Local or Micro or Minor Aerodynamic Modifications in Tall Buildings: A Critical Review

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Abstract - Tall buildings are going taller and taller in height, because of innovation in structural systems by new construction techniques and advances in engineering methodologies. Traditionally, architectural studies, design quality, site location, etc. have been taken into account in place of aerodynamic factors when determining the geometry and alignment of tall buildings. The exterior configuration of the structure is one of the key factors that influence designed wind pressure and reactions. As a result, they're bluff bodies associated with high motion induced by the wind structure. The most effective way to increase the safety and use of tall buildings in heavy winds is through aerodynamic modifications.Depending on the impact of modifying the outside geometry of the structure, the aerodynamic modifications are divided into two Varity, i.e. local or micro or minor (corner-cut, recession, etc.) and global or macro or major (twisting, setback, etc.) modifications. Also, this study comprehensively explores the recent/past local or micro or minor aerodynamic modifications on tall buildings. Local, micro, or minor modifications (corner-cutting, corner-rounding, chamfering, etc.) can reduce wind load by 30–60% because they make it easier for the shear layer to reconnect and reduce the trailing area on the building's windward side. This study presents a fast description of several local, micro, or minor aerodynamic improvements to reduce wind stress on tall buildings. Aerodynamic modifications considerably lessen the influence of dynamic loading on tall buildings.

Keywords: Aerodynamic modifications, Along wind, Across wind, Tall building

I. INTRODUCTION

Expanding interest for modern business, and private space, financial turn of events, advancements in auxiliary framework has promoted the extent of vertical extension of the buildings and with the advancement of the latest construction techniques and new design aspects, buildings are going taller and taller in height. Despite of what might be expected; these progressions in statures are for the most part amid expanded adaptability, slimness, absence of adequate damping, and low characteristics recurrence[1][2]. Tall buildings are vulnerable to transverse or twisting deflection due to varying wind loads, which end in oscillating movement and produce mild discomfort (acute nausea) to people. Accordingly, wind-prompted loads and movements normally administer the arranging of the sidelong burden opposing frameworks in tall buildings. The cross-sectional architectural style is one of the key factors influencing these loads and responses. The barrier to wind-induced pressure and the structure's response in both directions have been found to be significantly influenced by the configuration of the structure, i.e. along wind and across wind.Every perplexing shape and environmental factors produce a solitary arrangement of configuration wind loads. This shape dependence provides an unmistakable opportunity to reduce the wind load either globally or locally through change in external shape. This reduction in wind load dueto diffusions/ un-synchronization of vortices[3]. There are two main means of achieving the required performance of tall and super tall buildings: Structural and aerodynamic. This paper discusses the aerodynamic means for minimizing aerodynamics forces and responses. Here focus is only on local modifications on tall buildings. Chapter 2 and 3 discusses studies of shape effects on aerodynamic and response performance of tall and super tall buildings, Chapter 4 concludes those discussions.

II.AERODYNAMIC MODIFICATIONS FOR TALL BUILDINGS

Aerodynamic modifications are widely divided into two kinds, local or micro or minor and global or macro or major modifications, based on the outside geometry of the structure[1]. In this sense, local modifications by the small changes in the shape of the building effectively influence the structural and architectural plans. These include rounding, chamfering, recessed corners, holes, and vanes, on rectangular shapes are shown in Fig. 2.1. Consequently, later on in the original design process,the architects may introduce local modifications, which should also be considered by the structural engineer in the assessment of wind load on the structure[4].

