Wind Loads in Low-Rise Buildings with Parapet: A Systematic Review

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Abstract: A relevant analysis for the design of buildings is wind-induced loading. Although this has led to numerous studies, there have been relatively few investigations on the effects of parapets on wind loads. This systematic review addressed quantitative and qualitative behavior of wind loads in buildings with parapets in the *Web of Science, ScienceDirect, SCOPUS*, and *Compendex* databases. Using alternative methods such as citation searches and websites were selected 6 research articles were and added 6 papers. The results treat the influence of parapets on the behavior of the wind on roofs of low-rise buildings, especially wind loads, and its correlation with the building's geometric characteristics and parapets. The results identified pressure increases on roofs for low parapets (h<1.0 m); however, the dates vary according to the h/H ratio. Also, in general, the higher the parapets, the highest the reduction in the intensities of the pressure coefficients. Still, the porous and cantilevered parapets are more efficient and economically viable as a device to mitigate wind loads when compared to solid parapets in low buildings. Finally, for an open canopy, the height of the parapet is the main parameter, although the length of the building is also relevant.

Key-Words: Wind action, systematic review, low-rise buildings, parapet.

Received: May 19, 2022. Revised: October 22, 2022. Accepted: November 24, 2022. Published: December 31, 2022.

1 Introduction

A parapet, by definition, is a low protective wall that rises above a roof, balcony, or terrace, [1]. The intensity of wind load incident on buildings varies based on the profile of each building element and orientation. These factors considerably alter the pressure differences at various points along the building exterior.

While parapets add aesthetic features to a building, creating architectural elements, hiding rooftop equipment, and serving other functions, they can still act as an aerodynamic performance mitigation device, among other factors as well as the shape and size of the roof.

Studies have shown that parapets offer relief for roof assemblies in resisting wind uplift. Nevertheless, parapets themselves experience stress due to wind loads. There is no consensus about their effectiveness since the reduction in the magnitude of wind pressures is directly related to height, the wind direction angle, and the building's shape, among other factors, [2], [3].

Generally, solid parapets of varied sizes can alter wind pressures on large roofs because they can modify the flow pattern around buildings and change the mean and peak pressures. Still, the mean pressure pattern shows a reduction in the length of the separation bubble due to the parapet, [4], [5].

Initially, parapets were composed of a single, monolithic element beneath the coping, serving the dual function of structural support and weather-resistive barrier. Nowadays, they tend to have a structural core that offers more design options and integrates thermal and moisture control layers (Fig. 1). Subject to wind and weather on both the outboard and inboard sides, parapets are especially vulnerable to rain, wind, snow, and thermal forces. Notably, wind loads acting on the perpendicular face generate an overturning moment or the force attempting to topple the parapet, [6].

2 Methodology

The recommendations of the *PRISMA methodology,* [7] served as the basis for this systematic review elaboration. The search theme in the literature was the influence of parapets on wind loads on low-rise building roofs. The criteria used to define and conduct this review will be detailed below.

Eligibility criteria

Wind loads on low-rise building roofs were considered in the selection of articles.

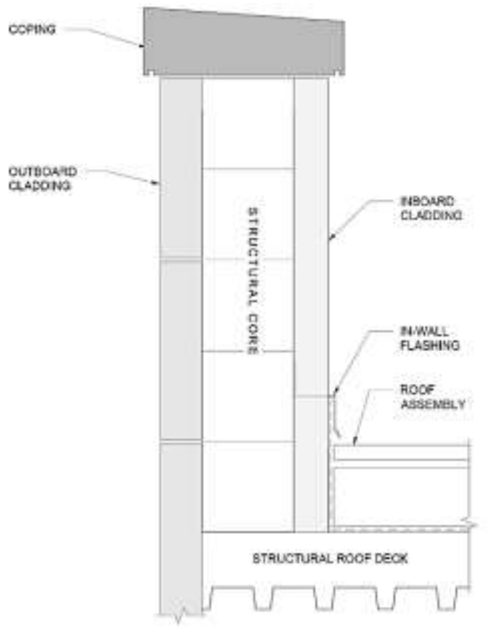


Fig. 1: Basic parapets components [6].

