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Guidelines for Improving Wind Resistance of Building Facades

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Abstract

Building facades are subjected to wind pressures since they are blocking the free flow of air. In comparison to streamline bodies such as aircrafts, buildings are in general not streamlined and they are rather bluff bodies, which attracts high wind pressures on the facades. However, through careful consideration at the design stage, one can improve the wind resistance of the façade elements. This paper addresses guidelines to improve the wind resistance of building facades in layman's terms. Most of the ideas are shown using hand sketches with simple explanations for practitioners.

Introduction

Buildings are obstructing the motion of air called wind, and thus, the wind is exerting force on buildings. Wind force can be classified into two: the first one represents the overall wind action on the building inducing overall integrated loads called structural loads on the structural systems. The second one refers to the action of wind on the building facade known as cladding loads. As we all know the cladding and the various building components are relatively small elements and their size is typically very small in relation to the entire structure. So, the localized wind pressure variations are very crucial for their design which is the subject matter of discussion in this paper.

In general, less attention goes into the wind loads acting on facades in contrary to the overall structural loads. This translated into several cladding failures worldwide especially in developing nations. Though the high wind speeds are being blamed for the failures, the reality lies with inadequate design and poor workmanship.

This paper addresses guidelines for improving wind resistance of building facades with the help of aerodynamic treatments using flow sketch diagrams and case studies. Most of the previous studies concentrated on the effect of aerodynamic treatments on the overall response of the buildings [1,2] and less so on their effects on local cladding pressures [3].

Fundamentals

Figures 1 and 2 pictorially show the localized wind phenomenon on claddings and building components. Depending on the location of the cladding elements and wind direction, the subjected wind pressure can be different. The maximum positive pressures generally occur on the windward wall and all the facades will become windward for certain wind directions. As far as positive pressures are concerned (Figure 1), the wind pressure increases as the height increases. This means the lower portion of the building will be subjected to lower pressure and the higher portion of the building will be subjected to higher pressure except the top edges where the wind tries to negotiate with the edges which results into lower positive pressures. Further, plan also shows the positive wind pressures are lower at the edges and higher at the middle of the façade.

On the other hand, the building facades on the leeward side as well as the side facades are subjected to negative pressures (Figure 2). The negative pressures (suction) can be very high at the corners due to the flow separation/vortex shedding. Suction pressures can also be very high at the top and bottom corner regions due to intense flow separations. So generally, the high suctions need not be associated with the higher heights/higher speed, instead associated more with the aerodynamic reasons.

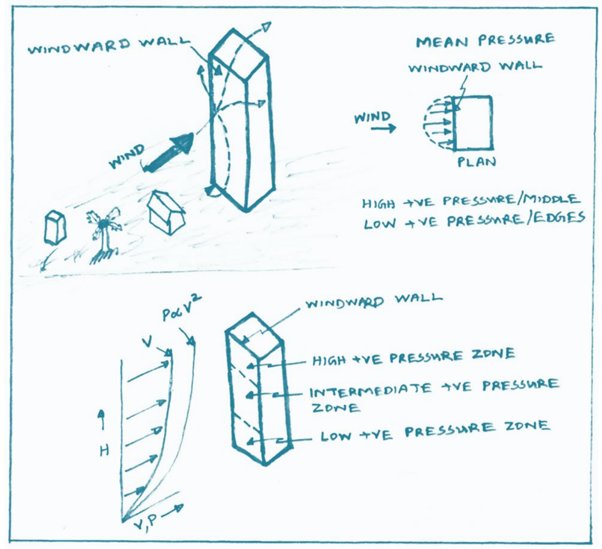

Figure 1. Portrayal of positive pressures acting on building facades.

