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Extreme wind events and risk mitigation: overview and perspectives for resilient building envelopes design in the Italian context

Mazzucchelli Enrico S. – Politecnico di Milano, Milano, Italy, e-mail: enrico.mazzucchelli@polimi.it

Scrinzi Giacomo – Politecnico di Milano, Milano, Italy, e-mail: giacomo.scrinzi@polimi.it

Pastori Sofia – Politecnico di Milano, Milano, Italy, e-mail: sofia.pastori@polimi.it

Rigone Paolo – Politecnico di Milano, Milano, Italy, e-mail: paolo.rigone@polimi.it

Lucchini Angelo – Politecnico di Milano, Milano, Italy, e-mail: angelo.lucchini@polimi.it

Trabucco Dario – Università IUAV, Venezia, Italy, e-mail: trabucco@iuav.it

Milardi Martino – Università Mediterranea di Reggio C., Reggio Calabria, Italy, e-mail: mmilardi@unirc.it

Abstract: 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. During extreme wind events, threats are mainly due to the detaching and flying of materials and pieces from buildings and other man-made structures: roof tiles, façade elements, antennas, etc. are dragged away becoming flying debris that endanger people and properties, hitting surrounding buildings at high speed. Therefore, wind can cause direct damages to the building envelope (building elements failure under wind loads or detachment from the source) and indirect damages (flying debris impact on other buildings). The paper deals with effects and consequences of strong wind events on the built heritage, with a focus on the Italian context, proposing risk mitigation strategies which are part of mitigation and adaptation actions to respond to current and future climate threats. The themes were explored in the new course "Strategies and tools for advanced building envelopes design towards resilient constructions" in the doctoral program in Architecture, Built environment and Construction engineering (ABC-PhD) – Politecnico di Milano.

Keywords: resiliency, risk mitigation, climate change, building envelope, storm wind

1. Introduction

The built environment adaptation to climate change is nowadays an essential challenge to be faced, from several different points of view. For what concerns the CO_2 emissions, much has already been done by governments and stakeholders in general. In 2015, the construction and operation of buildings was responsible for 38% of global energy-related CO_2 emissions. By 2020, CO_2 emissions in the sector had fallen by an estimated 10% to 11.7 gigatons, a level not seen since 2007. This trend was driven largely by the energy demand reduction due to the COVID-19 pandemic, but also by continued efforts to decarbonize the power sector [1]. Conversely, the world is experiencing a huge pressure on living conditions and an increase in damage to assets and asset value due to extreme weather events, notably in coastal areas where most of the world's population lives. In fact, the expected impacts of climate change, including sea level rise, heat waves, droughts, and storms, will increasingly affect the built environment and in turn the society as a whole (Table 1). The number of extreme weather events has increased by more than 250% since the period between 1980 and 2013, and this upward trend is continuing [2]. Recent research [3] predicts that by 2050, 1.6 billion urban dwellers will be regularly exposed to extreme high temperatures and over 800 million people living in more than 570 cities will be vulnerable to sea level rise and coastal flooding.

When ill-suited to their local environment and strongly exposed to extreme climate conditions, buildings become drivers of vulnerability, rather than providing shelter, leading to both human tolls and economic losses (Table 1) [2 - 4]. Low-income, informal, over-crowded and ill-planned 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 [5].

Table 1. Classification of climate change technical and social climate impacts on buildings and their users [2]

TECHNICAL		SOCIAL	
Safety	Building services	Construction & RE Sector	Society
Damages to buildings	Reduced comfort and well-being	Increase in building (capital) costs and reduced affordability	Displacement / migration
Risks to health and human safety	Loss of use of buildings	Increases in operations and maintenance costs	Instability
Premature aging of components	Reduced accessibility	Legal and professional liability	Loss of external services and networks
	Malfunction of building systems	Increases in insurance premiums	Loss of cultural property

The key climate-related hazards, such as windstorms, forest fires, heavy rain and floods, etc., lead to the growing necessity for buildings to be resilient to extreme and unpredictable weather conditions. The increased frequency, intensity and impact of extreme events call also for buildings designed for protection against physical damages and failures and 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, it generally appears to be quite detailed about seismic fragility and vulnerability and energy demands related to climate change, but definitely not towards other hazardous events, such as extreme wind events. Furthermore, the most commonly used climate data for buildings design and studies are no longer reliable, as traditional climate variables, fundamental inputs to most engineering disciplines, need to be seriously reconsidered [6].

