AERODYNAMIC INSTABILITY IN CLUSTER BUILDINGS

A Thesis

Submitted in partial fulfilment of the requirement for the award of the degree of

MASTERS OF TECHNOLOGY
in
Civil Engineering

with specialization in

Structure Engineering

under the guidance of

Dr. Gyani Jail Singh
(Assistant Professor)

by

Ishu Sharma
Roll No.162665

to

JAYPEE UNIVERSITY OF INFORMATION TECHNOLOGY
WAKNAGHAT, SOLAN-173234,
HIMACHAL PRADESH, INDIA
MAY, 2018

CERTIFICATE

This is to certify that the work which is being presented in the thesis titled ***"AERODYNAMIC INSTABILITY IN CLUSTER BUILDINGS"*** in partial fulfilment of the requirements for the award of the degree of Master of Technology in Civil Engineering with specialization in **Structural Engineering** and submitted to the Department of Civil Engineering, Jaypee University of Information Technology, Waknaghat is an authentic record of work carried out by **Ishu Sharma (Enrolment No. 162665)** during a period from July 2017 to May 2018 under the supervision of **Dr. Gyani Jail Singh (Assistant Professor),** Department of Civil Engineering, Jaypee University of Information Technology, Waknaghat.

The above statement made is correct to the best of our knowledge.

Date: ………………………

Dr. Ashok Kumar Gupta Prof. and Head of Department Department of Civil Engineering JUIT Waknaghat	Supervisor Dr. Gyani Jail Singh Assistant Professor Department of Civil Engineering JUIT Waknaghat	External Examiner

ACKNOWLEDGEMENT

As the professional courses not only require theoretical knowledge but practical knowledge too, that's why university conducts projects and seminars for the students, so that they can get ample view of practical problems and can be innovative in their work. I find it a matter of honour in showing the feeling of indebtedness and thankfulness to Dr Gyani Jail Singh, Assistant Professor, Jaypee University of Information Technology Waknaghat. His constant guidance and encouragement received have been a great help in carrying out the project work.

Apart from this I would like to express my sincere gratitude to Prof. Dr. Ashok Kumar Gupta, Professor and Head of the Department, Civil Engineering Department of Jaypee University of Information Technology Waknaghat, for providing me an opportunity to do the seminar.

This project bears on imprints of many people. I am also very thankful to my friends and family members who encouraged me all the time to go through this project work.

(Ishu Sharma)

ABSTRACT

With advancement in Building Construction Techniques and restriction of building construction to Limited area construction of tall building in a group so as to minimize the effect of wind turbulence and to get economical cluster to improve Aerodynamic performance of tall building. These above two requirements can be fulfilled with use of mass damper like Taipei 101 or with aerodynamically balanced structure like Burj Dubai. As the improvement has been made over aerodynamically designs like corner modification which has reduced formation of eddies and has reduced the effect of vortex shredding which are the main causes of wind induced oscillations where effects of corner cut, recession and roundness on aero-elastic instabilities such as vortex induced excitation and galloping oscillation were investigated by wind tunnel. Aerodynamic force measurements and wind pressure measurements were conducted for tall building models with various building shapes and the same height and volume. For comparison and discussion of the aerodynamic characteristics of tall buildings tests were performed and as results shows that, with change in direction of wind along with change of height of building surrounding high rise building can result into reduction of drag and drift increasing stability of high rise structure throughout.

Keywords: High rise building, drift and drag, Aerodynamic Force, Vortex

TABLE OF CONTENTS

LIST OF SOFTWARE

	Description
1	**AutoCAD**
2	**ANSYS**
3	**Microsoft Office 2010**
3.1	**Microsoft Excel**
3.2	**Microsoft Word**

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1 GENERAL

Wind causes load which is a random time dependent load which has a fluctuating component and can be seen as a mean. Commonly speaking all super tall structures experience these dynamic oscillations due to fluctuating component. In low rise design structures these oscillations are insignificant and have equivalent static pressure. Structure is termed to be rigid and short if its natural time is less than one second and the more flexible systems such as tall buildings undergoes a dynamic response to fluctuating component.

