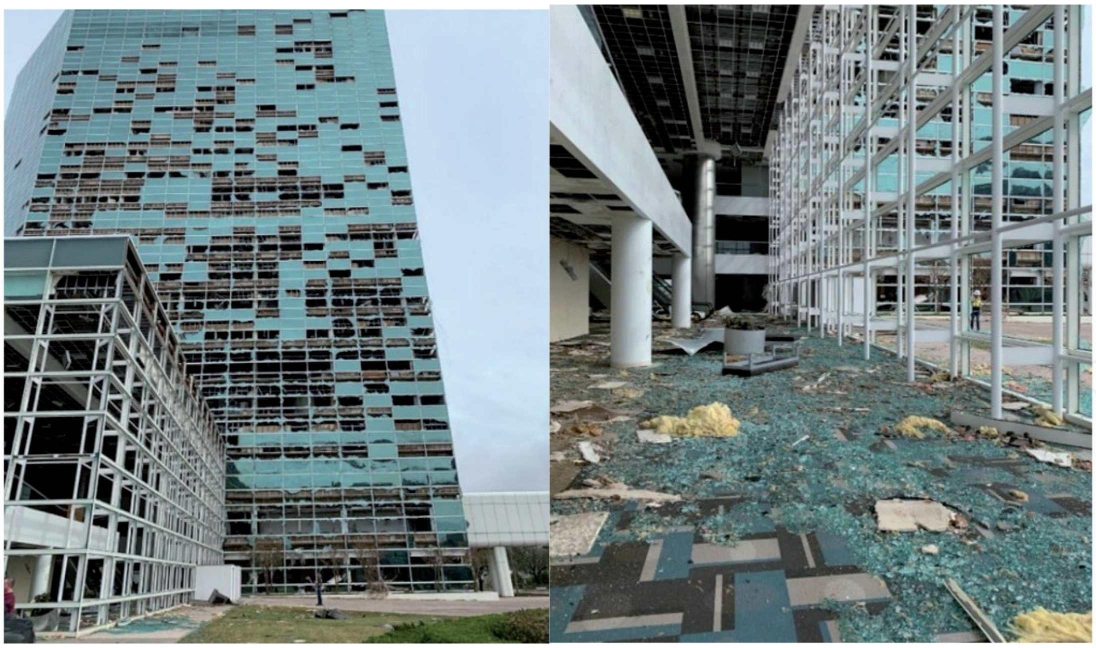

Figure 10.
Capital one tower (Louisiana) transparent façade damaged by hurricane Laura [34].

7. Conclusions

Climate change effects call for an urban transition to create resilient urban environments that can face the present environmental challenges, such as extreme weather events. The effects produced by windstorms are often devastating, despite this the topic is still very little studied. The resilience of the building envelope to extreme phenomena is fundamental and must be achieved through careful planning and accurate design. This must consider the meteorological and environmental boundary conditions of the building site, the identification of the most critical areas of the building and the localised adoption of building technologies and strategies specific design, with the aim of minimising the risk without excessive uneconomical design.

The considerations regarding the existing standards show the current lack of regulations on the topic in Europe. Insurance companies that protect buildings in the event of extreme events are already present, but there are no design requirements concerning the building envelope resistance against the impact of windborne debris. There is an urgent need, in the European context, to introduce adequate regulations and impact test requirements in order to ensure the building's functioning after hazardous events, at least for public and strategic buildings, that may also be used as extreme-weather shelters.

A design tool must be developed for façade engineers to assess adequate airborne debris resilience of façades, based on local environment and aerodynamic simulation of debris flight in strong wind conditions. This design implementation should lead to a safe building envelope design both for new constructions and retrofit solutions. By integrating local measures for the built environment adaptation to climate change, Authorities, project developers, funders and community members can motivate and educate people, provide incentives and develop a favourable environment for the promotion and innovation of a sustainable building design and construction standards for the community resilience to climate change.

Conflict of interest

The authors declare no conflict of interest.

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