Papers that analyzed the action of the wind on the parapets themselves, high-rise building roofs, or that did not mention the word "*parapet(s)*" in the abstract or title are outside the scope of this review. We also considered only research articles in English and open access. No time frame or filter was employed. The last search was on December 13, 2022.

Research bases
A query was performed on the *Portal de Periódicos Capes*, the virtual library for higher education and research institutions in Brazil – to assess the bases available for searching for articles. Hence, the following were selected: *Web of Science*, *ScienceDirect* (Elsevier), *SCOPUS* (Elsevier) and *Compendex* (Engineering Village – Elsevier).

Search strategy
Initially, a search was carried out on the *Google Scholar* website for an overview of the approach to the subject in the literature and, later, the search outline. From this were defined the keywords and Booleans: *parapet** AND "*wind load**" OR "*low-rise building**".

Selection of studies
Data screening was conducted using *Rayyan Intelligent Systematic Review software* - indicated as the more appropriate tool, [8] - and consisted of duplicate disposal, eligibility, and elimination of studies classified as inappropriate. After eliminating duplicates and articles that did not contain the word "*parapet(s)*" in their title or abstract, the reading of the titles and abstracts of the remaining papers began. After applying the filters, defined articles out of scope. Then a careful reading of the works included in the review. Finally, categorized the selected works by the type of parapets, the tool used (experimental or numerical), and the type of building (closed walls or open canopy).

3 Results and Discussions
With search strategy 735 papers were selected. Then, using alternative methods such as citation search and websites, 6 papers were added. Figure 2 presents the flowchart of the selection process of materials for this systematic review.

Next, we'll cover the influence of parapets on the behavior of the wind on roofs of low buildings, especially wind loads and its correlation with the geometric characteristics of buildings and parapets. However, analytical data will not receive much attention, since their comparison would require multiple experiments due to the possible combinations of buildings and parapets and variations in geometry, porosity, and influence of the surroundings, among others, [9]. Table 1 shows the grouping of papers.

3.1 Full-scale Field Experiment
Full-scale field experiments are those conducted outside the laboratory, with real-world conditions, [22]. A field survey of Wind Engineering consists of the actual model instrumentation (usually existing before the study) with devices for measuring wind pressure and speed and an adequate data acquisition system, [23]. The method may have some advantages, such as anchoring and validation for wind tunnel calibration and the decreasing scale effects compared to tests on reduced models [24],[25].

On the other hand, due to the high cost and time compared to other methods, like this a difficulty in controlling boundary conditions, tests like this are rare, [2]. As a reflection of this, this sample only has a single work carried out by [12] instrumented a small building with eaves in Canada (Table 1).

Despite the limitations of observing some wind incidence directions and obtaining data from some pressure taps after installing the parapets, the results showed that the higher the parapets, the highest the reduction in roof suction. This statement is consensus in the Wind Engineering community according on subsequent works of this review, [21]; however, these results are valid for low parapets ($h<1.0$ m). Compared to no parapets, a 30-35% reduction for a 0.25 m parapet was observed and another 20-25% for a 0.50 m parapet. This result goes in the opposite direction concerning the other studies that we will see, which indicate an increase in wind loads for low parapets, [10], [21]. In [12], the authors concluded that the increase in roof corner suctions may be some dependence on the parapet height in relation to the building dimensions.