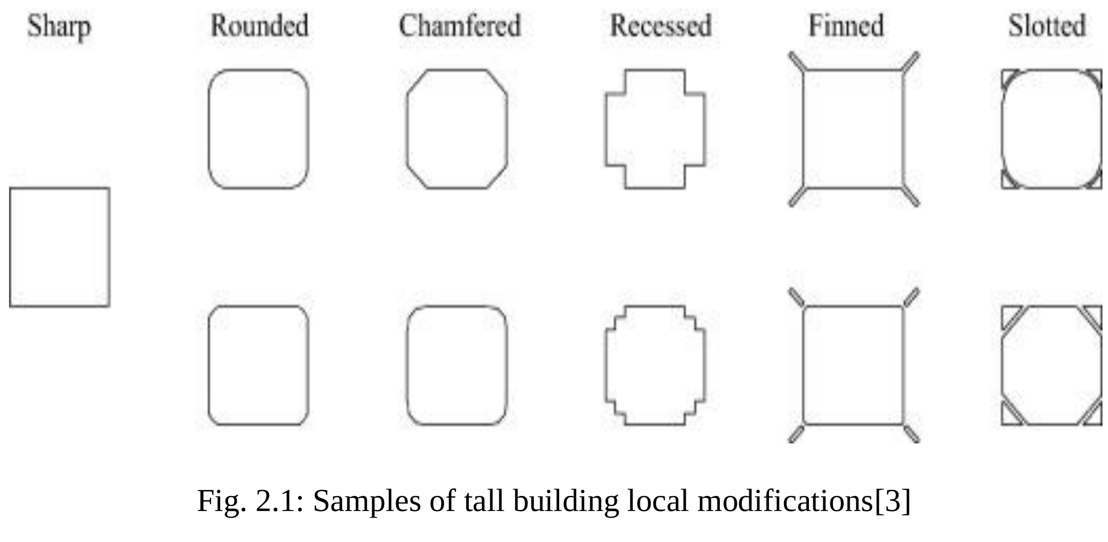

Fig. 2.1: Samples of tall building local modifications[3]

Global modifications, from the other side, include significant modifications to the building's shape that have a worthwhile impact on the whole design of the architectural and constructional elements.These include enormous gaps,tapering, twisting, set-back, etc. as represented in Fig. 2.2. On the building's basic conceptual plan, the architects may carry out global modifications, if the modifications do not interfere with the basic functionalities of the building[4].

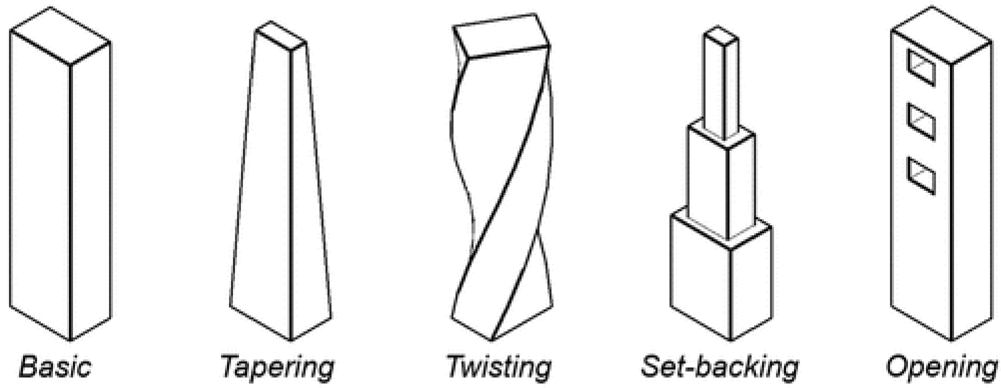

Fig. 2.2: Samples of tall building global modifications[5]

III.LOCAL OR MICRO OR MINOR AERODYNAMIC MODIFICATIONS IN TALL BUILDINGS

The conventional shapes like square and rectangular which are bluff structures are more susceptible to dynamic vortex shedding, which is responsible for vibrations, galloping, gusting, and oscillations because of strong winds. The arrangements of the shear layer are modified by corner modifications that minimize the wake area behind the leeward faces and also decrease along-wind and cross-wind excitations[1].

Davenport(1971) study the response of six building shapes on the boundary layer in wind tunnel. It is concluded that significant mitigation of wind loads is found on varied shapes and execution are often improved by legitimate decision of shape or detail. For a 100-year return period the maximum deflection is found for rectangular section and minimum deflection is found for circular section as shown in Fig. 3.1[6].