With advancement in Building Construction Techniques and restriction of building construction to limited area construction of tall building in a group so as to minimize the effect of wind turbulence and to get economical cluster to improve aerodynamic performance of tall building. These above two requirements can be fulfilled with use of mass damper like Taipei 101 or with aerodynamically balanced structure like Burj Dubai. As the improvement has been made over aerodynamic shape optimization which has reduced formation of eddies and has reduced the effect of vortex shredding.

The study on cluster building introduce an optimized group with CFD solver and Optimization algorithms to give enhanced cluster to reduce wind turbulence so to get optimized aerodynamically balanced structure. Wind tunnel test is a time-consuming approach in addition to be expensive while methods like CFD which is based on modeling can provide solutions that are that are 2D process using simplified geometry like to be with provide faster tool for good optimization. ANSYS fluent gave better results in 3d processing too. Double precision with 3D processing along with coupled pressure-velocity scheme and moment as second order of wind in spatial discretisation is used. Data file quantities such as static pressure, velocity magnitude, drag drift and moment are used for post processing in external applications through the standard data file.

1.2 NEED OF THE STUDY

The methods used for computing the dynamic effect of wind on super tall buildings have been introduced . Apart from tall buildings there are several other structural forms such as tall latticed towers, chimneys, guyed masts that need to be examined for aerodynamic effects.

1.3 OBJECTIVE

1. To analyse the building cluster under wind excitation By using Computational Fluid Dynamic (CFD); Ansys-Fluent Software.

2. To determine the optimum configuration of building cluster corresponding to least aero-dynamic instabilities.

CHAPTER 2

LITERATURE REVIEW

2.1 GENERAL

Kwai (1996) effects of corner cut, roundness and recession on the aero elastic instability like vortex induced excitation and oscillations due to wind galloping were investigated in wind tunnel test for rectangular prism and Square prism. Wind tunnel Test were performed and these results were obtained. Small recession and corner cut were very effective. 2 degrees aero elastic instability for square prism at large corner cut promotes the instability at minimum velocity to reduce the onset velocity when damping is very small. Providing corner roundness was also effective to prevent Aerodynamic instability suppressed by damping. Galloping at low speed, instability occurs for minimum depth rectangular prism. These corner modifications increases instability at low speed because of shredding is reduced by modification. Rectangular prism at Deep depth, in induced vibrations orchid and is less affected by corner modification. Among these corner modifications roundness at corner was the most effective to reduce the aero elastic instability in square prism. The amplitude caused by wind induced vibration also reduced due to Corner roundness increase. Small corner cut was also very effective to reduce the instability of a square prism. But large corner cut increased the instability at low velocity. The corner modifications like corner cut and recession had little effect on vibration but these helped in reducing the vibrations at high velocity.

Tanaka et al. (2012) Models with a typical building shape were tested in wind tunnel having 13 tall buildings under an urban developed area. The main purpose of this study was to know the similarity due to the wind load on a typical super tall building. Analysis was conducted choosing a frame model buy local wind forces at centre of floor. The peak normal stresses on the square model have the apex point among all the models.

Setback models show the smallest height of peak that of single modification model and others shows the smallest height of peak of the multiple modification model. The bending moment contribution for about 20% of total and most of the apex normal stresses were resulted from the axial forces. As the damping ratio decreases there is increase in the bending moment in across wind direction. For this analysis various conditions of loading were taken and it was found bending moment contributes largest in along wind direction and contribution of torsional moment can be said as zero because said as zero because it was almost negligible. With increase in damping ratio peak normal stresses reduces and attends the quasi static value. As the damping ratio decreases there is increase in bending moment for a cross wind direction and peak normal stresses for multiple modification model. Torsional moment was negligible and endowment of bending moment along wind direction was colossal than another loading conditions.