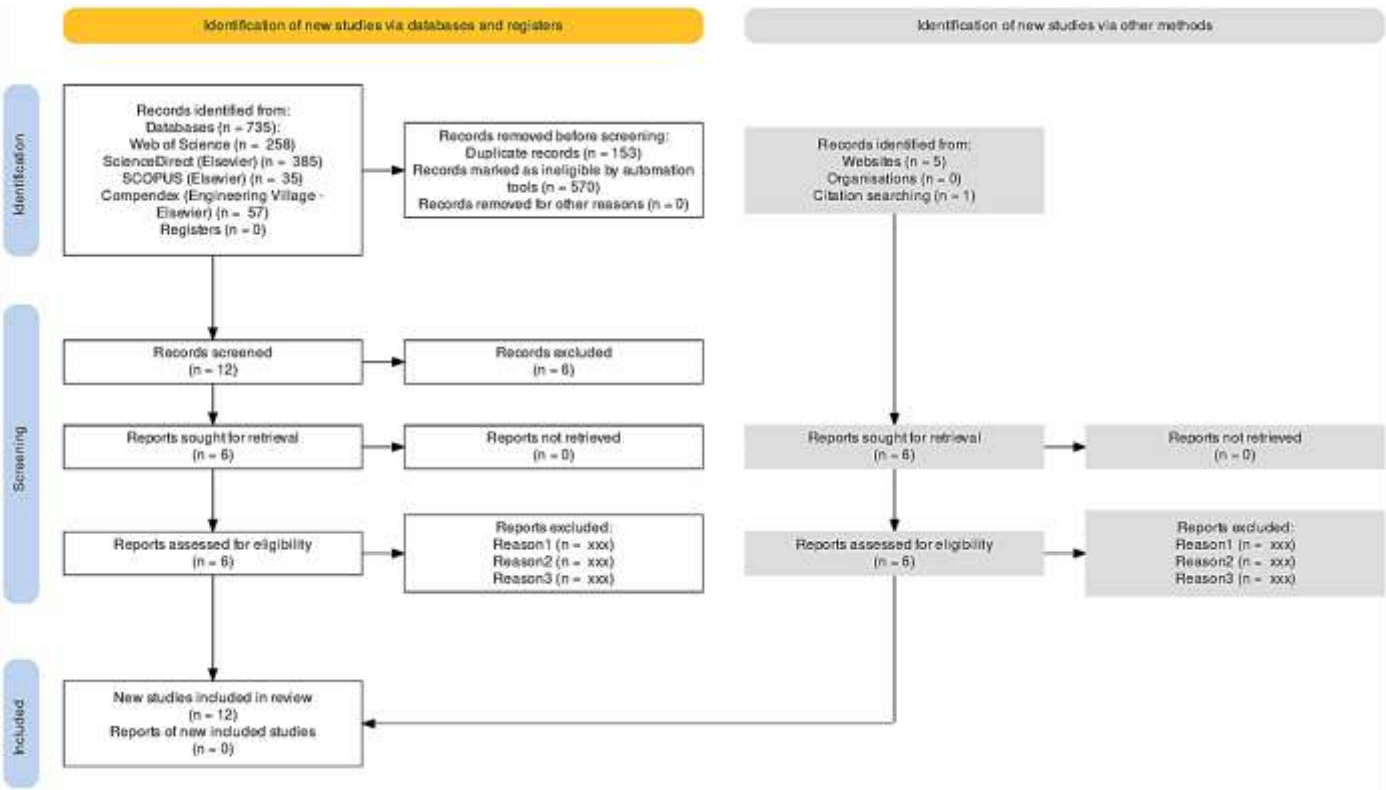


Fig. 2: Material selection flowchart for the systematic review.

Table 1. Main parameters of the full-scale field experiments.