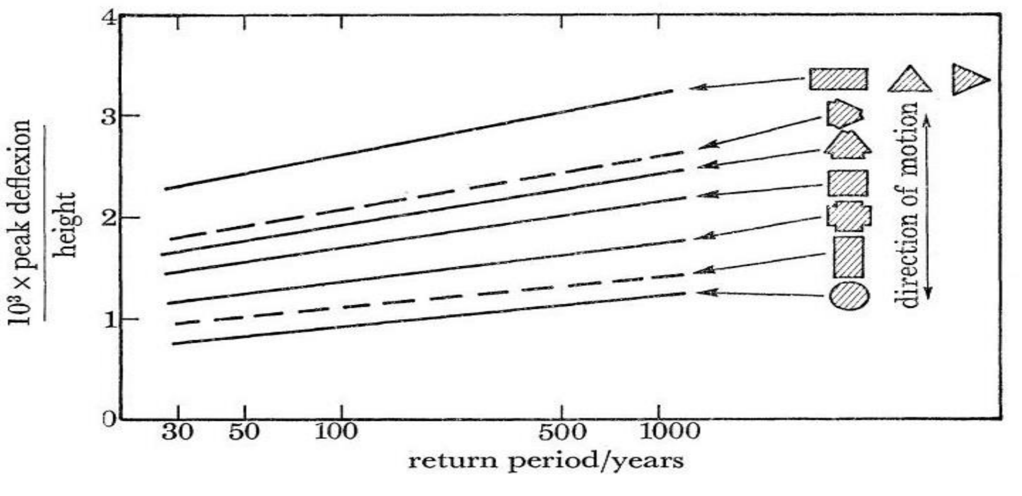

Fig. 3.1 Effect of shape of cross-section on maximum deflection of six buildings shapes[6]

Kwok and Bailey (1987) investigate five configurations of an aero-elastic model: Plan Square Tower, Tower with 10mm wide vertical fins fitted with corner, Tower with 5mm wide vertical fins and 5mm gap with both fins and corner, Tower with 5mm wide slots cut via corners well over entire tower height, and Tower with slotted corner about just the top half of the model are the five options. It is concluded that fins boost along-wind response while decreasing across-wind response for the slotted tower models, with a reduction of up to 25% in the wake aroused behavior at the small end of diminished wind velocity[7]. Whereas the chamfered corner consequence is more considerable than those of slotted corners, Kwok et al. (1988) also discovered that chamfered and slotted modifications decrease along wind (up to 40percent decrease in reaction) and cross wind responses (up to 30% reduction in response). This substantial reduction was discovered using chamfered corners along the 2/3 height of the building near top, as express in figure 3.2[8].

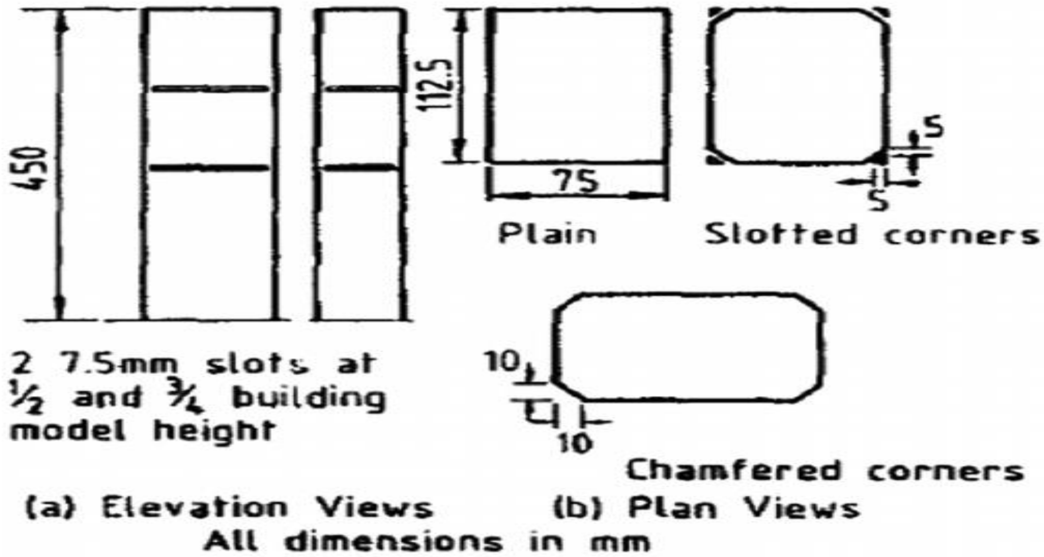

Fig. 3.2 Aerodynamic modifications of buildings shapes[8]

Kwok (1998) looked at how the design of a tall building with a rectangular cross section affected its reaction to wind-induced forces. Cross wind reaction was found to be reduced by up to 30% using horizontal slots and slotted corners. There is a 40% decrease in along wind reactions and a 30% decrease in across wind reactions with chamfered corners[9]. Shiraishi et al. (1988) investigate the effects of aerodynamic stability upon bluff rectangular cylinders with square corners that range in thickness from a/D = 1/18 to 6/18. He came to the conclusion that for the lowering in drag force in the cylinders, the ideal configuration with the ideal corner cut size is a/D = 2/18[10].When the design wind velocity is greater than 30 m/sec, crosswind response becomes greater than the along wind in the Hayashida and Iwasa (1990) analysis. Across wind displacements for various shapes of the buildings are shown in Fig. 3.3 with reference to various directions.The displacement of type A-1 (Square) was around three times greater than those of type B-2 (Y-shape with corner cut)[11].