Gu and Quan (2004) The previous studies have shown that the crossing dynamic response of tall buildings are larger than the along wind ones. With increase of height acrosswind dynamic response of all buildings has been a great concern. Event tunnel test of 15 typical tall building models with high frequency force balance technique. New formulas for power spectra of a cross wind forces, shear force and bending moment were derived. Parametric analysis of a cross wind loads of tall building work performed. A simple degree of freedom elastic model of a square tall building having aspect ratio of 6 was selected and was tested for across wind dynamic response and aerodynamic damping properties. The power spectrum of a cross wind force of square building morning was employed to compute its across wind response having aerodynamic damping and without having aerodynamic damping. The responses were computed and then compared with responses of aeroelastic model test to verify the across wind loads formulas of building.

Lam(2012) This paper focused on wind induced effects on a row of 5 square plan super tall buildings arranged in close proximity. Fluctuating wind loads were measured on each building member and wind induced responses of building were estimated with high frequency force balance technique. Wind tunnel experiments and response analysis were carried under all possible angles of wind flow direction on 4 buildings having different distances and for two buildings pattern arrangements which were diamond patterns and parallel patterns.

With complete study of results it was found that building interference leads to amplified dynamic response but reduction in response also occur at some wind directions. When the buildings are placed in a row the design of the dynamic response are not magnified. When the row of buildings are arranged in diamond pattern the effect of wind is found to result in small magnification at maturity of wind angles. This increases positive pressure when flow of wind is caught inside corner of adjacent building. Those fluctuating Wind loads became larger wide band of frequencies tour crosswind on single isolated building was absent. For the designing purposes of super tall building magnification of peak design dynamic responses are not much higher than 1.This gives information to design residential developments in large cities.

Kim (2008) Computational fluid dynamics CFD please an important role in designing of building. For all stages of building design and aspects, CFD is used to provide accurate and rapid predictions of building performance with respect to various aspects such as air flow, pressure, and temperature. CFD is used as designing assistance tool. Various studies have shown that CFD may be used as a tool for building related a Flow designing. Wind fluctuations can have a serious effect on building of fun with serious consequences such as roof failure. Aerodynamic loads on walls and roofs of low building interaction of wind flow with surface of building and this flow mainly depends on building geometry and the flow characteristics. Due to the time and cost issues in wind tunnel testing, CFD is widely used for prediction of flow field .CFD analysis is being applied in various field such as Marine Engineering electrical and electronic engineering, wind engineering, oceanography, nuclear power, hydrology and chemical engineering.

Kim (2008) Wind tunnel tests were performed on 13 helical tall buildings and straight buildings with different types of cross sections including polygonal triangular Pentagon square dodecagon circular and hexagon. The tests were performed to visualize the effect of increasing the numbers of side on response characteristic rather than of Aerodynamic characteristic for straight tall building and effect of different sections on helical shape and polygonal tall building. With increase number of sides overturning moment coefficients, responses and spectral values decreased and for street triangular model largest mean and overturning moments were found. First trade square model largest spectral values and responses were seen

When the number of sides were larger than 5 largest peak acceleration for design wind speed were similar but variations were seen in largest maximum displacement. Due to effect of helical shape on the response decreased with increasing sides. The effect of helical shape is reduced when number of sides are more than 5.

Elshaer (2015) In tall buildings the properties and dimension of various elements of lateral load resisting system are governed by wind induced loads and motions. To resist motions and loads caused by wind lots of expenses are spent on material and damping systems. Are saved by improving the Aerodynamic performance of super tall buildings introducing modifications on their outer shape. Corner shape mitigation is most effective modification which can be applied super tall buildings due to its minor effect on both architectural design and structural design. Optimization Framework studies are introduced which couples optimization algorithm, computational fluid dynamics solver (CFD), and the neural networks model(NN) in an automatic procedure. The objective of (ASO) Aerodynamic shape Optimization is to reduce drag force on super tall building by changing its shape at corners. Large Eddy simulation models were used for numerical simulation of wind behavior and genetic algorithm was used as an Optimization algorithm.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 GENERAL

The wind interacts with the various obstacles as it reaches in its way by transferring a portion of its energy 2 doors and tractions which are converted as forces over the bodies and giving them motion which are dependent on their aero-elastic and geometric characteristics. The force exerted on a body by flow in which body is immersed and due to motion of body and the gas is called as Aerodynamic force. (Aero-elasticity is the branch of engineering which studies the interaction between elastic, inertial and aerodynamic forces which occurs when an body is exposed to flow.)

