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

[1]Harish, [2]Awadhesh Kumar
[1]Research Scholar, Department of Civil Engineering, Delhi Technological University, Delhi-110042, India.
[2]Professor, Department of Civil Engineering, Delhi Technological University, Delhi-110042, India. [1]Email: harishpanghal2012@gmail.com, [2]Email: awadheshg@gmail.com

Article Info

Page Number: 1496 - 1509

Publication Issue:

Vol 71 No. 4 (2022)

Article History

***Article Received**: 25 March 2022*

***Revised**: 30 April 2022*

***Accepted**: 15 June 2022*

***Publication**: 19 August 2022*

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, instead of aerodynamic considerations, the shape and orientation of tall buildings are taken into account by architectural studies, design quality, and site location, etc. One of the most prominent parameters that influence design wind load and responses is the outer configuration of the building. As a result, they're bluff bodies associated with high motion induced by the wind structure. Aerodynamic modifications are the primary effective strategy to improve the safety and serviceability of tall buildings during strong winds. Based on the effect of change in the structure's outer geometry, the aerodynamic modifications are divided into two groups, 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 or Micro or Minor modifications(corner-cut, corner rounding, chamfering, etc can result in a 30-60 percent reduction in wind load as they facilitate the reattachment of the shear layer and narrow down the wake area on the building's leeward face. Aerodynamic modifications significantly reduce the impact of wind load on tall buildings, and this study provides a quick summary of different local or micro or minor aerodynamic modifications to reduce wind load 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]. Because of fluctuating wind loads, tall buildings are subjected to lateral or torsional deflection, 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. One of the main parameters affecting these loads and responses is the cross-sectional form of the building. It is identified that in opposition to wind-induced load and response of the structure in both directions i.e. along wind and across wind, the shape of the structure assumes a significant role. 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

Based on the outer geometry of the structure, aerodynamic modifications are broadly classified into two groups which are local or micro or minor and global or macro or major modifications[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. Thus, at a later stage of the conceptual design, 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].

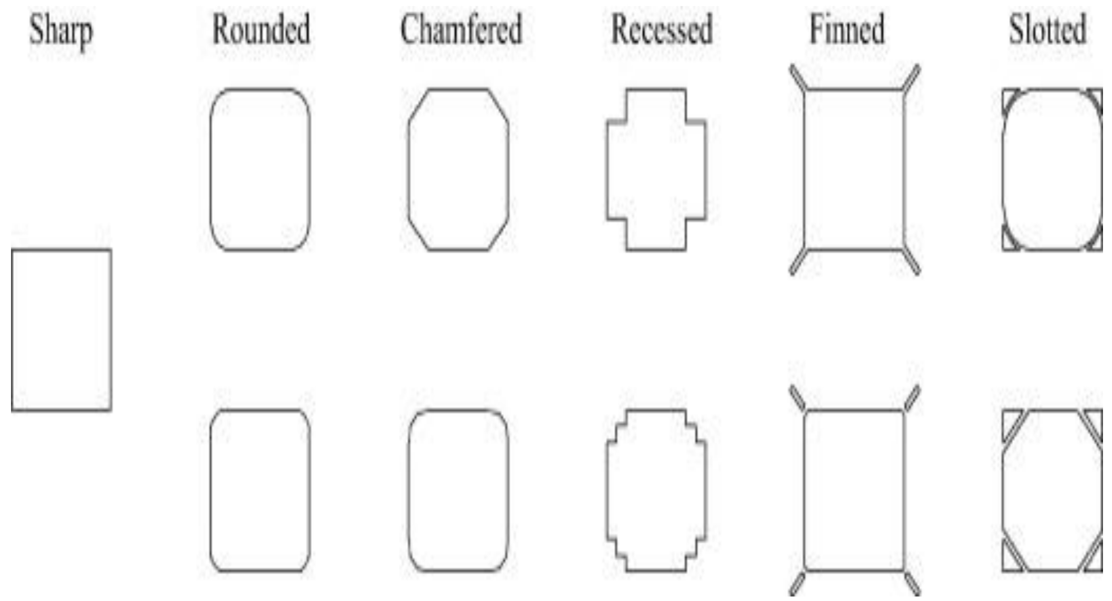

Fig. 2.1: Samples of tall building local modifications[3]

Global modifications, on the other hand, involve major changes in the shape of the building, with a significant effect on the overall architectural and structural plan. These include enormous gaps, tapering, twisting, set-back, etc. as shown in Fig. 2.2. On the primary conceptual plan of thebuilding, the architects may carry out global modifications, if the modifications do not interfere with the basic functionalities of the building[4].