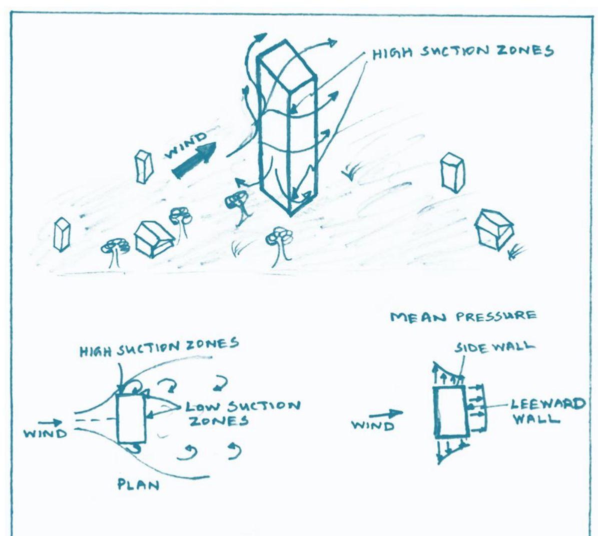

Figure 2. Portrayal of negative pressures acting on building facades.

Roofs

Roof claddings are in general subjected to very high suction pressures in comparison to the low positive pressures, Suresh Kumar & Stathopoulos [7]. As far as all roofs are concerned, generally the edges and corners are subjected to very high suction pressures. These high suctions are induced by intense flow separation at the edges, corners and ridges. In case of flat roofs as well as gable roofs, for nearly oblique wind direction, delta wing vortex is formed on either side of the windward edges causing high suctions. This is pictorially shown in Figure 3. Other common roof forms such as gable roof, hip roof and mono-slope roof are also shown in Figure 3. Though gable roofs are very common due to ease of construction, they are one of the vulnerable roof forms in intense storms. Gable end failures and uplifting roof are common in storms. All the edges of the gable roof shall be properly secured and held in place to avoid any failures. Typical failures start from the edges/ridges due to lack of resistance to wind uplift. Hip roof is one of the most wind resistant roof existing today. The wind resistance power of Hip roof is due to the reduction in aerodynamic loads obtained from the shape of it. On the other hand, hip roof construction is time consuming and costly.

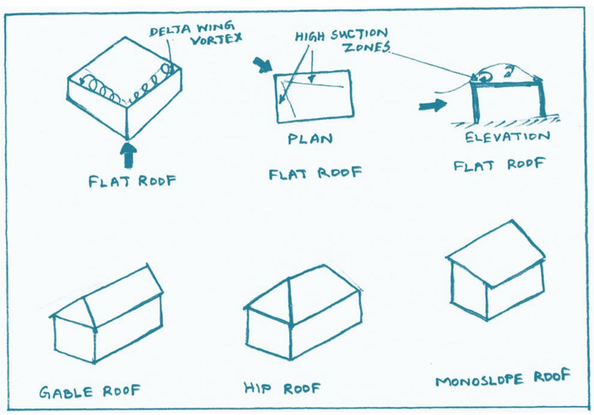

Figure 3. Common roof types.

It is well known that local wind pressures are high at roof edges, corners and ridges. Corner modifications will be of great help to reduce the local pressures acting on cladding elements. Typically, rounded edge at the wall/roof junction would be of great help for all types of roofs. If the roof extends beyond the wall which is typical for sloped roofs, then the eaves would be of help to reduce/eliminate the pressure from underneath at the edges. Further, the rain gutter at the edges would be a good addition for reducing the loading. Rounded and slotted edges at the overhang zone will also be good. For flat roofs, in addition to the rounded edge, parapets can also be of great help in reducing the loading at the edges/corners. Parapets can raise the vortices shed above the roof and thus their intensity felt at the roof cladding can be reduced. If roof pavers are used, parapets can be of help in reducing the wind loads on those elements. Basically, such edge features are restricting the sharp separations at the edges and thus reducing the wind loads on roof claddings (see Figure 4). Further, the wind resistance of the roof pavers can be further improved by connecting them together and this means interlocking pavers. The wind pressures on roofs are widely varying and the suction pressures are decreasing from the edges to the center. By using interlocking pavers, the wind pressures acting on pavers will reduce due to area averaging phenomenon.

Figure 5 shows few sketches of wind flow passing cantilevered roof of stadium under diverse conditions. The sketches are self-explanatory. Depending on the roof condition below, upstream blockage and roof edge condition, the uplift on the cantilevered roof can be very different. As soon as the downstream end of the roof is closed beneath, this will create pressurization underneath the roof along with high suction at the top induces overall high nets on the roof. This effect will be reduced as soon as the relief of flow underneath is introduced by opening the downstream end.

