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AERODYNAMIC MODIFICATIONS TO THE SHAPE OF THE BUILDINGS: A REVIEW OF THE STATE-OF-THE-ART

J.A. Amin[*a] and A.K. Ahuja[b]
[a]Department of Civil Engineering, Sardar Vallabhbhai Patel Institute of Technology, Vasad, India
[b]Department of Civil Engineering, Indian Institute of Technology Roorkee, Roorkee, India

ABSTRACT

The development of high strength concrete, higher grade steel, new construction techniques and advanced computational technique has resulted in the emergence of a new generation of tall structures that are flexible, low in damping, slender and light in weight. These types of flexible structures are very sensitive to dynamic wind loads and adversely affect the serviceability and occupant comfort. For a typical tall building, oscillations have been observed in the alongwind and crosswind directions as well as in the torsional mode. To ensure the functional performance of tall flexible structures and to control the wind induced motion of the tall buildings, generally different design methods, various types of passive as well as active control devices and various types of aerodynamic modifications to the shape/geometry of the buildings are possible. This review paper presents an overview and a summary of past/recent work on various aerodynamic modifications to the shape of the buildings like corner cuts, chamfering of corners, rounding of corners, horizontal and vertical slots, dropping of corners, tapering etc. to reduce the wind excitation of tall flexible buildings and its application in some of the tall buildings across the world.

Keywords: Aerodynamic modifications; chamfering of corner; tapering effects; wind-induced responses; tall buildings

1. INTRODUCTION

The advancements in the development of high strength materials, better understanding of structural behavior coupled with more advanced analytical tools and structural design procedures have led to a new generation of tall buildings which are slender and light as compared to their predecessors. This types of buildings, in addition to gravity loads, are subjected to time-varying loads arising from winds, earthquake etc. These loads are dominant over a certain frequency ranges. These types of tall flexible buildings are very sensitive to the wind excitation, which could be the important design criteria determining the structural system of tall buildings [1]. The design of such buildings is often governed by

* E-mail address of the corresponding author: jamin_svit@yahoo.com (J.A. Amin)

the need to limit the wind-induced accelerations and drifts to acceptable levels for human comfort and integrity of non-structural components respectively. The part of the research on flexible tall buildings has been devoted towards the reduction of wind-induced responses by means of global design modifications to the building aerodynamics or structural systems and the incorporation of auxiliary damping devices such as active, passive and hybrid devices. (Kareem, [2]; Kwok, [3-4]; Kwok et al. [5]; Banavalkar [6]; Banavalkar and Isyumov [7]; Housner et al. [8]). The momentum to study the effects of aerodynamic modification to the basic plan shape of the buildings to mitigate the wind induced responses occurred in the early eighties. The addition of helical strake to chimney stacks is one of the very familiar examples of an aerodynamic device used to suppress the resonant vibrations caused due to the vortex shedding phenomenon. Zdrakovich [9] presented the detailed review of various aerodynamic treatments to a structure of circular cross section. An early example of an aerodynamic form can be found from Buckminster Fuller's Dymaxion project, in which the aerodynamic shield rotates about an axis according to the direction of the wind to minimize the impact of the wind force (Abalos and Herreros [10]).

The shape of the buildings significantly affects the wind forces on it and the resulting motion. A careful coordination of the structural components and shape of tall buildings minimizes the wind excitation and offers a considerable saving in resources. The passive aerodynamic modifications in the form of building shape are one of the efficient and effective design approaches to significantly reduce/modify the effects of time varying wind forces and thus building motion as compared to non-modified building shape by changing/altering the flow pattern around the buildings. This review paper comprises the entire spectrum of aerodynamic techniques geared specifically toward reducing the wind-induced motions of tall buildings, particularly those which affect the serviceability requirement and occupant comforts and their applications in some of the tall buildings across the world to reduce the wind excitation.

2. AERODYNAMIC FORCES ON BUILDINGS

A structure immersed in a given flow field is subjected to aerodynamic forces. For typical tall buildings, aerodynamic forces includes are drag (along-wind) forces, lift (across-wind) forces and torsional moments. The alongwind forces act in the direction of the mean flow. The alongwind motion primarily result from pressure fluctuations on windward and leeward faces and generally follows fluctuations in the approaching flow.

The crosswind forces act perpendicular to the direction of mean wind flow. The common source of crosswind motion is associated with 'vortex shedding'. Tall buildings are bluff as opposed to streamlined bodies that cause the flow to separate from the surface of structure, rather than follow the body contours. For a particular building, the shed vortices have a dominant periodicity defined by the Strouhal number. Hence, the building is subjected to periodic cross pressure loading which results in an alternating crosswind forces. The wind tunnel test on the model of 420 m high Jin Mao Building, Shangai showed that its maximum acceleration in acrosswind direction at its design wind speed is about 1.2 times of that in alongwind direction. (Gu and Quan [11]).