The paper deals with effects and consequences of strong wind events on the built heritage, with a focus on the Italian context. In fact, Italy is located in an area identified as particularly vulnerable to climate change, as the Mediterranean region is considered to be a hotspot of climate change impacts [7], making it notoriously prone to natural hazards and climate change which are expected to critically increase the Italian vulnerability to climate-related hazards over the next decades. This, combined with the economic, social and environmental pressures, makes Italy one of the most vulnerable countries in Europe nowadays. In any case, it should be highlighted that several European countries have experienced an increased number of extratropical cyclones and hazardous storms, about which no observed trends are known due to insufficient monitoring [8]. In the next future, mid-latitude cyclones are projected to increase in frequency, and their intensity will likely increase too [9 -10 -11], resulting in wind speed peaks way higher than those provided by the NTC 2018 standard [12]. The themes were explored in the new course education program “Strategies and tools for advanced building envelopes design towards resilient constructions” in the doctoral program in Architecture, Built environment and Construction engineering (ABC-PhD) – Politecnico di Milano.

2. Extreme wind events: effects and consequences

While, in the past, Europe was not particularly affected by extreme wind events, in the last few years the intensity and frequency of such natural hazards have been increasing [13]. Relevant damages to the environment, properties and people's safety are produced by these events, especially in countries which had not been used to them. In 2019, strong winds were responsible for the 38% of the recorded injuries and the 16% of the recorded fatalities caused by extreme weather in Europe [14]. Among others, the impact of wind-borne debris on building envelopes at high speed is one of the major risks related to powerful storms and extratropical cyclones [15]. These flying objects are capable of damaging the building envelope and its content, also eventually resulting in wind-driven water infiltration [16 - 17]. The related potential losses are significant, as property and people's safety might be affected. However, very few investigations have been conducted concerning debris impacts and resulting damages [18]. Wind has been investigated extensively to prevent the failure of major building elements. Accordingly, codes and standards have been developed since decades, but recent extreme wind events in Italy and Europe prove that our existing buildings are nowadays very vulnerable [15]. The combination of increased wind actions and meteorological events characteristics different from the past (i.e.: downbursts) on the average old/historic building stock is the main reasons of wind-induced damages. Building components and urban furniture are considered as vulnerable elements when subjected to strong wind events, and namely potential flying debris.

Governing bodies in areas prone to extreme weather events (i.e.: Florida - USA, Honk Kong, Japan, Australia) already implemented several measures to mitigate the effects on the built environment, with special attention to wind. Studies and field observations have been conducted on the consequences of major past and recent hurricanes, typhoons and tornadoes on the built environment and human safety. The major goal of such measures is preventing damages to people and properties due to flying debris. The aim is pursued by adopting two sets of actions:

- reducing the likelihood of the flying debris phenomenon, by improving the resistance of man-made elements to wind;
- mitigating the consequences of flying debris, by setting design guidelines and testing methodologies to ensure the resistance of the building envelope to the flying debris impact.

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

These measures apply to all buildings in areas prone to severe winds. Mitigation and adaptation both need to be pursued actively to address and respond to current and future climate threats. Future-proofing the building sector must be a centre piece of the human environment resilient design strategy. Easier target performances are requested for common buildings, while strategic infrastructures (hospitals, emergency services, schools, etc.) are requested to meet very demanding requirements, especially for their envelopes, in order to act as a shelter in case of need. Currently there are no requirements concerning the consequences of wind-borne flying debris in Europe, nor in Italy, because in the past such events were considered so exceptional not to represent a threat. However, it is a matter of fact that several European countries experienced an increased number of extra-tropical cyclones and tornadoes in the very last years including multiple so-called Medicanes (Fig. 1).