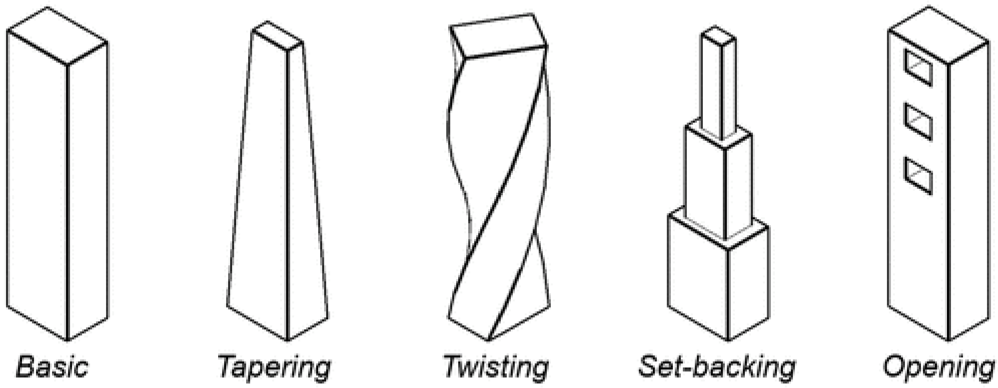

Fig. 2.2: Samples of tall building global modifications[5]

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 return period of 100 years the maximum deflection is found for rectangular section and minimum deflection is found for circular section as shown in Fig. 3.1[6].

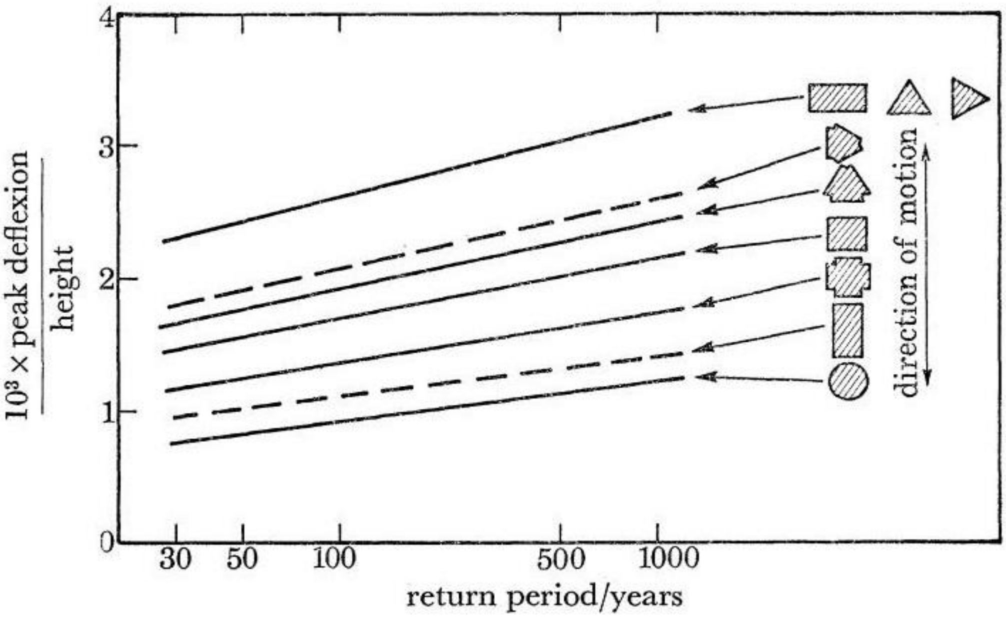

Fig. 3.1 Effect of shape of cross-section on maximum deflection of six buildings shapes[6]

Kwok and Bailey (1987) study five aero-elastic model configuration: 1) Plan Square tower, 2) Tower with 10mm wide vertical fins fitted with corner, 3) Tower with 5mm wide vertical fins and 5mm gap between fins and corner, 4) Tower with 5mm wide slots cut through corners over the entire tower height and 5) tower with slotted corner about the top half of the model. It concludes that for the slotted tower models, there is up to 25% reduction in wake excited response at the low range of reduced wind velocities,while fins increase along-wind response and decrease across-wind response[7]. Kwok et al. (1988) further found that chamfered and slotted modifications reduce along wind (up to 40% reduction in response) and cross wind responses (up to 30% reduction in response) while chamfered corner effect is more substantial than those of slotted corners, this substantial reduction was found using chamfered corners along the 2/3 height of the building near top as shown in figure 3.2[8].