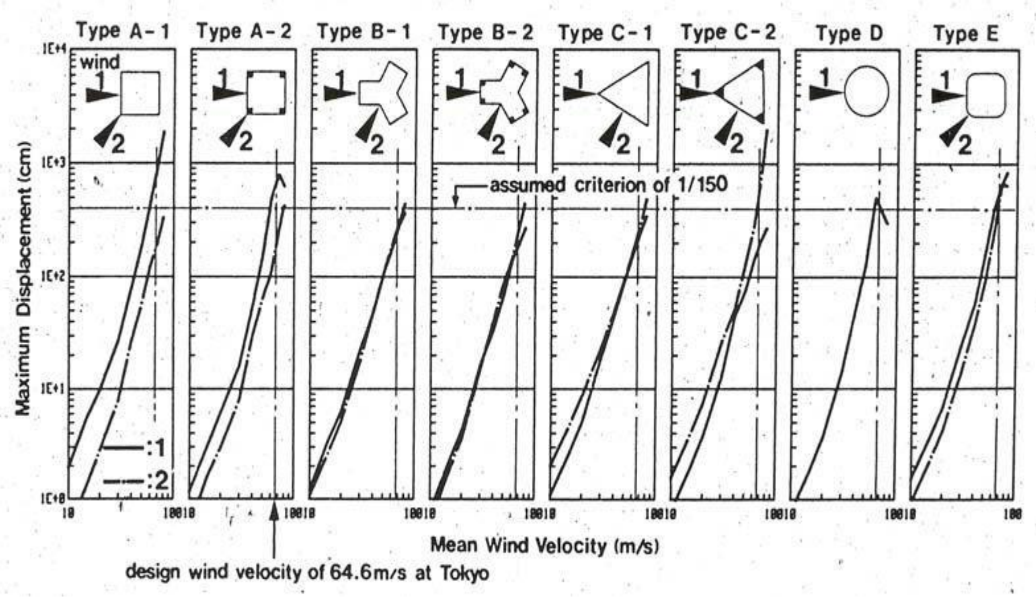

Fig. 3.3maximum wind displacement of different building designs under two common wind directions with standard mean wind speed[11]

Jamieson et al (1992) study various corner configuration like 90° angle corner, small beveld corner, larged beveled, re-entrant corner, smoothened corner with various radiuses. For various corner configurations, they discovered the lowest and maximum peak pressure coefficients at the building's 2/3 height. For each configuration, the minimal coefficient of pressure ranges from -3.4 for large bevel corners to -4.8 for different sizes of curved corners[12]. According to Miyashita et al. (1993), for normal wind angle of incidence, the fluctuating fraction of crossing wind is reduced. The Type-6 square model with cut corners has the highest recorded vortex shedding frequency compared to the other variants. Cross-wind fluctuation wind force coefficient is lower in the design with corner cuts or openings than in the square plan[13].In Kawai's (1998) analysis of the aero-elastic destabilization of tall buildings with different corner modifications in a residential neighborhood (power law index =0.2), as can be seen in Fig. 3.4, small corner cuts and recession, or 0.05B, are very effective in preventing aero-elastic destabilization for a square prism by broadening aerodynamic damping, whereas broad corner cuts and recession are more likely to cause instability at low speed. The best solution to remove the aero-elastic destabilization of a square prism between the 3 corners alterations is to make the corner rounded[14].