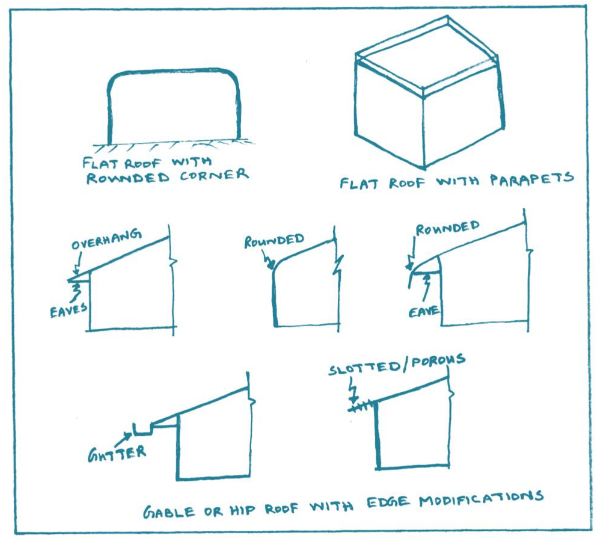

Figure 4. Edge treatments to improve wind resistance of roofs.

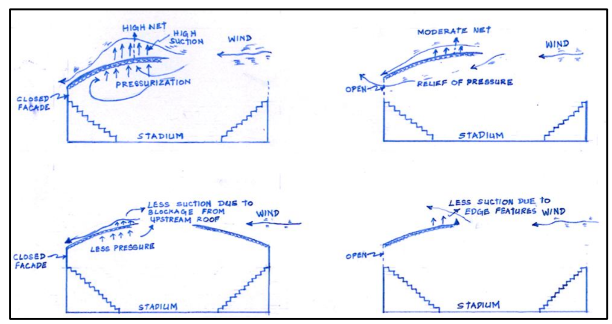

Figure 5. Sketches of wind flow passing cantilevered roof of a stadium.

Also, time and space correlation of the pressures diminishes exponentially as the distance between the locations of comparisons increases on the same structural element itself. Hence forth, overall loading on the structural element can be very low compared to the local peak pressures acting on the structural member at multiple locations.

Walls

Regarding improvement of wind resistance of building walls, plan form changes can have a noticeable effect on the subjected façade pressures. Buildings with sharp corners attract high suction loads at the edges. This can be reduced by changing the corners in the form of chamfered, rounded, recessed and slotted. Further protruded balconies as well as flushed balconies can also help in reducing the local loads on claddings. Basically, these edge treatments will disturb the flow separations which will result into lower suction pressures. Figure 6 shows the various edge treatments on the plan forms just discussed. Taipei 101 tower in Taiwan used the recessed corners as depicted in Figure 6 and due to this, the local wind pressures as well as the overall wind loads reduced significantly.

Several elevation form changes such as tapering, twisting, sculpted top, puncturing the structure with holes are classic examples and they have been implemented in many buildings across the world. Figure 7 shows a few of these cases. Vertical fins towards the edges are also useful in reducing local loads. These features will basically disturb the flow by not providing with any uniformity for the wind to act coherently.

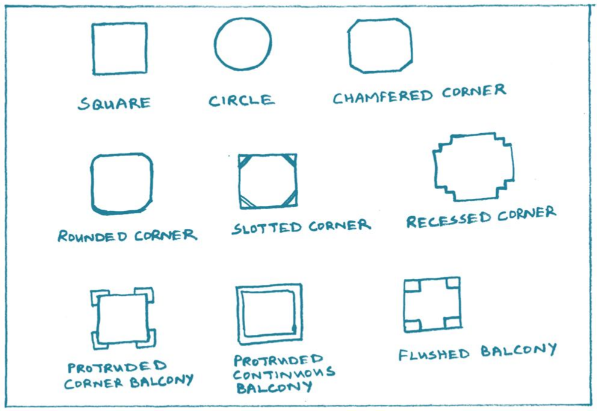

Figure 6. Edge treatments to improve wind resistance of walls.