The torsional motion is developed due to imbalance in the instantaneous pressure distribution on each face of the building. In other words, if the distance between elastic center of the structure and aerodynamic center is large, the structure is subjected to torsional moments that may significantly affect the structural design. It has been recognized that for many high-rise buildings, the crosswind and torsional responses may exceed the alongwind response in terms of both limit state and serviceability designs (Holmes [12]).

3. SERVICEABILITY REQUIREMENTS

The design of typical structure requires the engineering of system that efficiently and effectively carries the anticipated lifetime loads. The increase in height, often accompanied with increased flexibility and even low damping, caused the structure becomes even more susceptible to the action of the wind, which governs the design of the lateral system. While a given design may satisfactorily carry all the loads, the structure may still suffer from levels of motion causing significant discomfort to its occupants. Wind-induced serviceability issues are of concern in two areas; (1) building envelope performance under wind-induced deformations, and (2) occupant discomfort due to building motion. Thus many design modifications are explicitly incorporated, be they aerodynamic or structural, to improve the performance of structure to meet the serviceability or perception requirements. Before discussing the various aerodynamic techniques to reduce the wind-induced responses, serviceability requirements are briefly discussed in subsequent paragraph.

For the performance of the building envelope to be adequate, the peak interstorey drift must not exceed 1/300 to 1/500 of the storey height under unfactored loads, although this criterion may vary depending on type of cladding or glazing and cladding attachment details. In absolute terms, interstory drift should not exceed 10 mm unless special details allow nonstructural partitions, cladding, or glazing to accommodate larger drift. However this criterion must also be qualified, depending on specific building features (Simiu and Miyata [13]).

Occupant comfort is affected by the visual perception of building oscillations. Wind-induced motions have various categories like the sway motion of the first two bending modes termed along and acrosswind motions, a higher mode of torsional motion about the vertical axis, or for buildings with stiffness and mass irregularities, complex bending and torsion in the lower modes. Any of these motions can be quite unnerving and unsettling to the occupants and symptoms may range from concern, anxiety, fear to headaches. It is hypothesized that occupant comfort is affected by rapid changes of acceleration, but unfortunately, no criteria based on such changes have been developed so far. The occupant perception of accelerations is highly uncertain and complex, therefore criteria on acceptable accelerations vary among codes and practioners. For example, in typical North American practice the allowable peak ground acceleration with 10-year MRIs is taken as 10-15 milli-g (0.1-0.15 m/s^2) at the top floor for residential buildings and 20-25 milli-g (0.2-0.25 m/s^2) for office buildings. However, it has been determined that acceptable acceleration levels decrease as the oscillation frequency increases, so it has been suggested that these limits be reduced for higher frequencies of vibration, from the values stated above, which are assumed to be valid for frequencies of 0.1 Hz, to about half of those values for frequencies of 1 Hz (Simiu and Miyata [13]). British standard defines the comfort criterion as complaint by more than 2% of people in the upper floors of the building during the worst 10 minutes of a storm with a return period of 1 in 5 years.

4. AERODYNAMIC MODIFICATIONS TO BUILDING SHAPE AND CORNER

4.1 Geometry

Wind-induced motion of a tall building can be controlled either by reduction at the source or by reducing the response. An appropriate choice of building shape and aerodynamic modifications can result in the reduction of motion by altering the flow pattern around a building. The aerodynamic concern for wind-induced responses has prompted many researchers to study the relationship between the aerodynamic characteristics of a structure and the resulting wind–induced excitation level (Kwok and Bailey [3]; Kwok, [4]; Melbourne [14]; Melbourne and Cheung [15]; Dutton and Isyumov [16]; Hayashida and Iwasa [17]; Miyashita et al. [18]; Karim and Tamura [19]; Kawai [20]; Kim and You [21]). The aerodynamic modifications of a building’s cross-sectional shape, variation of its cross-section along the height, or even its size, can significantly reduce building response in alongwind as well as acrosswind direction by altering the wind flow pattern around the building. Aerodynamically efficient plan shapes are shown to be an effective means of suppressing wind-induced loads, and hence construction cost, but may come at the cost of reducing both the size and value of saleable/rentable floor area (Tse et al. [22]). The various aerodynamic modifications applied to the tall buildings to mitigate the wind excitations may be classified in two groups:

Minor modifications: aerodynamic modifications having almost negligible effects on the structural and architectural concept, for examples corner modifications like fitting of fins, fitting of vented fins, slotted corners, chamfered corners, corner recession, roundness of corners and orientation of building in relation to the most frequent strong wind direction.