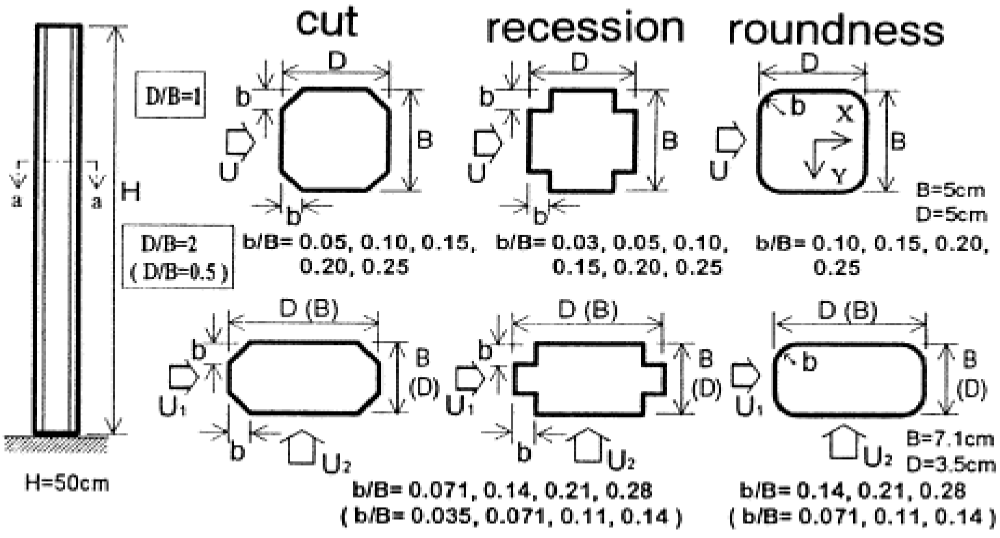

Fig. 3.4Model sections with rounded corners, recessions, and corner cuts[14]

Tamura et al. (1998) use numerical analysis to examine the effects of fluctuating pressure on a square cylinder with different corner shapes. It has been determined that, if corner shapes are marginally altered, aerodynamic characteristics are drastically altered, and the adjusted drag may be reduced by as much as 60% of its original value. The square cylinder, chamfered cylinder, and rounded cylinder are in decreasing order of the CD and CLrms values[15].The solitary shear layer travels to the outer side with corner-cutting and corner-rounding, this slow reattachment, and this lowering of drag force, according to Tamura and Miyagi's (1999) Wind Tunnel investigations. When the angle of attack is very narrow, CLRMS on a square cylinder having chamfered and rounded corners is decreased to approximately 50% of that on a cylinder with sharp corners[16]. Gu and Quan (2004) used the high frequency force balance approach in a wind tunnel to investigate 15 typical tall buildings. Crosswind forces are greatly affected by corner adjustments. In general, the changes result in a sharp decrease in wind force spectrum amplitude. Furthermore, among these models, the building with the side proportion of 10% has the lowest peak amplitude and frequency in the across wind force spectra[17].

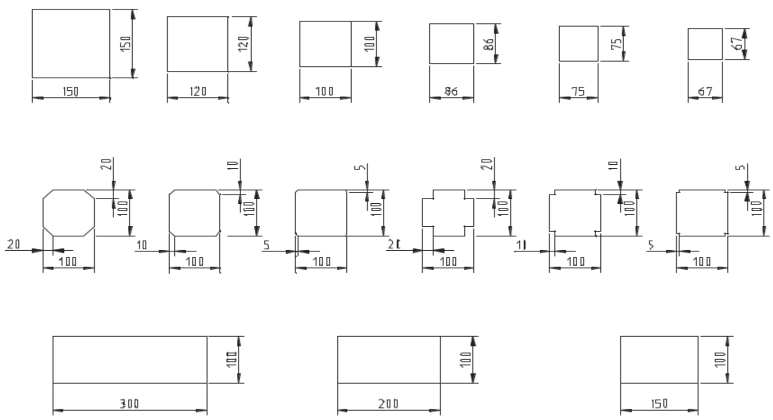

Fig. 3.5 Sectional view of the architectural models [17]

By Merrick and Bitsumlak (2009), it's concluded that for the torsion sensitive case circular are better than elliptical, square is better than rectangular and therefore the triangular section may be a very poor choice[18]. Recessing is more efficient in both directions, according to Tse et al. (2009), and building costs are also decreased where rental income increases with the number of storeys and the rental rate (Rn) coefficient is 0.5 percent. Recessed corners are more effective than chamfered corners in minimizing both along wind and cross wind because of buffeting and vortex shedding[19]. According to Mandal and Faruk's experimental investigation of the static pressure distribution on a collection of square or rectangular cylinders with rounded corners, the drag coefficient on the rear cylinder with either a square or rectangular cross-section or a rounded corner significantly decreases when compared to the single cylinder. The front cylinder's drag coefficient differs just little from that on the single cylinder. Interspacing and side ratio have a large impact on the rear cylinder's drag coefficient. The front cylinder's drag coefficient is somewhat influenced by interspacing and side ratio[20].