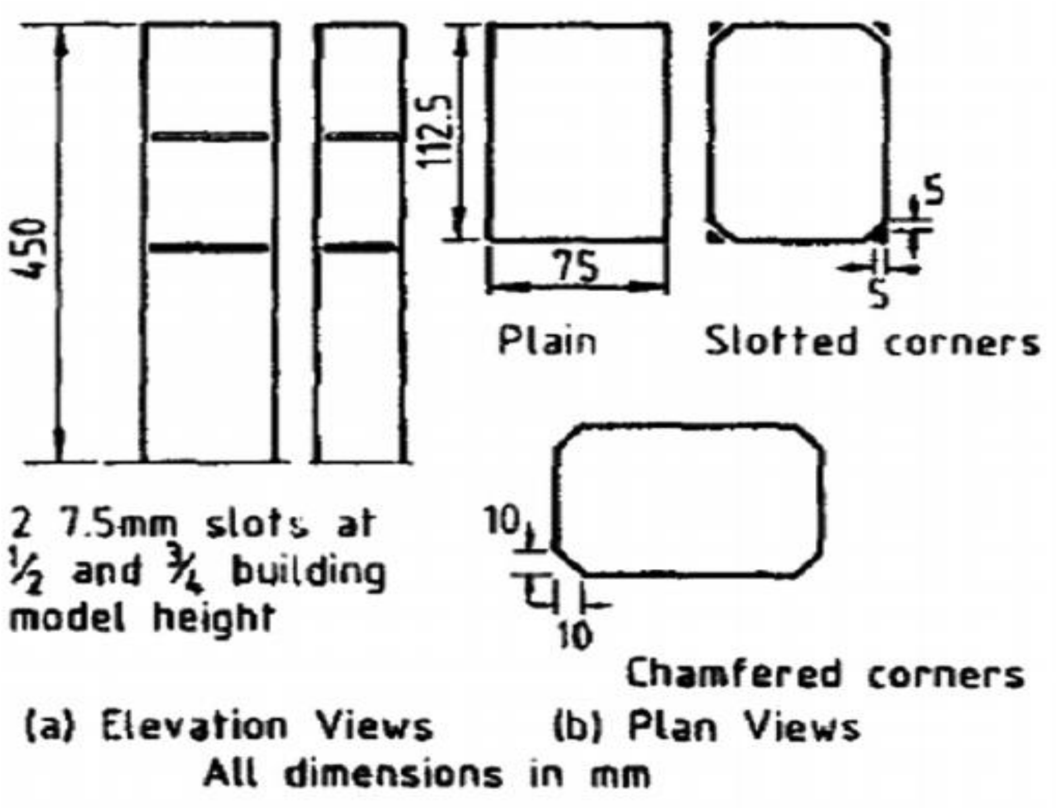

Fig. 3.2 Aerodynamic modifications of buildings shapes[8]

Kwok (1998) investigate the effect of building shape on the wind induced response of a tall building with rectangular cross section. It was found that with horizontal slot and slotted corners, there were up to 30% reduction in cross wind response. With chamfered corners, there is 40% reduction in along wind responses and 30% reduction in across wind responses[9].Shiraishi et al. (1988) study aerodynamic stability effects on bluff rectangular cylinders by their square corner cut from a/D = 1/18 to 6/18. He concluded that the optimum configuration with the optimum corner cut size is a/D = 2/18 for the reduction of drag force in the cylinders[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 type A-1 (Square) displacement was approximately three times higher than that of type B-2 (Y-shape with corner cut)[11].

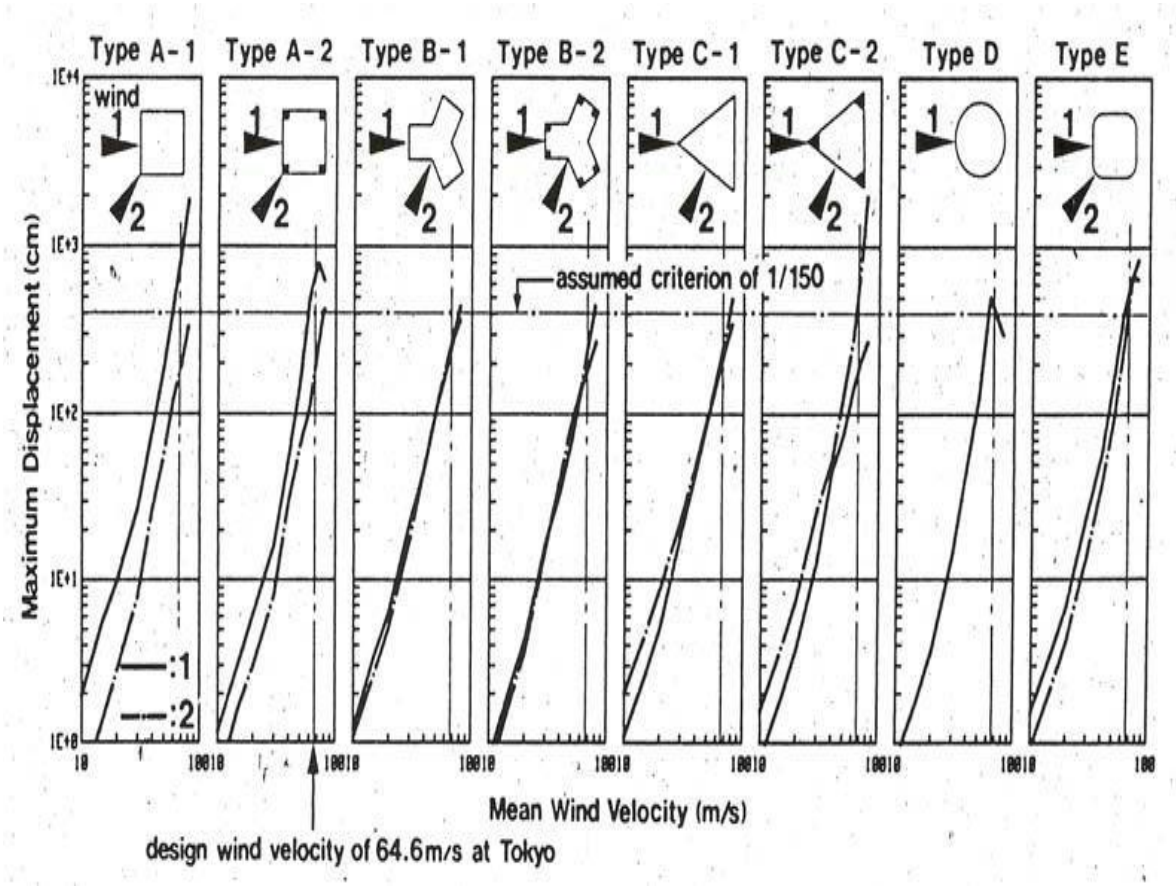

Fig. 3.3 maximum across wind displacement of various buildings shapes under two typical wind directions with reference mean wind speed[11]