Major modifications: aerodynamic modifications having considerable effects on the structural and architectural concept, for examples setbacks along the height, tapering effects, opening at top, sculptured building tops, varying the shape of buildings, setbacks, twisting of building etc.

4.2 Effects of Fins and Vented fins

The aerodynamic modifications to basic square cross-sectional shape of buildings by using small fins or vented fins have significant effects on the alongwind and crosswind response characteristics. Small fins/vanes fitted to the corners of a prismatic building with a gap between the vanes and the corner can help to alleviate negative pressures under the separated shear layers on the side faces. However, the added drag introduced by these vanes increases the along wind responses (Karim [2]).

Kwok and Bailey [3] investigated the effects of fins and vented fins using aeroelastic testing of building models of dimension 60 mm x 60 mm x 540 mm with 10 mm wide vertical fins fitted to corners and with 5 mm wide vertical fins and 5 mm gap between fins and corners at reducing velocities ranging from 4 to 24 in wind tunnel. The fitting of fins to the corners increases the projected area normal to wind direction, causing an increases in the drag force, and the resulting mean and standard deviation alongwind responses compared with plain square tower. Venting of fins, however, caused increases in response of smaller magnitudes. The fittinf of fins and vented fins to square tower model causes significant reductions in the crosswind response at the lower range of reduced wind velocities up to about 10. The fitting of fins served only to increase the critical wind speed without any noticeable disruption to vortex shedding process. At the high range of reduced velocities, there was an apparent reduction in galloping response when vented fins were fitted. The fitting of fins or vented fins is acceptable for general usage only for certain range of reduced wind velocities.

The aerodynamic modifications to buildings like fitting of fins and vented fins causes noticeable increase in the alongwind response due to an increase in the projected area normal to wind direction. The aerodynamic modifications, which in general increase the projected area or the effective width of a building, would not be beneficial (Kwok and Bailey [3]).

4.3 Effects of Slotted corners, Chamfered corners and Corner recession

Investigations have established that corner modifications such as slotted corners, chamfered corners/corner cut, corner recession are in general effective in causing significant reductions in both the alongwind and crosswind responses compared to basic building plan shape. The modification of windward corners is very effective to reduce the drag and fluctuating lift through changing the characteristics of the separated shear layers to promote their reattachment and narrow the width of wake. This type of modifications is also effective to suppress the aeroelastic instability.

The effects of slotted corners and chamfered corners were investigated by Kwok and Bailey [3]; Kwok et al. [5] and Kwok [4] through wind tunnel tests on aeroelastic square and rectangular models of dimension 60mm×60mm×540mm and 112.5mm×75mm ×450mm respectively with and without slotted and chamfered corners. The modifications to the building corners ranged from 9% to 16% of building breadth. Authors concluded that, slotted corners and chamfered corners were causing noticeable reductions in both the dynamic alongwind and crosswind responses as compared to plain rectangular shape building. Venting through the slotted corners appears to be effective in reducing the drag force without undesirable effect of using vented fins. With chamfered corners, the reductions in responses were more substantial, with up to a 40% reduction in the alongwind response compared with the plain rectangular shape building within a tested reduced velocity range of 3 to 20. The magnitude of the response reduction was not significantly affected by the change in terrain category. With wind normal to the wide face of the rectangular building, the wake-excited crosswind responses of the modified buildings were found to be up to 30% smaller than that of the plain building at the low range of reduced wind velocities. The critical reduced wind velocity changed from a value of approximately 10 for the plain building to the 9 and 8 for the building with slotted corners and chamfered corners respectively. With the incident wind normal to the narrow face of the building, the crosswind response was found to be wake excited. Building modifications such as horizontal slots, slotted corners and chamfered corners causes major disruption of the vortex-shedding process and result in a 30% or more reduction in the crosswind response.

Melbourne and Cheung [15] and Melbourne [14] studied the effect of plan shape on the crosswind responses of tall building through wind tunnel aeroelastic test. Authors concluded that for normally symmetrical or square plan shape, modest chamfering of corners up to 10% does not significantly reduce the crosswind response at low values of reduced velocities. However significant reductions in the ultimate limit state design loads can be achieved at higher reduced velocities. The crosswind force spectrum was found to reduce at both lower and higher ranges of reduced velocities, in the case of more substantial chamfering of corners such that building plan shape approaches that of an octagonal or hexagonal shape.