Figure 7. Examples of elevation form changes.

Double Skin Facades

Double skin facades are becoming popular in the building industry due to advantages on the performance side such as energy efficiency, rain penetration resistance, etc. to name a few. Previously, these were known as rain-screen walls where the gap between the outer and inner skins is too small typically less than 100mm. In modern era, the gap between the inner and outer skins has increased up to about 2m, where the gap is used for many other purposes including ventilation, energy production etc, as per Suresh Kumar [4,5].

Despite of the advantages on the performance side, both skins must be designed for wind loads. For economic reasons, the load sharing between the skins needs attention. The influencing parameters are outer skin venting area, gap/volume between outer and inner skin, cavity compartmentalization, inner skin leakage and skin flexibility, as per Suresh Kumar [4]. The principle behind is wind flows into the cavity through venting and pressurizes the cavity which in turn reduces the outer skin wind loads due to the net effect of the external pressure and the scaled down external pressure in the cavity. The inner skin loads also reduce due to the dampening of the external pressure fluctuations through venting.

Based on past research as per Suresh Kumar [4], the following guidelines can help in optimizing loads on double skin facades: (1)provide large venting area maximizing the rate of flow into the cavity, (2)provide minimum gap width/cavity volume minimizing change in air volume necessary in the cavity to equalize the pressure between cavity and exterior, (3)provide compartment seals in the cavity at corners restricting cavity cross flows from positive to negative pressure zones, (4)provide vertical/horizontal compartment seals throughout the façade restricting cross flows and minimizing change in air volume, (5) provide airtight inner skin minimizing change in air volume inside cavity.

Figure 8 shows a sketch of a double skin façade with corner sealing and compartmentalization. Wind loads on such facades can be assessed using analytical simulations or large scale wind tunnel tests.

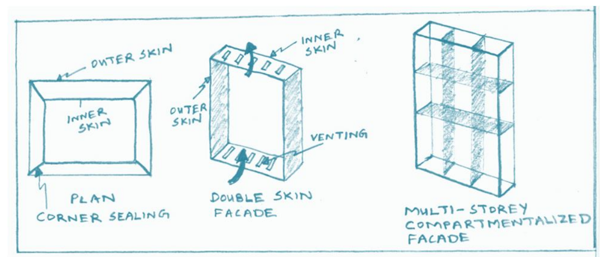

Figure 8. Double skin façade.

Wind Tunnel Testing

Practitioners mostly refer local codes/standards to arrive at the wind pressures for façade design. However, the codes/standards have their own limitations. Considering the code's concise nature for ease of usability, codes in general only covers typical boxlike geometries, isolated buildings and constant speed from all directions. As we all know, nowadays the buildings come with all kinds of unconventional shapes with external appurtenances such as fins, balconies etc. Further, when the building is surrounded by other buildings, the oncoming flow is influenced by the adjacent buildings. In addition, wind speeds are also not constant from all directions. Detailed extreme value statistical analysis of the actual nearby airport wind speed data is required to predict the actual wind speed direction by direction at a specific risk level. For the same reasons, all the codes/standards suggest wind tunnel tests to alleviate these issues to come up with the accurate results, as per Suresh Kumar [6].

Wind tunnel tests have been widely accepted in the world as the most reliable method for the determination wind-induced loads on the façade. In wind tunnel tests, scaled models of structures are subjected to scaled atmospheric wind in a controlled laboratory set-up. Typical model scales are in the range of 1:300 to 1:500. Then sensors installed on the model can measure the physical quantities of interest such as wind pressures on facades. Later in the analysis, these model scale quantities are converted to prototype using model scale laws. Most of the complex architectural and structural innovations are constructed only after being confirmed through wind tunnel tests.