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. Theyfoundminimum and maximum peak pressure coefficients at 2/3 height of the building for several corner configurations. The minimum coefficient of pressure for each configuration varies from -3.4 for large bevel corners to -4.8 for various sizes of curved corners[12]. As per Miyashita et al (1993), the fluctuating portion of across wind is decreased for normal wind angle of incidence. Among the other models, the square model with corner cut (Type-6) is the maximum vortex shedding frequency. The model with corner cuts or opening has a Cross-wind fluctuating wind force coefficient smaller than the square plan[13].In Kawai (1998) analysis of aero-elastic instability of tall buildings with various corner modifications in a suburban area (power law index α=0.2), as shown in Fig. 3.4, small corner cut and recession i.e., 0.05B, are extremely effective in forestalling aero-elastic instability for a square prism by expanding aerodynamic damping, encouraging instability at low speed by broad corner cut and recession. The roundness of the corner is the best way to eliminate the aero-elastic instability of a square prism between the three corners modifications[14].

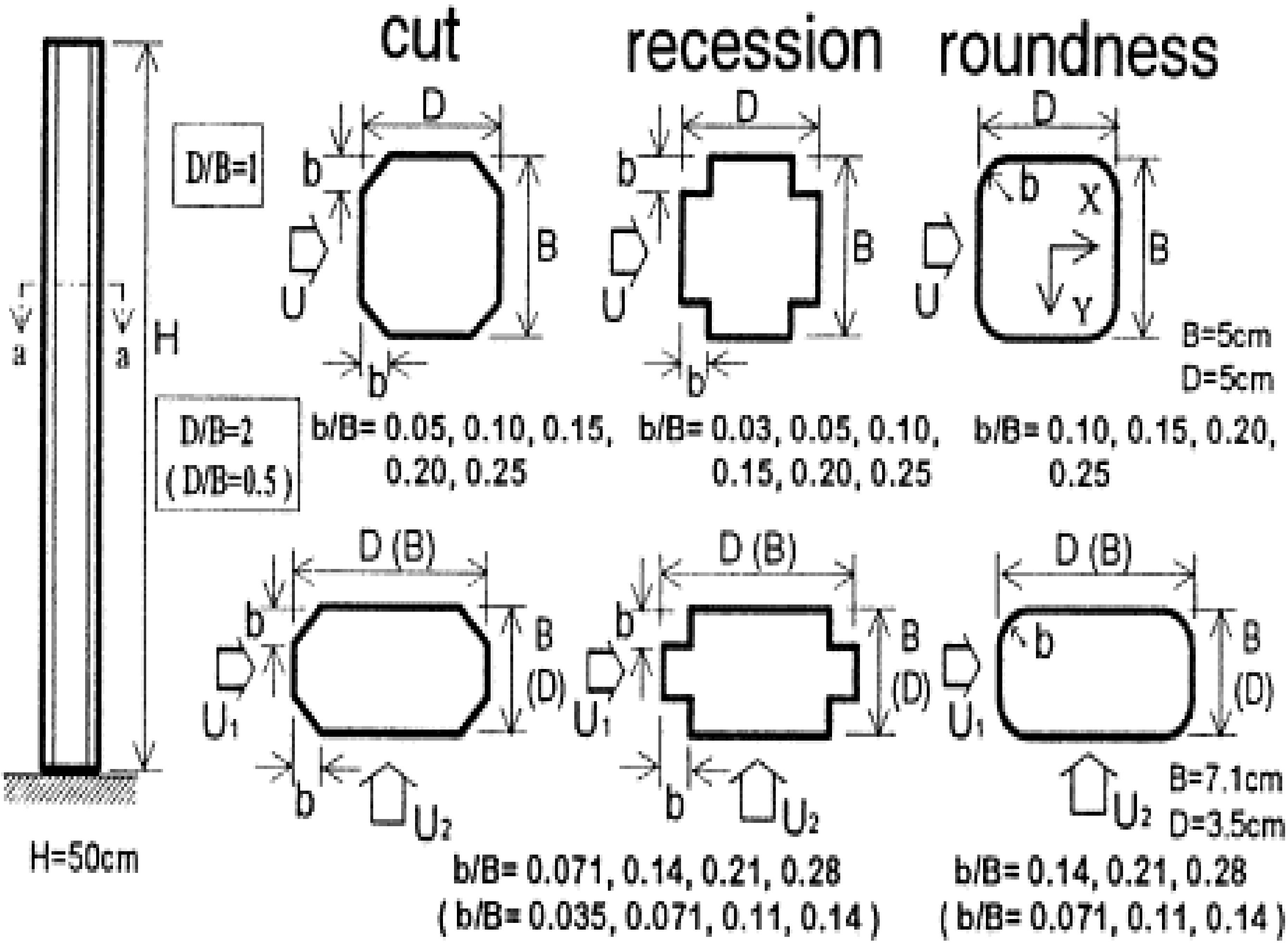

Fig. 3.4 Sections of the models with corner cut, recession and roundness[14]