The effects of chamfered/notched corners and roundness of corners on the aerodynamic forces and aerodynamic response of a 600m high, 150 storey super tall building of plain square shape having prototype floor area of $6400m^2$ were investigated by Hayashida and Iwasa [17] and Hayashida et al. [23] using force balance, aeroelastics and pressure model technique. Authors concluded that the critical reduced wind velocity at which resonant vibration occurs, and which is define by Strouhal number, was found to be vary according to the shape and modification to the corners. Modification to the corners were found to cause marked reductions in crosswind forces around the vortex shedding frequency and at the low reduced frequencies. For a prototype design wind speed of 64.6 m/s, the maximum crosswind displacement response measured using force balance test were ranked in descending order of magnitude as follows: 1) square shape; 2) square shape with notched corners; 3) square shape with rounded corners; 4) circular shape. The ranking at a lower design wind speed for occupant comfort consideration is different but the plain square shape still has the highest value of crosswind displacement and hence acceleration response. The results obtained from the aeroelastics tests were found to be significantly different to those derived from force balance tests. While the plain square shape was found to generally have a larger alongwind and crosswind displacement responses than the other shapes, the circular shape clearly exhibited aeroelastics lock-in type response at a critical reduced velocity of about 8, around which the crosswind response was considerably larger than the other shapes, including the plain square shape. This highlights that aeroelastics effects can be significant for super tall buildings and force balance technique can severely underestimate the dynamic response.

Miyashita et al. [18] investigated the effects of corner cut and corner recession on characteristics of wind forces acting on square prism of dimension 13 cm x 13 cm x 79 cm using force balance technique in wind tunnel. Modifications to the building corners are 10% of the breadth. Authors concluded that the corner cut and recession reduces the acrosswind fluctuating wind force coefficient of a model as compared to square plan at normal wind incidence. However, modifications to the building corners, particularly corner cur/notched corners were found to be not particularly effective and can cause an increase in response at low angles of wind incidence.

Kawai [20] investigated the effects of cornet cut and corner recession on aeroelastics instabilities such as vortex induced excitation and galloping oscillation by wind tunnel tests on square and rectangular prisms with aspect ratio of 10. Author concluded that small corner cut and recession of 5% of breath are very effective to prevent aeroelastics instability for a square prism by increasing the aerodynamic damping, but the large corner cut and recession promote the instability at low velocity to reduce the onset velocity of the instability when damping is small enough. The suppression of aeroelastic instability by smaller cut and recession does not come from the suppression of the vortex shedding but from the increase of the aerodynamic damping. The motion-induced vibration occurs for a deep depth rectangular prism, and it is little affected by the corner modifications.

Gu and Quan [11] investigated the effects of corner cut and corner recession on the acrosswind loads on square building of dimensions 100 mm x 100 mm x 600 mm and having a ratios of corner-cut size to the width of the cross section are 5%, 10% and 20% using high-frequency force balance technique in a wind tunnel. Authors concluded that the corner modification decreases the peak amplitudes of acrosswind force spectra. Among all the tested models, the peak amplitudes in the acrosswind force spectra is lowest for a building having a ratio of corner-cut size to the width of the cross section is 10%.

The double step corner configuration to a building significantly reduces the dynamic crosswind loading as compared to the square plan shape. Suresh Kumar et al. [24] investigate the effects of double step corner recession through wind tunnel test on a model of 505 m tall representative building. The results show that, rms acrosswind forces and mean alongwind forces on a building with double step corner configuration reduce as much as 40% and 20% respectively as compared to building of original square configuration. This reduction in loading is caused due to the disruption of severe vortex shedding by the corner modification. This type of geometry can also reduce the typical high corner suction pressures on sidewalls. Note that usually the design/shape of tall building is driven by crosswind loading and any reduction in crosswind loading by changing the geometry of the cross-section will result in cost effective design.

Tse et al. [22] investigated the impact and value of aerodynamic modifications like chamfered and recessed corners on tall building responses, while maintaining the total usable floor area of the modified building form by including additional compensatory storeys. Authors concluded that, for the range of building configurations tested, i.e. building heights ranging from 240 to 280 m and aspect ratios ranging from 5.0 to 5.8, the recessed corners are more effective than the chamfered corners in reducing both alongwind and crosswind moments due to buffeting and vortex shedding excitations respectively, particularly for the buildings with shorter aspect ratio and smaller corner modifications. However, the effects of aspect ratio for buildings with different sizes of recessed corners are more pronounced than those with chamfered corners, suggesting that the effectiveness of the two tested corner configurations may converge as aspect ratio increases. In general, for the range of building forms and heights tested, the construction cost was reduced with the introduction of chamfered and recessed corners even though the building height was increased to maintain the total usable floor area for the entire building.