3. Environment assessment and risk analysis issues

During wind events, threats are mainly due to the detaching and flying of materials and pieces from buildings and other man-made structures: roof tiles, façade elements, antennas, etc. are dragged away becoming flying debris that endanger people and properties, hitting surrounding buildings at high speed. Therefore, wind can cause direct damages to the building envelope (building elements failure under wind loads or detachment from the source) and indirect damages (flying debris impact on other buildings) (Fig. 2).

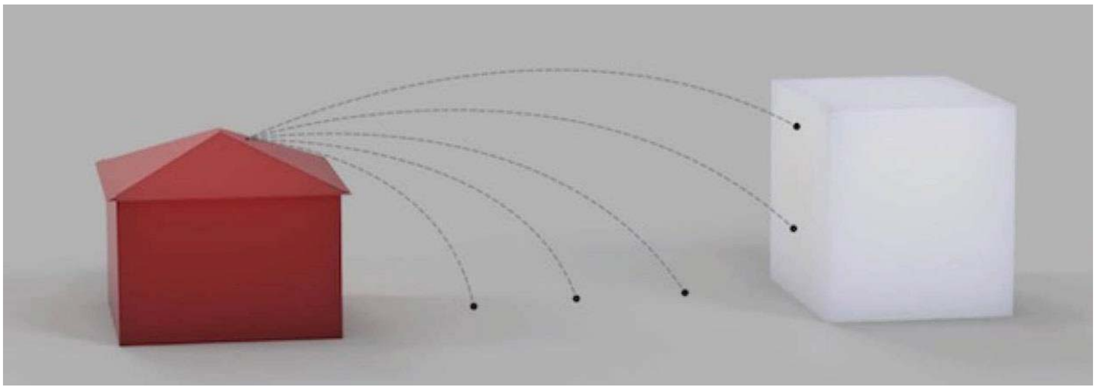

Figure 2. A building can be a source and/or a target for flying debris.

The risks related to the environmental context are highly variable according to the levels of vulnerability that characterize cities and communities [15 - 19]. In particular, the urban landscape structure and the characteristics of the urban land surfaces can alter the microclimate and contribute to the urban heat island [20], aggravating local impacts [21]. Also, the presence of old/historical buildings affects the vulnerability of the area, together with existing buildings refurbished using new technologies and solutions, without considering their behaviour under potential strong winds. Therefore, it is necessary to promote the assessment of local vulnerability levels (Fig. 3) as well as the mitigation and adaptation capacity of places [22].

International and European codes and standards are considered as primary reference documents for the study of local building protection requirements. The values provided are to be referred to the context and the location of specific and strategic buildings (i.e.: hospitals, schools, etc.) through the analysis of extreme wind events records and the aid of GIS (Geographic Information System), in order to identify the existing threats to such fundamental facilities. Collected data could be used to develop risk maps and to better define catastrophic wind events in Italy on a probabilistic scale.

The increasing risk of wind-induced damages should raise the awareness of designers, builders, building managers, building owners and authorities on the importance of a careful building envelope design to resist against the rising wind loads recorded in Italy due to climate change. It is a common perception, as also clearly stated in several studies and reports by insurance companies, that the increased frequency and severity of extreme weather events is causing more and more damages and even higher repairing costs.

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

In order to improve the resilience of the building envelope different components, it's fundamental to strengthen the resistance of new and refurbished buildings against wind, not only during their normal life but also considering construction and renovation operations when their strength characteristics usually do not meet the design final performance.