The relatively close flow structure is susceptible to changes in the shape of cut-corners, according to the computational research by Xu et al. (2011). With corner cutoffs, the distinct shear layers are much closer to the side surface, making reattachment and drag force minimization easier.[21]. Zhengwei et al. (2012) in hisstudyof two types of corner recession as shown in Fig. 3.6, single and double recession with a recession rate from 5%, 7.5%, 10%, 12.5%, 15%, 20%, 30% for 0 to 45° wind incidence angle, concluded that with a rate of 7.5% of corner recession, base movement and torque of the square high rise building are often reduced[22].

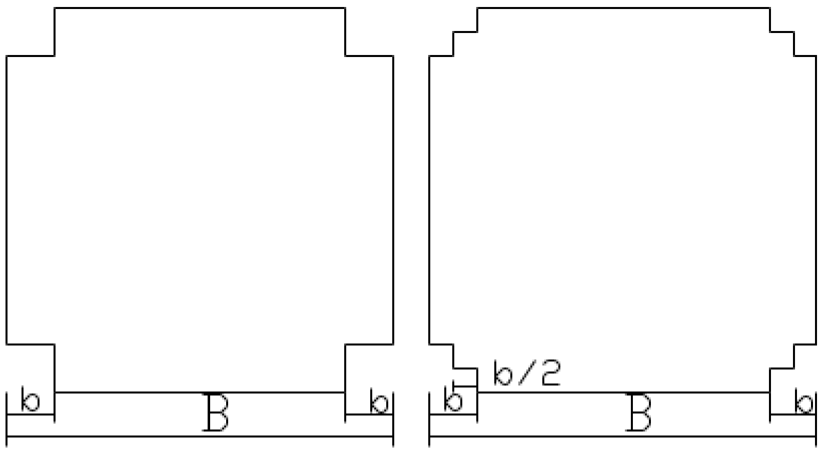

Fig.3.6 Cross Section of the Building Models- a)Type-1 Single Corner Recession, b) Type-2 Double Corner Recession[22]

According to Huang et al (2013) study, along-wind aerodynamic damping is typically beneficial and gradually rises with the decrease in wind speed (Ur). For the square cross-section building, the cross-wind aerodynamic damping typically has a positive value at low Ur but surprisingly changes to a negative value when Ur exceeds 10.5[23]. According to C. K. et al (2014) examination of square cylinders with different square shapes, chamfered and rounded corners reduce the wake width and, consequently, the lift and drag coefficient values.

The coefficient of lift and drag is decreased by the fast velocity behind the cylinder. A square cylinder with a modified corner has lower lift coefficients than a square cylinder without a modified corner, but its Strouhal number is higher[24].According to Luigi Carassale et al (2014) study, the critical angle of incidence related to the flow reattachment on the lateral face accessible to the flow lowers as r/b rises and an intermittent flow situation develops. The critical angle of incidence Cr for which the flow is reattached to the wind-exposed side face is reduced by rounded corners[25].

In his studies, Elshaer et al. (2014) concludes that corner roundness is the most effective form for drag reduction, followed by chamfering, and then recessed shapes. The drag coefficient could be decreased to up to 40% of that of a square cylinder with a sharp edge[26]. By study ofElshaer et al. (2015),it's concluded that the fluctuating lift coefficient of optimal solution where minimize the coefficient of drag 24% but that of the square cross-section. C_D for the optimal solution in case of steady state is 1.337 and for transient state is 1.427[27]. By finding of Bernardini et al. (2015), it's concluded that with the utilization of kriging based methodology we just required 0.75% of CFD runs to legitimately look for a Parsto optimal solution. The strong capability of surrogate-based multi-objective optimization plans to obtain aerodynamic configuration of civil structures that substantially reduce their aerodynamic effect will seem to be recommended in this paper[28]. According to Wakchaure and Gawali's (2015) investigation, the building's wind speed, floor drifts, lateral displacement, and floor shear are all reduced when the building's shape is changed from square to elliptical. Wind forces are reduced by a maximum percentage for an elliptical layout. When compared to the gust factor, the peak wind intensity is lowered by 4.471 percent for circular and 63.38 percent for elliptical shapes, and it is increased by 15 percent for rectangular shapes[29]. According to a study by Boonyapinyo and Wangkansirkun (2016), corner adjustments significantly reduce wind loads and response both along and across the wind. For the 1:1, 1:1.5, 1:2, 1.5:1, and 2:1 aspect ratios of the model depth to width, the recession of the corner at 10% of the building face causes a decline of the base moment around the x-axis (0-degree wind direction) of 18%, 25%, 14%, and 3%, respectively. The base moment around the y-axis is reduced by 13 percent, 16 percent, 14 percent, 18 percent, and 10 percent, respectively, for the models mentioned above when the corner recession is 10%[30].