Still, there is no definitive consensus on the benefits of corner geometry modifications, since studies have also shown that modifications to building corners, in some cases, were ineffective and even had adverse effects (Miyashita et al. [18]; Kwok and Isyumov [25].

This type of corner modifications (corner recession) had been applied to the 150 m high

Mitsubishi Heavy Industries Yokohama Building as shown in Figure 2, which was located in a water front area in the wake of peripheral tall buildings. To reduce the wind-induce responses, all the four corners were chamfered, which consequently reduced the wind forces. The double step corner recession modifications had been applied to the cross section of 508 m high, 101 storey, Taipei101 building, Taiwan as shown in Figure 3**.** A corner modification applied to the Taipei101 building reduces the base moment by 25% as compared to building of basic square section (Irwin [26]).

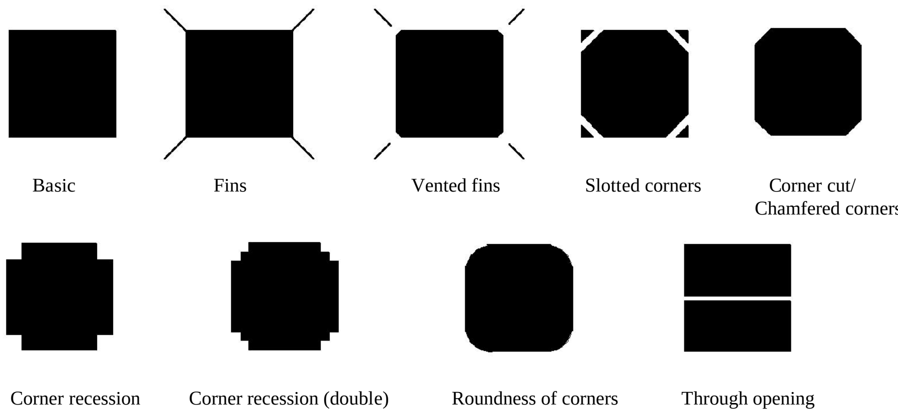

Figure 1. Various aerodynamic modifications to corner geometry

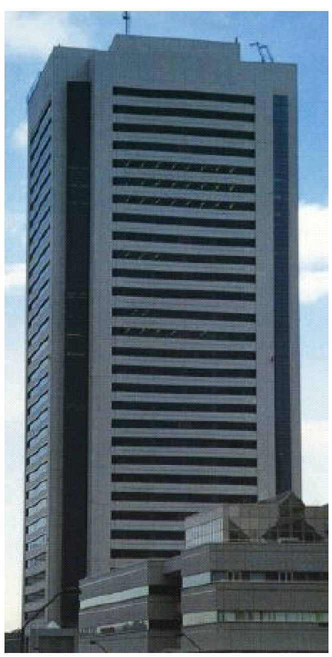

Figure 2. MHI Yokohama Building

Figure 3. Taipei 101 Building

4.4 Effects of Roundness of Corners

The configuration of building can play an important role in minimizing or suppressing vortex excitation and other aeroelastic effects. The corner roundness is one of the effective means of improving the aerodynamic behaviors of the tall buildings against the wind excitation (Kwok [27]; Karim et al. [28].

[29] investigated the response of six buildings of identical height and dynamic properties, but with different cross-sections to develop an optimum building shape for the U.S. steel building, Pittsburgh. The results showed that circular cross-section produces the lowest response and an equilateral triangular cross-section the highest. From geometrical point of view, rectangular plan shape rather susceptible to lateral drift. However other building shapes like cylindrical, elliptical and crescent are not as vulnerable to lateral force action as rectangular shape (Ali and Armstrong [30]). These types of building shape offers improved aerodynamic behaviors and allow the greater building height at comparatively lower cost. The wind pressure design loads for circular and elliptical building shape can be reduced by 20% to 40% as compared to similar sized rectangular buildings (Schueller [31]).