Tamura et al. (1998) numerically study unsteady pressure on a square cylinder with various corner shapes. It is concluded that as the corner shapes is slightly changed, the aerodynamic characteristics result in drastic modification, the modified drag has a possibility to decrease up to approximately 60% of the original value. The C_D and C_{Lrms} values decrease in the order of the square cylinder, the chamfered cylinder and the rounded cylinder[15].Tamura and Miyagi (1999) Wind Tunnel studies concluded that the isolated shear layer travels to the side surface with corner-cutting and corner rounding, this gradual reattachment and reduction of drag force. C_{LRMS}on a square cylinder with chamfered corner and rounded corner is reduced to about 50% that on a sharp- cornered cylinder when the angle of attack α is very small[16]. Gu and Quan (2004) study 15 typical tall buildings with high frequency force balance technique in a wind tunnel as shown in Fig. 3.5. The corner modifications have large effect on across wind forces. The modifications, generally speaking, decrease dramatically amplitude of across wind force spectra. Moreover among these model, the peak amplitudes in the across wind force spectra of the building with the side ratio of 10%are the lowest[17].

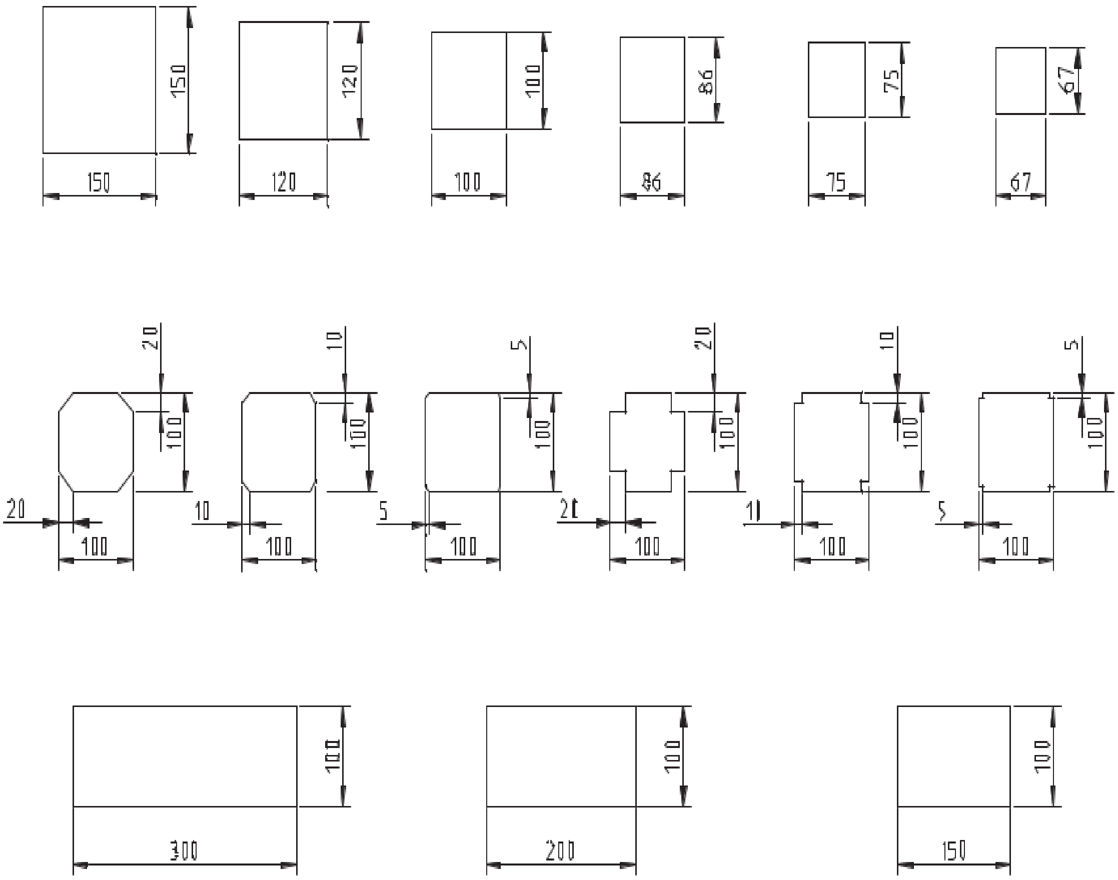

Fig. 3.5 Cross-section of the building models[17]

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]. By Tse et al. (2009), 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%. Due to the buffeting and vortex shedding, the recessed corners are more viable than the chamfered corner in reducing both along wind and crosswind[19]. An experimental study of the distribution of static pressure on a group of square or rectangular rounded corner cylinders byMandal and Faruk (1970) concludes that, relative to the single-cylinder, the drag coefficient on the rear cylinder with either a square or rectangular cross-section having a rounded corner decreases significantly. Compared with that on the single-cylinder, there is a small change in the drag coefficient on the front cylinder. There is a significant effect of interspacing and side ratio on the drag coefficient of the rear cylinder. Interspacing and side ratio have a slight impact on the front cylinder's drag coefficient[20].