A wind tunnel test case at 1:400 model scale is shown in Figure 9. Note that the fan behind the spires is used to blow the wind through the test section. The upwind spires and appropriate floor roughness elements are used to generate the full-scale wind characteristics (i.e., mean and turbulence profiles). Surrounding buildings for half a kilo-meter in radius around the study building are also modelled and placed in the disk to get the influence of immediate surroundings. The disk is rotated at every 10 degree to subject the building to various wind angles similar to full-scale condition. In this case, the façade was double skin type, however we couldn't simulate this condition at 1:400 scale considering the small gap between inner / outer façade with all the miniscule details. To address this issue, we built 1:100 scale model of a section of the building and tested without surroundings (Figure 10), as per Suresh Kumar [5]. Later, both the 1:400 and 1:100 test results were utilized to provide design wind pressures.

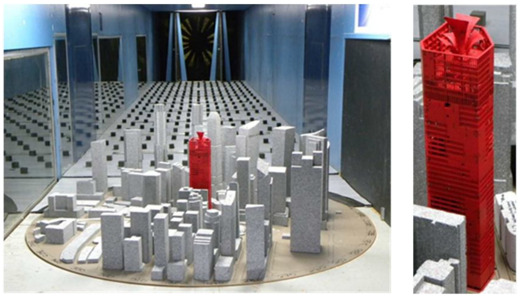

Figure 9. Wind tunnel study model (1:400) with surroundings.

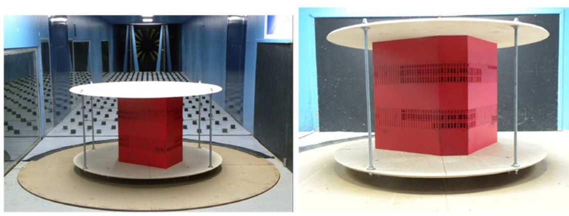

Figure 10. Wind tunnel study model (1:100) without surroundings.

Such large-scale model testing is carried out at times to confirm the predictions made at small scale model at the order of 1:400. One such example is shown in Figure 11, which is currently the tallest building in the world Burj Khalifa in Dubai.

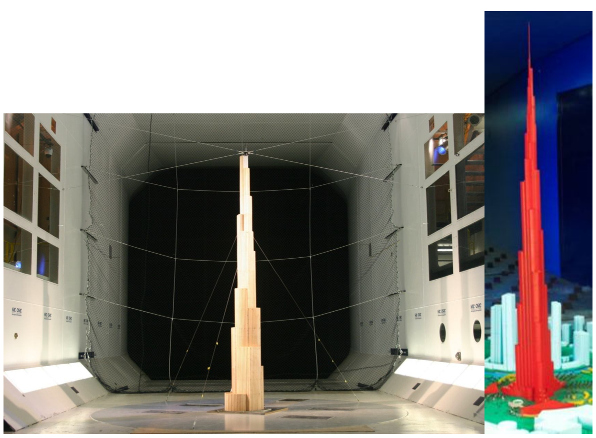

Figure 11. Large & small scale wind tunnel model – Burj Khalifa, Dubai.

Since this building has nearly rounded wings, there were questions concerning the small-scale simulation and Reynolds number sensitivity of surface pressures. Therefore, a portion of this building was built at 1:50 scale and tested in a large wind tunnel where the maximum wind speed was 54 m/s. We could generate 100 times higher Reynolds number in this test; however, the surface pressure results were like the earlier small scale test.

Comparison of the Aerodynamic Treatments

Numerous wind tunnel testing with various edge treatments have been performed at RWDI primarily for reducing wind-induced overall response of tall buildings without giving much importance to the advantage of obtaining reduced cladding pressures. Recessed corners, rounded corners, chamfered corners, and corners with balconies did produce cladding pressures in the range of 10 to 30% lower than a typical sharp corner case. The corner changes must be at least 10% of the width in order to get noticeable reduction in pressure. All the case studies will be elaborated during the presentation.

Concluding Remarks

High wind pressures on claddings often evolve from suction action. These high suctions can be reduced by simple aerodynamic treatments especially at the edges. This paper presents various guidelines to reduce wind pressures on roof/wall claddings and double skin facades in a qualitative format. Wind tunnel testing is also recommended for the quantity assessment of the load reduction. Many case studies will be discussed at the presentation.

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