Parapet type	Tool employed	Building type	Building dimensions (L x W x H, in meters)[1]	Parapet heights (in meters)	References
Solid continuous perimetric	wind tunnel	flat-roof	35.50 x 23.50 x 10.00	0.00; 0.75; 1.50; 2.25; 3.00	[10]
	wind tunnel	large flat-roof	36.60 x 18.30 x 6.10	0.55; 1.00; 1.10; 1.45; 2.00	[11]
	wind tunnel	flat roof	3.70 x 2.60 x 3.30 (roof: 4.0 0x 3.20)	0.00; 0.05; 0.10; 0.15; 0.20; 0.25; 0.50	[12][2]
	wind tunnel	open canopy	7.50 x 7.50 x 3.60	0.91; 1.20; 1.22; 1.52; 1.83	[13]
	CFD	open canopy	7.50 x 7.50 x 3.60; 12.20 x 7.60 x 3.60; 15.20 x 7.60 x 3.60	0.91; 1.20; 1.22; 1.52; 1.83	[13]
	wind tunnel	low-rise	13.37 x 8.91 x 9.14	0;…; 2.06	[14]
	CFD	low-rise	30 x 30 x 15	1.00	[15]
	wind tunnel	low-rise	32 x 32 x 16	0.00; 0.80; 1.60; 2.40	[16]
	wind tunnel	large industrial	49.68 x 39.62 x 6.55	0.91	[17]
	wind tunnel	low-rise	0.20 x 0.20 x 0.10; 0.40 x 0.20 x 0.10	0.00; 0.005; 0.01; 0.02	[18][2]
	wind tunnel	square building	61 x 61 x 12	0.0; 0.50; 0.75; 1.50	[21]
Porous continuous perimetric	wind tunnel	low-rise	32 x 32 x 16	0.00; 0.80; 1.60; 2.40	[16]
	CFD	low-rise	30 x 30 x 15	1.00	[15]
Cantilevered continuous	wind tunnel	low-rise	32 x 32 x 16	0.00; 0.80; 1.60; 2.40	[16]
	wind tunnel	low-rise with curved roofs	0.48 x 0.48 x 0.12	0.005	[19][2]
Discontinuous porous parapet	wind tunnel	low-rise	19.05 x 12.20 x 3.66	0.128	[20]
Discontinuous on the corner	wind tunnel	square building	61 x 61 x 12	0; 0.50; 0.75; 1.50	[21]

[1] L is the length, W the width, and H the height of the building.
[2] Reduced scale model dimensions.

3.2 Wind Tunnel Experiment

"Measuring the wind effects on a structure is difficult because this process is highly sophisticated due to the random and spatiotemporally variable nature of the wind" [26]. For this, wind tunnel tests have been widely and satisfactorily applied to evaluate wind loads on structures [27]. Wind tunnels are installations capable of reproducing, to some extent, wind flow on a reduced scale.
Several systems are employed to generate velocity, turbulence, and terrain roughness profiles and, in general, supply the limitations of full-scale field experiments [28].

It is worth highlighting some of the advantages of this method. They are accuracy, independent control of the variables, efficiency, and simplicity of operation [29,30]. On the other hand, one of the disadvantages is the effect of the Reynolds number associated with atmospheric turbulence [31]. The different types of wind tunnels are highly standardized, such as the boundary layer wind tunnel and open-jet tunnel, and present a significant number of results within this review (see Table 1).

3.3 Computational Fluid Dynamics (CFD)

Even though wind tunnels constitute an alternative in wind-induced experiments, their limitations are questionable, such as the high cost of operation and the divergence of results for different tunnels using the same methodology, [32]. With the advancement of technology, computer power, and data storage and acquisition, *Computational Fluid Dynamics* (CFD) techniques have gained space in studies of wind actions in buildings, [33]. CFD consists of solving fluid flow equations through computer codes, [34]. Some highlights of the advantage of this methodology are the detailed processing reports, the low instrumentation - only computers, depending on the case - and the ease of controlling boundary conditions. On the other hand, the simulation of complex geometries is still a challenge, and the accuracy of the results is constantly questioned and submitted to several validations [35,36]. In this review, although no filter was applied and, consequently, several studies using CFD were expected, only [13] and [15] were among the results (see Table 1).