The results of the computational analysis byXu et al (2011), shows that the near-surface flow structure is sensitive to the modification of the form of cut-corners. The separate shear layers are far closer to the side surface with corner cutoffs, facilitating reattachment and drag force reduction[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].

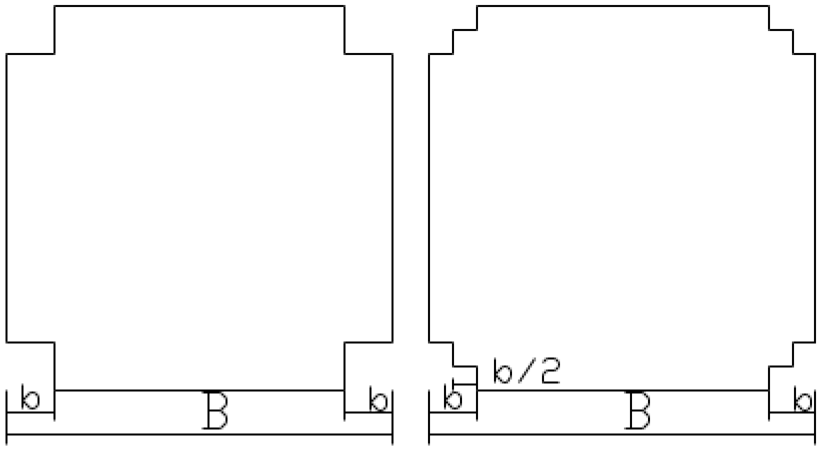

Fig.3.6 Cross Section of the Building Models- a)Type-1 Single Corner Recession, b) Type-2 Double Corner Recession[22]

In his research, Huang et al. (2013) found that along-wind aerodynamic damping is positive in most cases and increases gradually with the increase in reduced wind speed (Ur). In most situations, the cross-wind aerodynamic damping is also a positive value at low Ur but unexpectedly becomes negative when Ur becomes greater than 10.5 for the square cross-section building[23]. An analysis by C. K. et al. (2014) of square cylinders with various square shapes concludes that the wake width is decreased and thus the lift and drag coefficient values are decreased in the case of chamfered and rounded corners in square cylinders. The high velocity behind the cylinder reduces the coefficient of lift and drag. The lift coefficients of a square cylinder with corner modification decreases, but when compared to a square cylinder without corner modification, the Strouhal number increases[24].In his research, Luigi Carassale et al. (2014) found that as r/b increases and that an intermittent flow condition occurs, the critical angle of incidence corresponding to the flow reattachment on the lateral face exposed to the flow decreases. Rounded corners minimize the critical angle of incidence α_{cr} for which the flow is reattached to the side face exposed to the wind[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 of Elshaer 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]. In the analysis ofWakchaure and Gawali (2015), it is concluded that when the shape of the building is modified from square to elliptical, the wind speed, floor drifts, lateral displacement, floor shear of the building are reduced. For an elliptical plan, wind forces are decreased by a maximum percentage. The peak intensity of wind is reduced by 4.471% for circular and 63.38% for elliptical, and it is greater by 15% for rectangular shape during the comparison with the gust factor[29]. A research by Boonyapinyo and Wangkansirkun (2016)concluded that corner modifications lead to substantial reductions in wind loads and response along wind and across wind. For example, the recession of the corner at 10% of the building face contributes to a reduction of the base moment around the x-axis (0-degree wind direction) of 18%, 25%, 14%, 3%, and 2% for the 1:1, 1:1.5, 1:2, 1.5:1 and 2:1 aspect ratio of the model depth to width. Similarly, for the above models, the corner recession at 10% results in a reduction of the base moment around the y-axis of 13%, 16%, 14%, 18%, and 10%, respectively[30].

Elshaer et al. (2017) discovered that the mean drag coefficient is reduced by 30% and the lift coefficient is thus reduced by 24% for the ideal corner compared to the sharp edge one. Drag optimization's overall outcome is reduced to 29%, while lift optimization is reduced to 52%[30]. In the analysis of Li et al. (2018) it was found that the along-wind loads can be significantly reduced by chamfered corner in the wind direction of 0°, while the crosswind loads can also be reduced by recessed corner in the same unfavorable direction. Compared to the recessed and chamfered corners, the rounded corner is not an efficient way to reduce these wind loads[31].