The dispersion of windborne debris is caused by a number of factors including variability of the wind speed and direction at the instant a particular object breaks free, the non-uniform flow field created by buildings and other structures, and the aerodynamic forces and moments that act on the debris. The damage caused by windborne debris is a complex function of the wind conditions, the availability of debris, the point of release, the aerodynamic characteristics of the debris, the impact dynamics and the strength of the structure impacted.

A clear distinction can be drawn between loose material lying on the ground (such as stones or building materials) and attached elements (e.g. roof tiles). Loose materials will start to move under wind action if the wind load exceeds the product of their weight and a friction coefficient (having a wider definition than usual to account for the likelihood that particles are not in general lying on a smooth surface but may fall into holes or be trapped behind fixed objects).

The fixture strength integrity '*I*' is defined as the ratio between the wind force required by an object to start flying and its own weight. For the great majority of real fixed objects, the value of '*I*' is likely to be much greater than one, meaning that the wind force required to break them loose is greater than their own weight. Instead, for loose objects with an effective friction coefficient of about unity, *'I'* will be of order unity. The distinction becomes important when the conditions for flight to occur are considered.

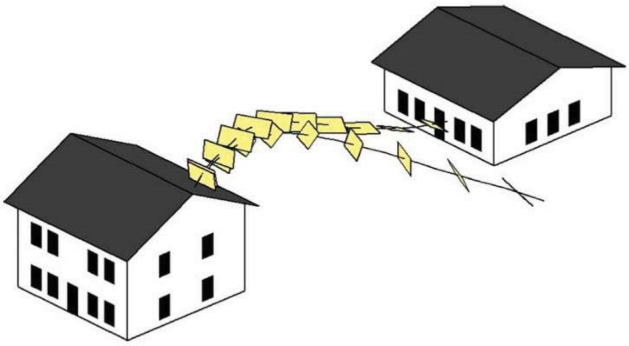

Figure 4. Example of probabilistic wind-borne debris trajectories of a typical roof-sheathing panel with identical initial conditions [23].

The path followed by a piece of debris is also influenced by the wind speed and direction at the moment the item breaks free from the structure it is a part of, which will depend on how well it was fixed in place and the loads created by the wind, as discussed by Wills et al. (2002) [24]. For example, if a roofing tile is reasonably securely fixed during a hurricane, then it may stay in place until the winds are near their maximum strength, and then if failure occurs during a strong gust, it is likely to be carried a considerable distance. On the other hand, if it had been less securely fastened then it may have broken free during a slightly weaker gust and fallen to ground more quickly.