Melbourne and Cheung [15] and Melbourne [14] studied the effects of corner roundness on the crosswind response of tall buildings through wind tunnel aeroelastic test. Authors concluded that for normally symmetrical or square plan shapes, modest rounding or chamfering of corners up to 10% does not significantly reduce the crosswind response at low values of reduced velocities. However significant reductions in the ultimate limit state design loads can be achieved at higher reduced velocities. The crosswind force spectrum was found to reduce at the both the lower and higher ranges of reduced velocities, in the case of more substantial rounding of corners such that building plan shape approaches that of a roughly circular shape. Excessive rounding of the structure’s corners, approaching a roughly circular shape in the cross section or cylindrical shape of building, significantly improve the response of building against wind forces (Karim et al. [28]). However, the building plan shapes which are elliptical or elongated octagonal with a major to minor axis ratio of about 3:2, the critical reduced wind velocities were found to be significantly lower. The resultant high crosswind response and acceleration level makes it more difficult to meet occupancy comfort criteria. Furthermore, these plan shapes were found to exhibit significant torsional response about the vertical axis (Kwok [27]).

Kawai [20]) investigated the effects of corner roundness on aeroelastic instabilities such as vortex-induced excitation and galloping oscillation by wind tunnel tests on square and rectangular prisms with aspect ratio of 10. Author concluded that corner roundness is the most effective to suppress the aeroelastic instability for a square prism as compared to corner cut and corner recession/chamfered corners. The amplitude of the wind-induced vibration reduces as the extent of the corner roundness increases. In case of rectangular prism of side ratio (depth/breath) 1/2, the corner roundness has no or a little effect on the instability when the damping ratios are 0.2 to 1.2%, whereas corner roundness is effective to prevent the instability at damping ratio of 4%.

The Millennium Tower in Tokyo shown in Figure 4 exploits the use of circular plan shape to mitigate the wind excitation. The top portion of proposed 301 m high Shreepati Skies Tower, Mumbai, India as shown in Figure 5 and Marina City towers in Chicago, USA shown in Figure 6 had also utilised the advantage of cylindrical plan shape and/ or roundness of corners.

Figure 4. Millennium tower

Figure 5. Shreepati skies

Figure 6. Marina city towers

4.5 Effects of Tapering and Changing the Cross Sectional Shape along the Height

The aerodynamic modification of a building shape like changing the cross-section of building with height through tapering, reducing their upper level plan areas by cutting corners or dropping off corners progressively as the height increases, which alters the flow pattern around the building, could reduce the wind induced excitation of tall buildings. Buildings with tapered and nonuniform cross-section along the height would inhibit any formation of coherent wake fluctuations resulting in a reduction of transverse periodic loading (Karim [2]). Changing the cross-sectional shape of tall building along the vertical axis, along with effective tapering, might spread the vortex-shedding over a broad range of frequencies, can be especially effective in reducing the crosswind forces (Davenport [1]; Shimada and Hibi [32]; Kim and You [21]). More sculptured building top, in this case a triangular pyramid shape for the top 15% of the building, can moderate both the alongwind and crosswind response (Isyumov et al. [33]).

Cooper et al. [34] studied the unsteady wind loads acting on a super-tall building with a tapered cross-section and chamfered corners were measured as functions of reduced velocity and motion amplitude using aeroelastic model tests. Authors concluded that the tapered model with beveled/chamfered corners showed much lower levels of unstable aerodynamic damping due to vortex shedding than measured on a model having a constant square cross-section.

Kim and You [21] and You et al. [35] investigated the effects of tapering for reducing the wind-induced response of tapered tall buildings of square plan shape through wind tunnel test on the four types of building models of 400 mm height having tapering ratio of 2.5%, 5%, 7.5%, 10%, 15% and one square model using high-frequency force-balance technique. The results shows that mean alongwind pressure coefficients reduced 10% to 30% over an extended range of wind direction. Tapering effect for reducing fluctuating acrosswind forces appeared evidently when wind direction is 0º, that is, normal to windward face. Maximum reduction ratio of fluctuating across-wind forces is about 20% and about 30% for suburban terrain and urban terrain respectively. However, tapering effect is decreased as the wind direction is increased. Tapering effect has a more significant effect in acrosswind direction than that in alongwind direction and tapering effect is much more effective for suppressing the large size of vortex-shedding than the small size. Tapering effect in suburban flow environment is more efficient than that of urban flow environment. Authors also note that wind-induced responses of a tapered building model are not always reduced as compare to the responses of a basic building model of a square cross-section.

Kim et al. [36] investigated the effect of tapering in reducing the rms acrosswind displacement responses of a tall building using an aeroelastic test on three tapered tall building models with taper ratios of 5%, 10% and 15%, and one basic model of a square cross-section without a taper in a wind tunnel which simulated the suburban environment. The tapering effect appeared, when the reduced velocity was high and the structural damping ratio had a moderate value of 2–4%. However, the increase in tapering could have an adverse effect, increasing the rms acrosswind displacement responses when the structural damping ratio is very low.