An analysis of the wind tunnel by Deng et al. (2018) on super tall buildings concludes that aerodynamic loads of structures can be significantly reduced by opening ventilation. The maximum peak base mixing time corresponding to the return duration of 100 years (YTP) and 50 YTP is decreased by 15.5% and 15.2%, respectively. At the top of the building, the peak acceleration corresponding to 10 YTP is reduced by 16%[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-	Displacements reduced, For type B-2(Y-shape with corner cut) was about 3times less

		shape Corner-Cut Roundness, Surface Roughness	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 fluctuating component of across wind is reduced.
(Kawai, 1998)[14]	AEM	Chamfering, Recession, Rounded	For a square prism to defeat aeroelastic 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	There is an appreciable effect of side dimension and interspacing on the drag coefficient of cylinders.
(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]	ETABB's 13.1.1 v.	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

The shape and orientation of the buildings are driven by practical prerequisites, site conditions, and architectural considerations. Aerodynamics modification of tall buildings should be taken into account; Even a small amount of the change in the basic geometric form of the building is very effective in reducing a fair amount of wind-induced loads on the tall buildings.

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. Local modification or Micro or Minor (corner-cut, corner rounding, chamfering, etc can result in a 30-60 percent reduction in wind load as they facilitate the reattachment of the shear layer and narrow down the wake area on the building's leeward face.

It is found that chamfered model is able to reduce along wind and across wind response by 40% and 30% respectively.102 Incheon Tower, South Korea is provided with slots at the corner and it was observed that it could reduce the base moment by 60%.Holmes reported that providing chamfering of the order of 10% can reduce the along wind response up to 40% and across wind response up to 30% compared to rectangular shaped building.

CFD and ANN modeling study evaluated that the mean drag coefficient is reduced by 30% and a reduction of 24% can be Aceh vied for optimal corner modification. The dynamic response of drag is lowered by 29% and dynamic lift by 52%.Double recessed corner modification resulted in suppression of transverse load by 25%.The optimal modification length at which best mitigation effects can be found is about 10% of the width of the building.

Different types of Local or Micro or Minor aerodynamic modifications are studied in the present work to reduce wind-induced loads and responses, and researchers may obtain a detailed overview and perception of the technique of aerodynamic modifications and an appropriate design approach to reduce wind-induced loads and responses. In selecting the required Local aerodynamic modification for a tall building, this analysis may be used to make the right decisions.

ACKNOWLEDGMENTS

The authors wish to thank Delhi Technological University (DTU), Delhi, India for providing all the facility for our research work in Civil Department. The authors wish to acknowledge the pseudonymous reviewers for his or her valuable remarks and opinion on the manuscript.

REFERENCES

[1] A. Sharma, H. Mittal, and A. Gairola, “Mitigation of wind load on tall buildings through aerodynamic modifications: Review,” *J. Build. Eng.*, vol. 18, pp. 180–194, Jul. 2018.
[2] P. A. Irwin, “Wind engineering challenges of the new generation of super-tall buildings,” *J. Wind Eng. Ind. Aerodyn.*, vol. 97, no. 7–8, pp. 328–334, Sep. 2009.
[3] A. Elshaer, G. Bitsuamlak, and A. El Damatty, “Enhancing wind performance of tall buildings using corner aerodynamic optimization,” *Eng. Struct.*, vol. 136, pp. 133–148, Apr. 2017.
[4] M. Asghari Mooneghi and R. Kargarmoakhar, “Aerodynamic Mitigation and Shape Optimization of Buildings: Review,” *J. Build. Eng.*, vol. 6, pp. 225–235, Jun. 2016.
[5] A. Elshaer and G. Bitsuamlak, “Multiobjective Aerodynamic Optimization of Tall Building Openings for Wind-Induced Load Reduction,” *J. Struct. Eng.*, vol. 144, no. 10, p. 04018198, 2018.
[6] DAVENPORT A. G., “Response of six building shapes to turbulent wind,” *Phil Trans Roy Soc*

London Ser A. Math Phys Sci, vol. 269, no. 1199, pp. 385–394, 1971.

[7] K. C. S. Kwok and P. A. Bailey, “Aerodynamic devices for tall buildings and structures,” *J. Eng. Mech.*, vol. 113, no. 3, pp. 349–365, 1987.

[8] K. C. S Kwok, P. A. Wilhelm, and B. G. Wiikie, “Effect of edge configuration on wind-induced response of tall buildings,” *Eng. Struct.*, vol. 10, p. 35, 1988.

[9] K. C. S. Kwok, “Effect of Building Shape on Wind-Induced Response of Tall Building,” *Journalof Wind Eng. Ind. Aerodyn.*, vol. 28, pp. 381–390, 1988.

[10] N. Shiraishi, M. Matsumoto I, H. Shirato, and H. Ishizaki, “On aerodynamic stability effects for bluff rectangular cylinders by their corner-cut,” *J. o[Wind Eng. Ind. Aerodyn.*, vol. 28, p. 380, 1988.

[11] H. Hayashida and Y. Iwasa, “Aerodynamic shape effects of tall building for vortex induced vibration,” *J. Wind Eng. Ind. Aerodyn.*, vol. 33, no. 1–2, pp. 237–242, 1990.

[12] N. J. Jamieson, P. Carpenter, and P. D. Cenek, “Wind induced external pressures on a tall building various corner configurations,” *J. o[Wind Eng. Ind. Aerodyn.*, no. 41–44, pp. 2401–2412, 1992.

[13] K. Miyashita, J. Katagiri, and O. Nakamura, “Wind-induced response of high-rise buildings effects of corner cuts or openings in square buildings,” *J. Wind Eng. Ind. Aerodyn.*, vol. 50, pp. 319–328, 1993.