3.4 Low-rise Building with Closed Wall

Low-rise buildings, by definition, are those in which the lateral dimensions are predominant or equivalent to the height, that is, L~W~H, L~W>H, or L>W>H, [37]. Nowadays, most institutional, commercial, and industrial buildings have parapets, [2], whether solid, porous, continuous, or not, or even billboards that create obstructions similar to parapets. For certain regions, this practice has become increasingly recurrent for residential buildings. It is necessary to study the behavior of loads on their roofs due the scope and vulnerability of these structures. These have more critical suction on their corners. Also, how different parapet configurations can reduce the effect of conical vortices, also known as delta wing vortices, [16], [31], [38].

Since solid continuous perimetric is the most common type of parapet, it appears more frequently in the results analyzed in this work. Whiteman *et al.* [14] optimizing the mitigation of the wind action in the preservation of the aesthetics of the tested buildings, concluded, by varying the heights of the parapet (h), that height of 0.90 m is ideal (in a ratio h/H = 0.10, H being the height of the model).
Similarly, [16] determined the “optimal shape” by varying porosity settings. He observed that solid and continuous parapets were less efficient than porous ones at an h/H ratio <0.05 to decreasing negative pressure peaks on roofs.

Aly *et al.,* [17], showed in a large industrial building that different parapet heights are more effective depending on the wind direction. Despite obtaining significant reductions (on the order of 50%) at the roof corners for some directions, the height referring to 14% H was the most effective in reducing mean and peak pressures across the roof surface for different wind incidences (up to 40% in the roof corner). Blessmann, [18], evaluated how the different h/H ratios, varying the flow turbulence, interfere with the pressure and force coefficients on roofs. He found significant differences for the first and a small effect for the second.

According to the previous section, a range of parapets - partial, porous, discontinuous, one-side, and variable height - have been tested to mitigate the intensity of pressures on low-rise building roofs [17] (Fig. 3). Also, the study in [16] observed that cantilevered parapets, at a ratio of about h/H<0.03, reduce negative pressure coefficients on flat roofs. In addition, they performed better than solid and continuous parapets. In the h/H ratio, the space created between the roof and the parapet dispersed the conical vortices, although, above that, the parapet effect became ineffective. In contrast, different arched roofs, [19], showed that the efficiency of cantilevered parapets does not depend on curvature in reducing wind loads. The authors attribute this effect to the reduction of delta wing vortices due to the flat jet injected into the roof surface.