The Millennium Tower in Tokyo, Japan shown in Figure 4 exploits the use of circular plan shape and tapering effects along the height of the building. The Transamerica pyramid, San Francisco shown in Figure 7 had utilized the advantage of tapering effects along the height to reduce the surface area and plan areas at top and thus mitigating the wind forces (Ali and Armstrong, [30]; Schueller [31]). The advantages of tapering effects and cutting corners were also integrated into the design of 421 m high Jin Mao building, china shwn in Figure 8 and 450m high Petronas tower in Malaysia shown in Figure 9. The Jin Mao building exploits the use of setbacks and tapering up to its 421 m façade and is crowned by ornate tiers shifted from the major axis of the structure creating an effect reminiscent of the ancient pagoda. The advantages of reducing the plan area along the height effects and roundness of corners were integrated into the design of 421m high Burj Dubai Tower, UAE shown in Figure 10. The Sears Tower in Chicago, USA shown in Figure 11 exploits the advantage of reducing the plan area along the height to minimize the wind-induced motion at the top of the building. The 551 m high Doha Convention Center in Qatar exploits the use of square plan shape and tapering effects along the height to reduce the plan area of building at top, which helps in mitigating the wind forces.

Figure 7. Transamerica pyramid

Figure 8. Jin mao building

Figure 9. Petronas towers

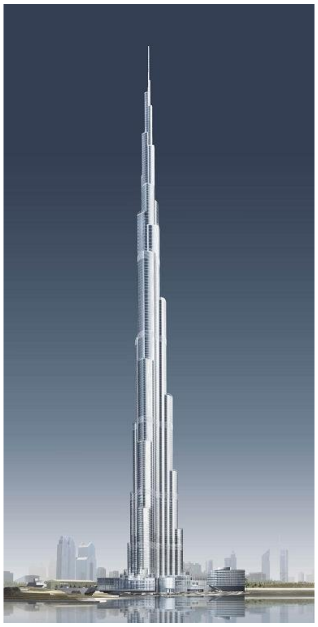

Figure 10. Burj dubai

Figure 11. Sears tower

Figure 12. Shanghai world financial center

4.6 Effects of Openings and Vertical/Horizontal slots

The addition of openings to a building provides yet another means of improving the aerodynamic behaviors of the structure against wind forces by reducing the vortex-shedding forces particularly at top, which cause the acrosswind motion. Open passages in the building would allow the air to bleed into the wake and separated regions thereby increase the base pressure and consequently reduce aerodynamic forces. However this approach, as true of any aerodynamics modification, must be used with care to avoid adverse effects.

Dutton and Isyumov [16] studied the effects of different vertical gap widths on the crosswind response of a square cross-section tall building with a height to breadth ratio of 1 to 9 using wind tunnel test. The building’s aerodynamics are modified by the introduction of openings in the upper half of the buildings and information is presented in the form of effects of these gaps on overall forces, responses and on the time-varying pressures. Authors found that providing the alongwind through building opening and in particular combined alongwind and crosswind openings, particularly near the top can be effective in reducing vortex- shedding induced forces, and hence the crosswind dynamic response of the tall buildings, but that effectiveness varies with the gap width. The provision of acrosswind gaps alone is not as effective as comparable alongwind gaps. The level of disruption to the vortex-shedding process varied with the width of opening and large reductions were observed for opening of 4% of building width. The critical reduced wind velocity shifted to a slightly higher value, which implied that resonant vibrations of the building would be postponed to a higher wind speed with a longer return period. The effectiveness of these gaps may be influenced by the level of turbulence in approach flow.

The potential beneficial effects of a through buildings opening in a 390 m high office tower project were studied by Isyumov et al. [33] using force balance and aeroelastics model technique in a wind tunnel. Authors concluded that a more sculptured building top, in this case a triangular pyramid shape for the top 15% of the building, can moderate both the alongwind and crosswind responses. A venting or bleeding of the building wake provided by through building opening near the top resulted in additional reductions in these responses.

Miyashita et al. [18] investigated the effects of openings of 25% of breadth on characteristics of wind forces acting on square prisms of dimension 13 cm x 13 cm x 79 cm using force balance technique in a wind tunnel. Authors concluded that the through building opening reduces the acrosswind fluctuating wind force coefficients of a model as compared to square plan at normal wind incidence. In particular the through opening along both directions, i.e. alongwind and crosswind direction is significantly reduces the acrosswind fluctuating wind force coefficients as well as responses of a model as compared to square plan of through opening along one direction at normal wind incidence.