[14] H. Kawai, “Effect of corner modifications on aeroelastic instabilities of tall buildings,” *J. Wind Eng. Ind. Aerodyn.*, vol. 74–76, pp. 719–729, 1998.

[15] T. Tamura, T. Miyagi, and T. Kitagishi, “Numerical prediction of unsteady pressures on a square cylinder with various corner shapes,” *J. Wind Eng. Ind. Aerodyn.*, vol. 74–76, pp. 531–542, 1998.

[16] T. Tamura and T. Miyagi, “The effect of turbulence on aerodynamic forces on a square cylinder with various corner shapes,” 1999.

[17] M. Gu and Y. Quan, “Across-wind loads of typical tall buildings,” *J. Wind Eng. Ind. Aerodyn.*, vol. 92, no. 13, pp. 1147–1165, Nov. 2004.

[18] R. Merrick and G. T. Bitsuamlak, “Shape effects on the wind-induced response of high-rise buildings,” *J. Wind Eng.*, vol. 6, no. 2, pp. 1–18, 2009, [Online]. Available: https://www.researchgate.net/publication/271198030.

[19] K. T. Tse, P. A. Hitchcock, K. C. S. Kwok, S. Thepmongkorn, and C. M. Chan, “Economic perspectives of aerodynamic treatments of square tall buildings,” *J. Wind Eng. Ind. Aerodyn.*, vol. 97, no. 9–10, pp. 455–467, Nov. 2009.

[20] A. C. Mandal and G. M. G. Faruk, “An Experimental Investigation of Static Pressure Distributions on a Group of Square or Rectangular Cylinders With Rounded Corners,” *J. Mech. Eng.*, vol. 41, no. 1, pp. 42–49, 1970.

[21] F. Y. Xu, X. Y. Ying, and Z. Zhang, “Prediction of unsteady flow around a square cylinder using RANS,” *Appl. Mech. Mater.*, vol. 52–54, pp. 1165–1170, 2011.

[22] Z. Zhang, Y. Quan, M. Gu, and Y. Xiong, “Effects of corner recession modification on aerodynamic coefficients of square tall buildings,” in *The Seventh International Colloquium on Bluff Body Aerodynamics and Applications (BBAA7)*, 2012, pp. 959–968.

[23] P. Huang, Y. Quan, and M. Gu, "Experimental study of aerodynamic damping of typical tall buildings," *Math. Probl. Eng.*, vol. 2013, 2013.
[24] C. K. Vikram, Y. T. Krishne Gowda, and H. V. Ravindra, "Numerical investigation on flow past square cylinders with different corner shapes," *Int. J. Sci. Eng. Res.*, vol. 5, no. 10, pp. 479–486, 2014.
[25] L. Carassale, A. Freda, and M. Marrè-Brunenghi, "Experimental investigation on the aerodynamic behavior of square cylinders with rounded corners," *J. Fluids Struct.*, vol. 44, pp. 195–204, 2014.
[26] A. Elshaer, G. Bitsuamlak, and A. El Damatty, "Wind Load Reductions due to Building Corner Modifications," *22nd Annu. Conf. CFD Soc. Canada*, pp. 1–5, 2014.
[27] A. Elasher, G. T. Bitsuamlak, and A. El Damatty, "Aerodynamic shape optimization for corners of tall buildings using CFD," 2015, [Online]. Available: https://www.researchgate.net/publication/277720644.
[28] E. Bernardini, S. M. J. Spence, D. Wei, and A. Kareem, "Aerodynamic shape optimization of civil structures: A CFD-enabled Kriging-based approach," *J. Wind Eng. Ind. Aerodyn.*, vol. 144, pp. 154–164, Sep. 2015.
[29] P. M. R. Wakchaure and G. Sayali, "Effects of Shape on Wind Forces of High Rise Buildings Using Gust Factor Approach," *Int. J. Sci. Eng. Technol. Res.*, vol. 4, no. 8, pp. 2979–2987, 2015.
[30] V. Boonyapinyo and P. Wangkansirikun, "Aerodynamic Modifications of High-Rise Buildings for Wind Load and Response Reductions," *Adv. Civil, Environ. Mater. Res. Jeju Island, Korea*, vol. August 28-, 2016.
[31] Y. Li, X. Tian, K. F. Tee, Q. S. Li, and Y. G. Li, "Aerodynamic treatments for reduction of wind loads on high-rise buildings," *J. Wind Eng. Ind. Aerodyn.*, vol. 172, no. November, pp. 107–115, 2018.
[32] T. Deng, J. Fu, Z. Xie, and Y. He, "Study on opening ventilation to reduce the wind load on a super tall building with recession corner," *2018 World Congr. Adv. Civil, Environ. Mater. Res.*, 2018.
[33] B. E. Lee, "Some observations of the effect of aspect ratio on the influence of turbulence on the drag of rectangular cylinders," *J. Wind Eng. Ind. Aerodyn.*, vol. 33, pp. 107–111, 1990.
[34] A. Elshaer, G. Bitsuamlak, and A. El-Damatty, "Vibration control of tall buildings using aerodynamic optimization," 2014.