Elshaer et al. (2017) found that for the ideal corner comparing to the sharp edge one, the mean drag coefficient is decreased by 30% and the lift coefficient is therefore lowered by 24%. The total result of drag optimization is decreased to 29 percent, while the overall result of lift optimization is reduced to 52 percent[30]. According to Li et al(2018) investigation, chamfered corners in unfavorable wind directions can greatly reduce along-wind loads, and recessed corners in the same unfavorable direction can significantly reduce cross-wind loads. Round corners are less effective in reducing these wind loads than recessed and chamfered corners[31].

According to Deng et al(2018) review of wind tunnel data on extremely tall buildings, allowing ventilation dramatically lowers the aerodynamic loads of structures. The 100-year return duration (YTP) and 50-year return duration (YTP) maximum peak base mixing times are shortened by 15.5 percent and 15.2 percent, respectively. The peak acceleration equivalent to 10 YTP is 16 percent lower near the top of the structure[32].

Table 1: Summaries of Local or Micro or Minor Modification

Reference	**Method**	**Modification**	**Remarks**
(Davenport, 1971)[6]	BLWTL	Recession	Maximum deflection is reduced.
(Kenny C. S. Kwok, 1987)[7]	AEM	Vertical Fins, Vented Fins, Corner Slots	By Fins along wind response increase and the across wind response decrease. The Slotted corner reduces both, along wind and across wind response.
(K. C. S. Kwok, 1988)[8]	BLWTL	Chamfering, Corner Slot	Along wind (40%) and across the wind (30%) excitation and responses are significantly reduced.
(Kwok, 1988)[9]	AEM	Chamfering, Corner Slot, Horizontal Slot	With horizontal and slotted corner, there were up to 30% reductions in responses.
(N. Shiraishi, 1988)[10]	BLWTL	Corner Cut	Considerable reduction in drag force at corner cut size of a= 2/18, Vibrational response characteristics changed drastically.
(Lee, 1990)[33]	BLWTL	Change of Aspect Ratio	The maximum coefficient of drag is found when a/b is 2/3= 0.67.
(Iwasa, 1990)[11]	BLWTL	Circular, Triangular, Y-shape Corner-Cut Roundness, Surface Roughness	Displacements reduced, For type B-2(Y-shape with corner cut) was about 3times less than type A-1 (square).
(N.J. Jamieson a, 1992)[12]	BLWTL	Recessed, Rounded, Beveled	Max. And Mini. Peak pressure coefficients are calculated at 2/3 height. Mini peak C_p is -3.4 for large bevels and -4.8 for curved corners.
(K. Miyashita, 1993)[13]	BLWTL	Chamfering, Recession, opening along the height	For normal wind angle of incidence, The crosswise wind's changing component is diminished.
(Kawai, 1998)[14]	AEM	Chamfering, Recession, Rounded	For a square prism to defeat aero-elastic instability Corner roundness is very

			effective.
(Tetsuro Tamura, 1999)[15]	BLWTL	Chamfering, Rounded	Drag forces are reducing by Corner cutting and corner roundness.
(M. Gu, Y. Quan, 2004)[17]	HFFB	Chamfering, Recession	Coefficients of base moment and shear force and wind force power spectral density across wind are derived; The effect of damping is also investigated.
(Ryan Merrick and Girma Bitsumlak, 2009)[18]	BLWTL	Square, Circular, Triangular, Rectangular, Elliptical	There is an effect of high torsion loading on Elliptical, Triangular, and Rectangular shaped buildings.
(K.T. Tse, 2009)[19]	BLWTL	Chamfering, Rounded	Recessing is more effective in both directions and construction cost is also reduced where rental income increased with the number of storey and rental rate (Rn) coefficient is 0.5%.
(A. C. Mandal and G. M. Faruk, 2010)[20]	BLWTL	Rounded Corners	The drag coefficient of cylinders is significantly influenced by side dimension and interspacing.
(Fu You Xu, 2011)[21]	CFD	Beveled, Recession, Rounding	Drag force is effectively reduced.
(Zhang Zhengwei, 2012)[22]	HFFB	Recession	A corner recession rate of 7.5% is the most effective and optimal. Both types of recession single and double reduce coefficients of base moment and torque.
(Peng Haung, 2013)[23]	AEM	Chamfering, Recession	Along wind damping increase with increase in Ur, Across wind damping increase with low value of Ur but limited to 10.5 for square section.
(Ahmed Elshaer, 2014)[26]	CFD	Chamfering, Recession, Rounding	Drag Coefficient is reduced up to 40% as compared to sharp edge square cylinder.