Okada and Kong [37] investigated the effects of open passage for reducing the wind dynamic responses of tall buildings resulting from the periodic vortex-shedding of building corners using dynamic balance wind tunnel test on a model of square cross-section at aspect ratio of 8. The results show that very small opening of 1.5% on its four walls significantly reduces the acrosswind dynamic deflection by about 20-25%. The results also indicate that the arrangement with open passages on all its four walls is the more effective as compared to the arrangement of open passages either only on the side and front walls or on front and back walls.

Hitomitsu and Okada [38] investigated the effects of open passage configurations and its vertical position on acrosswind aerodynamic responses using dynamic models. Authors concluded that sections with alongwind open passages tend to obtain relatively more aerodynamic damping effect, while acrosswind open passages have an adverse influence on the separated shear layer, which results in having less aerodynamic damping coefficient. The aerodynamic responses are the most reduced in the case of open passages introduced on 0.8-0.9 of reference height, whereas the acrosswind aerodynamic responses tend to be not so conservative in the case of open passages introduced on 0.6 of reference height.

However, the effectiveness of this modification diminishes if the openings are provided at lower levels of the building. Provision of opening and other such type of changes adversely affect the habitability if they reduce the resonant vortex frequency (Tamura [39]). The benefits of providing opening at top were integrated into the design of 460 m high Shanghai World Financial Centre as shown in Figure 12, featuring a 54 m square shaft and diagonal face that is shaved back with the opening of 51 m provided at the top of the building to relieve pressure at this location. The design exploits not only the benefits of through-building openings but also those provided by shifting and decreasing the cross-section with increasing height, essentially tapering the 460 m tower. The Kingdom Center in Riyadh shown in Figure 13 also employs a large through building opening at the top combined with a tapered form to reduce the wind-induced forces.

4.7 Effects of Twisting or Rotating of Buildings

A twisted form is an interesting approach to be employed for today's tall buildings. Twisted forms are effective in reducing vortex-shedding induced dynamic response of tall buildings by disturbing vortex shedding. Twisting or rotating of building minimize the wind loads from prevailing direction and avoid the simultaneous vortex shedding along the height of the building. Rotating the building can be very effective because its least favorable aspect does not coincide with the strongest wind direction. The crosswind sensitive buildings can see their peak responses change by 10 to 20% within a 10-degree wind direction change. But to our knowledge, no specific study to investigate the effects of twisting of building is available in literature till date.

This twisted form can be found in today's tall building designs such as the 190 m high Turning Torso, in Malmo, Sweden and proposed Chicago Spire Project in Chicago,USA designed by Santiago Calatrava. Chicago Spire Project shown in Figure 14 would be constructed along the Chicago lakefront west of navy pier. The structure of the Chicago Spire will benefit greatly from its design, because curved designs tend to add strength to the structure, and in addition the curved face of the exterior will minimize wind forces, which is important in the windy city. The curved design will not completely negate wind forces, so a tapering concrete core and 12 shear walls emanating from it will also be installed to counteract these forces. The benefits of twisting of building are integrated into the design of

632 m high Shanghai Centre as shown in Figure 15 and Infinity tower, currently under construction in Dubai, UAE which is twisted by 90°.

Figure 13. Kingdom center

Figure 14. Chicago spire

Figure 15. Shanghai center

5. CONCLUSIONS

On the basis of wind tunnel studies on tall building available in literature, it is clearly noticed that aerodynamic modification to the building shape like, slotted and chamfered corners, horizontal and vertical through building openings, roundness of corners, tapering and dropping of corners can significantly reduce the wind excitation of tall buildings. The aerodynamic modifications can significantly mitigate wind excitation of tall buildings, but cannot eliminate them totally, and additional passive preventative measures like tuned mass damper, tuned liquid damper may be provided. However, care must always be taken in order to engineer modifications that will produce the desired effects through comprehensive program of wind tunnel model testing to verify the effects of altering the plan shape or employing other forms of aerodynamic modification. Engineers may achieve significant reduction in wind excitation by providing aerodynamic modifications, which do not increase the projected area or breath of a building. Modifications to the building corners such as slotted or chamfered corners need to be applied to the corner region greater than about 10% of the building breadth to be beneficial.

- The plan shape, which has a lower Stroughal Number, is beneficial and it is a parameter, which can offer significant benefit when correctly selected.

- The corner roundness is the most effective to suppress the aeroelastic instability for a square building. The amplitude of the wind-induced vibration reduces as the extent of the corner roundness increases.
- Tapering effect has a more significant effect in acrosswind direction than that in alongwind direction.
- The through building opening along the alongwind and crosswind direction, particularly at top significantly reduces the wind excitation of the building.

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