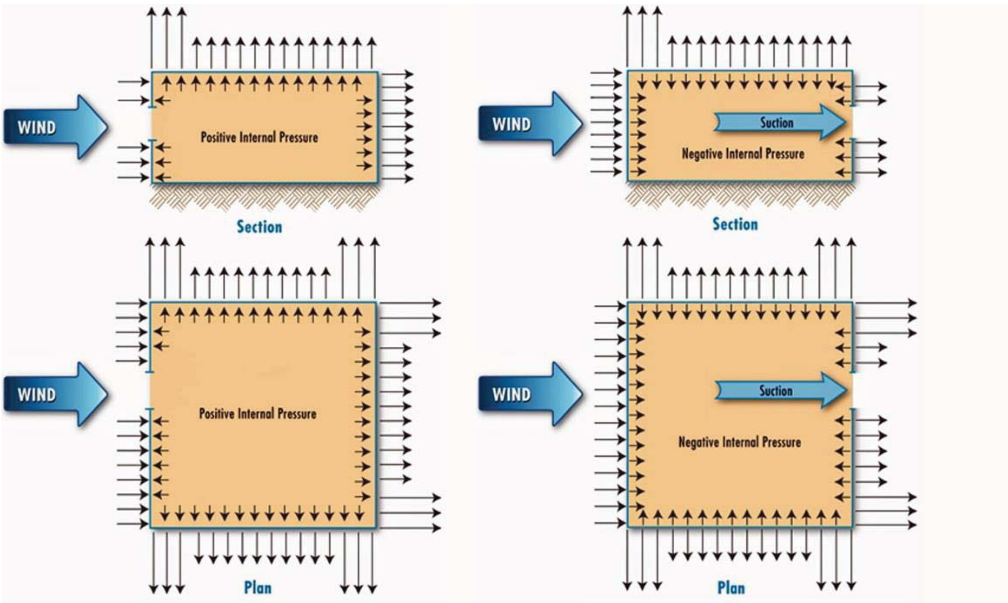

Figure 5. Schematic of internal pressure condition when the dominant opening is in the windward wall (on the left) and Schematic of internal pressure condition when the dominant opening is in the leeward wall (on the right [26].

Storm damage surveys tend to suggest that the removal of one roof tile can either start to lift a neighbour 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. Hence, even if the tiles originate from similar locations, they may be dispersed by the variability in wind speed and direction. As noted by Baker (2007) [25] in his theoretical analysis, small changes in initial conditions can completely change the whole character of a flight path.

Finally, the breaking of even a small window due to flying debris impact is typically sufficient to cause the full pressurization of a building interior. When a building becomes fully pressurized, the loads applied to the exterior walls and roof are significantly increased (Fig. 5) and the build-up of high internal pressure can also blow down interior partitions and blow ceiling boards out of their support grid. Furthermore, once damaged, the façade can't stop rainwater (often associated with the meteorological events described above), and this causes further damage to the building (Fig. 6).

Figure 6. Flying debris damages on a building façade and view of a floorplan damaged by the combined action of rain and wind.

4. Resilient building envelopes design methodology and risk mitigation

A proposed assessment methodology for resilient building envelopes design is shown in Fig. 7. Based on the building location analysis, the design wind loads should be first identified according to current standards and local regulations. The data concerning the maximum records over the past decades should be analysed to check whether they are in line with the minimum design wind load requirements. The analysis of the surrounding environment should highlight which of the building components could potentially fly under extreme wind conditions and hit the façade. This phase is fundamental to identify the various flying debris typologies where the wind engineering studies should be conducted on, for an integrated design.

The assessment of the wind impact on the building envelope is then carried out based on the potential threats, the class of building (which determines the importance of the social and economic life) and the building characteristics and technologies. The results of the analysis should meet the requirement in terms of safety, serviceability, durability and robustness. The safety is the most important issue during the design, and it shall be strictly guaranteed. Moreover, serviceability and durability are also fundamental, hence designers are supposed to minimize the risk of out-of-services and maintenance costs during the service life.

In general, if requirements provided by the construction standards are not considered appropriate, a building design optimization should be considered. The design details can eventually be defined after the expressly-designed experimental tests, as well as finite elements modelling. The further optimized parameters can be used as a guideline for re-designing the whole envelope. 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 effectiveness against flying debris protection. To perform this kind of impact test on façades, it is necessary to set up specific testing equipments. In fact, compared to existing test conducted by the use of missiles, the projectile to be shot on the façade must have different size, material, weight, and impact speed. The test aims to verify the façade solution effectiveness in withstanding the impact of wind-borne objects which have been identified as a potential danger in extreme wind conditions. The upgrade of existing building envelopes might be more complex and lead to different solutions to be evaluated case by case.