(Ahmed Elshaer, 2014)[34]	CFD	Chamfering, Recession	The fluctuating lift co-efficient of the resulted optimal solution is 24% less than that of square cross-section.
(Vikram C. K., 2014)[24]	CFD	Chamfering, Rounding	Drag and Lift coefficient is decreased for chamfered and rounded corners as compare to the square cylinder.
(Luigi Carassale, 2014)[25]	BLWTL	Rounded Corners	Rounder corners produce some significant effects on the lateral faces by promoting the reattachment of the flow.
(Enrica Bernardini, 2015)[28]	CFD	Chamfering, Recession, Rounding	Optimization of each side is taken into account. Only 0.75% of CFD runs are required for optimal solution by kriging-Based approach.
(Ahmed Elshaer G. B., 2015)[27]	CFD	Chamfering, Recession, Rounding	Optimal corner shape of a square building to minimize the drag is obtained.
(Prof. M. R. Wakchaure, 2015)[29]	ETAB B's 13.1.1v.	Rounding Circular, Elliptical	When the shape of the building change from Square to Elliptical, storey shear and drifts, lateral displacements, the wind intensity, of the building are decreased.
(Virote Boonyapinyo, 2016)[30]	BLWT	Chamfering, Recession	There is a significant reduction of across and along wind responses by corner modifications.
(Ahmed Elshaer G. B., 2017)[3]	CFD	Chamfering, Various corner configurations for optimal shape.	For finding the best optimal shape, The drag optimization results were reduced to 29% whereas lift optimization results were reduced to 52% as compared to other optimal shapes.
(Yi Li, 2017)[31]	BLWTL	Chamfering, Recession, Rounding	Corner recession and chamfered are very helpful for reducing of wind loads.
(Ting Deng, 2018)[32]	BLWTL	Recession, Opening Slot	Cross wind responses are significantly reduced by opening ventilation slots.

*BLWTL-Boundary Layer wind Tunnel. *AEM- Aero Elastic Modeling. *CFD-Computational Fluid Dynamics *HFFB- High Frequency force Balance

IV.CONCLUSION

Practical requirements, site limitations, and architectural considerations determine the buildings' shape and orientation. Tall buildings should have their aerodynamics modified; The number of wind-induced strains exerted on a buildings can be dramatically decreased even with a small alteration to its fundamental geometric form.

The outcome of this study is compiling within the following:

The vortex shedding phenomenon and wake excitations are disturbed by aerodynamic modifications in the structure shape, either by local or micro or minor and global or macro or major modifications. As they make it easier for the shear layer to reattach and reduce the wake area on the building's leeward face, local modifications such as micro or minor (corner-cut, corner rounding, chamfering, etc.) can reduce wind loads by 30–60%.

The results show that the chamfered model can lower the along wind and across wind response by 40% and 30%, respectively. The slots at the corner of the 102 Incheon Tower in South Korea was found to be able to minimize the base moment by 60%. According to Holmes, in relative to a building with a rectangular shape, chamfering of the scale of 10% can diminish the along wind responsiveness by up to 40% and the across wind performance by up to 30%.

The results of a CFD and ANN modeling study showed that a reduction of 24 percent can provide the best corner modification, with a mean drag coefficient reduction of 30 percent. Drag dynamic response is reduced by 29%, while lift dynamic response is reduced by 52%. The alteration of the double recessed corner reduced the transverse load by 25%. About 10% of the building's width is the ideal alteration length for finding the optimum mitigation effects.

Researchers may get a thorough overview and impression of the technique of aerodynamic changes as well as an acceptable design approach to diminsh wind-induced loads and reactions by studying various sorts of local, micro, or minor aerodynamic modifications in the current work. This research may be used to help choose the necessary local aerodynamic adjustment for a tall building.

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