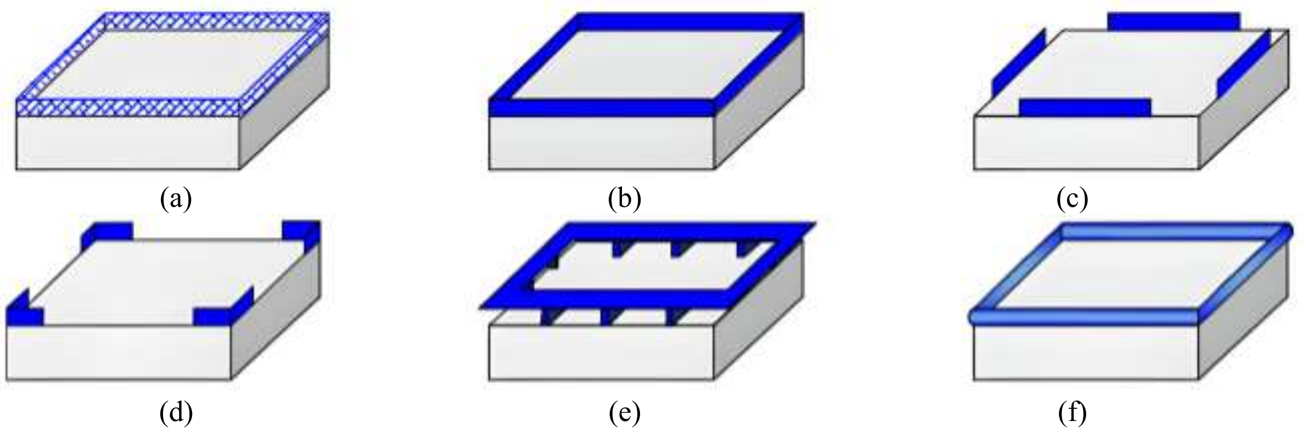


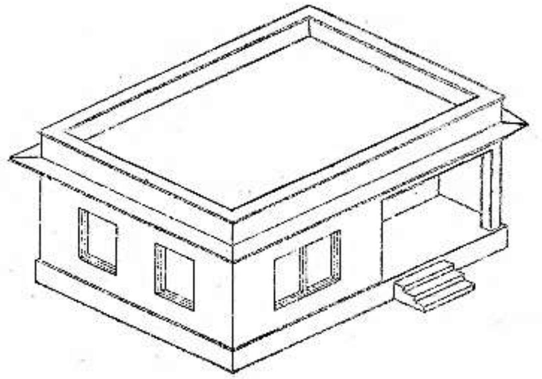
Fig. 3: Various aerodynamic mitigation features for reducing wind loads on the roofs of low-rise buildings [17]: (a) porous parapet, (b) solid parapet, (c) discontinuous parapet, (d) partial parapet, (e) parametric spoiler, and (f) aerodynamic edge.

Now, [20], for a large-scale model, obtained economically viable results for discontinuous and porous parapets positioned in the corners and ridge regions compared to a continuous and solid one. It demonstrated a 45% reduction in peak pressure coefficients at the corner roof (similar to that of [17] with solid parapets, for example). Likewise, the authors in [21] observed an increase in peak pressure coefficients at low heights h and a decrease with increasing h (as well as in continuous parapets). Using continuous and porous parapets, the study in [15] obtained similar results. For the mean pressure coefficients, the parapets with openings showed a negligible variation in these coefficients. Even so, both cases proved to be more efficient against wind action than the continuous parapets in the corners of the roofs.

3.5 Low-rise Building with Open Canopy

Unlike buildings with closed walls, open-canopy buildings have a low aspect ratio under-roof structure and only a few rows of supporting columns and beams, and are commonly used in gas stations, [13] (Fig. 4).

Consequently, they become very vulnerable to wind actions. In terms of mitigating wind loads depending on the parapets, research indicates that the height h of the parapets is the most relevant parameter, [13], [17]. Also, the study [13] based in experiments in wind tunnels and CFD, observed that the diagonal directions (30º) were more severe than the orthogonal ones (0º) (as well as in low-rise buildings with closed walls). Also, the longer the building, the more intense the net pressure coefficients. As for the cost-benefit ratio, the authors stated that CFD proved to be the most viable alternative to study the parameters that action of the wind influence.



(a)

(b)

Fig. 4: Building with (a) closed walls and (b) open canopy.

4 Conclusions

This systematic review investigated the influence of parapets on wind loads on low-rise buildings. The similarities and differences between the works were summarized as follows:

- For low parapets (h<1.0 m), pressure increases are identified on roofs and have been a consensus in the Wind Engineering community. However, the result varies according to the h/H ratio;

- In general, the higher the parapets, the higher the reduction in the intensities of the pressure coefficients. Despite this, the "*optimal height*" needs to be investigated for each h/H ratio;

- Porous parapets and cantilevered parapets are more efficient and economically viable as a device to mitigate wind loads when compared to solid parapets in low buildings;

- For an open canopy, the height of the parapet is the main parameter, although the length of the building is also relevant.

Other works may study the turbulence in these flows due to the various parapet configurations. Also, the analysis of the combinations of elements of parapets is possible, such as the partial parapet, the aerodynamic edge, the one side, the increased height at the corners, and the different thicknesses. Finally, the investigation of different configurations of buildings with canopy, since in this systematic review, only one reference in the literature was reported.

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Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

Guilherme Teixeira was responsible for the methodology and writing the results. Marco Campos carried out the conceptualization, review, and editing.