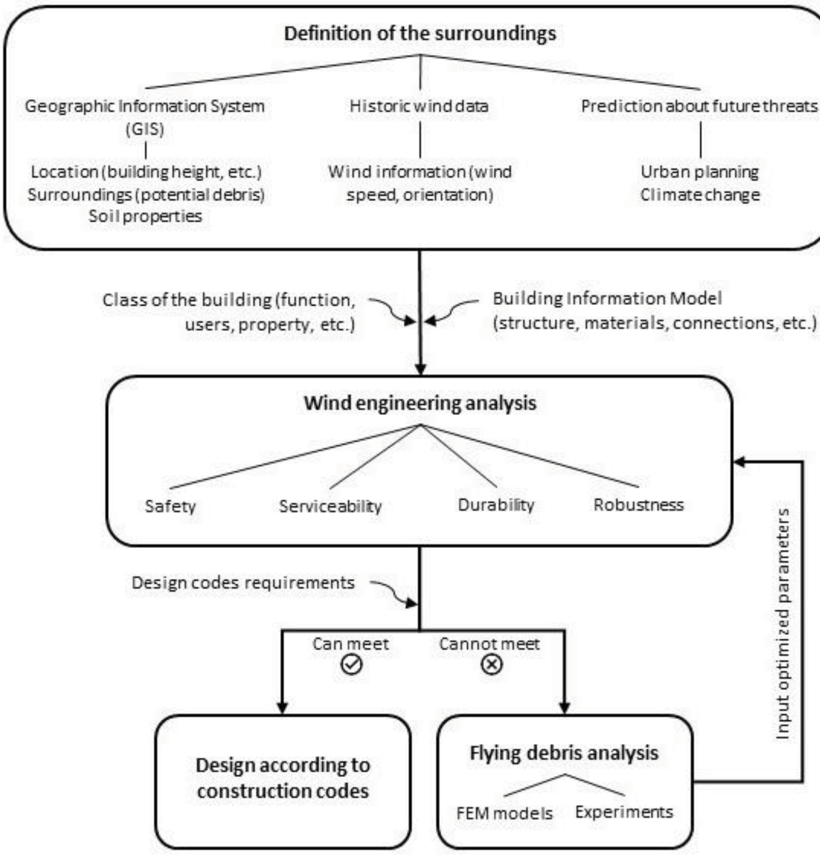

Figure 7. Proposal of a resilient building envelope design strategy flowchart.

Concerning flying debris impact, windows and glazed facades are the most critical part of the building envelopes. In this case, it is important to assess the resistance of the external glass against surface impacts and, if in presence of a double glass, the bending resistance of the inner glass in case of breakage of the external one. One of the possible strategies to improve the behaviour of a glazed façade against strong wind loads and flying debris impact is to replace the existing glass with another characterized by better mechanical performances. For improving the glazing resistance against impacts, the use of laminated glass is recommended, made by coupling float and toughened glass. Further resistance to impacts can be achieved by using ionoplast interlayers instead of standard PVB.

Also, 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 envelope. Thus, they should be fixed to the façade in appropriate way and their easy substitution should be guaranteed in case of breakage.

Considering opaque envelopes, those integrating an external façade cladding are the most vulnerable in case of strong wind. In this case, the use of a ductile material for the cladding (e.g. metal panels) ensures a good behaviour against non-penetrating flying debris, while fragile materials might break in case of impact. In addition, the size and anchor type of the cladding are relevant, since the panels might detach from the substructure, causing troubles to the people outside and damages to the buildings (e.g. water infiltration). The anchors of the facade should be tested under cyclic loads, as well as under localized impacts, to evaluate their mechanical resistance. The cladding panels should allow the substitution of each module independently in case of damage.

5. Conclusions

Flying debris resilience of building façades is fundamental to avoid building envelope failures and internal pressure growth with consequential damages to the building. There is an urgent need for impact test requirement introduction in European countries to have adequate façade solutions against wind-borne debris in extreme winds, at least for public buildings and constructions of primary importance. In fact, during disaster events and in post-emergency conditions, structures such as hospitals or police stations must not interrupt their public service. As a matter of fact, these buildings must be operational particularly during disaster events, to also work potentially as extreme-weather shelters.

For this reason, façade resilience to windborne debris has to be achieved, avoiding uneconomical design based on existing solutions. 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 locally adapted climate adaptation measures in post-disaster reconstruction, owner-driven construction or slum refurbishment, as well as building retrofits and new constructions, authorities, project developers, funders and community members can motivate and educate people, provide incentives and develop a conducive environment for the promotion and innovation of sustainable building design and construction standards that progress community resilience to climate change.

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