This relative motion between body and gas gives away basic three factor that are

1) Drag- Drag force is the force component which is parallel to the direction of motion.

2) Lift- Lift is the force component which is perpendicular to the direction of motion.

3) Thrust- Thrust is the force created by propeller or jet engine.

Variation of wind velocity with height

As the height of building increases the viscosity of air also increases and on earth surface viscosity of air is almost zero

For high rise building analysis of vortex shredding is main because this factor induce crosswind force with a certain frequency if these frequencies generated from across wind motion coincide with natural frequency of structure it could result in to enhancement of motion causing damage to structure or even worse that is failure of whole structure.

1) Wind turbulence

2) Vortex Shredding

Wind turbulence

When it comes to wind turbulence definition, it can be described mainly having two components: Mean velocity the component which increases with height and another one is Turbulent velocity which remains equal over the height.

Vortex shredding

It is that two-dimensional wind flow which is divided into two parts:-

1) Along wind

2) Across wind

When velocity of wind is low, vortex shredding occurs on either side at same time of building. It is hence subjected to a long wind oscillation which is parallel to direction of wind. When velocity of wind is low vortex shredding happens alternately first from one and then from the other side so there is impulse all along wind direction but with addition to another impulse which happens in transfer direction. While designing a high rise structure wind velocity nature profile and wind turbulence on upper level should be examined. Buildings which are having height more than 15 m are classified as high rise buildings.

3.2 RESEARCH METHODOLOGY

To analyze the building cluster under wind excitation in Indian contest a finite element software ANSYS-Fluent is to be utilized. Since the finite element is an approximate method, therefore, the methodology is validated with existing literature (Kawai 1996) in which wind tunnel tests was performed in the boundary layer wind tunnel having working section was 1.2 m x1.2 m x10 m. A square prism of dimension 50 mm x 50 mm x 500 mm and density of 120 kg/m^3. The solid line below shows the response of the square prism without corner modification.

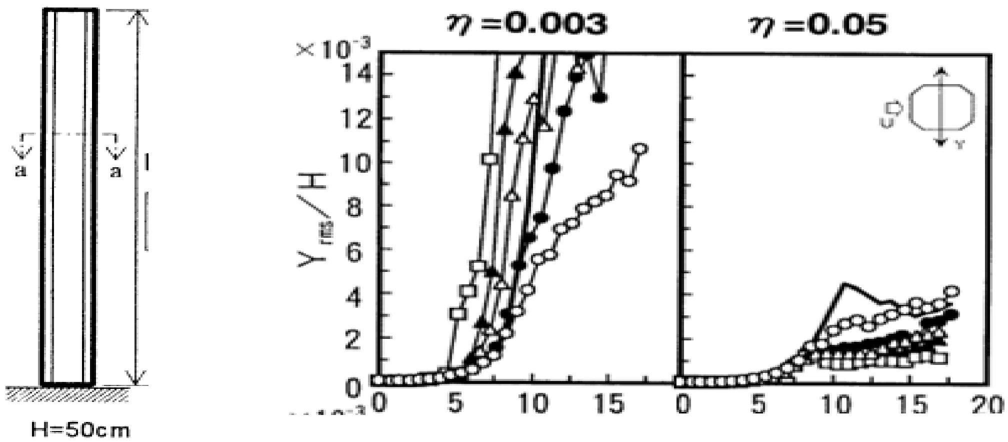


Fig. 1. Geometry of model along with response of the square prism from H. Kwai (1996)

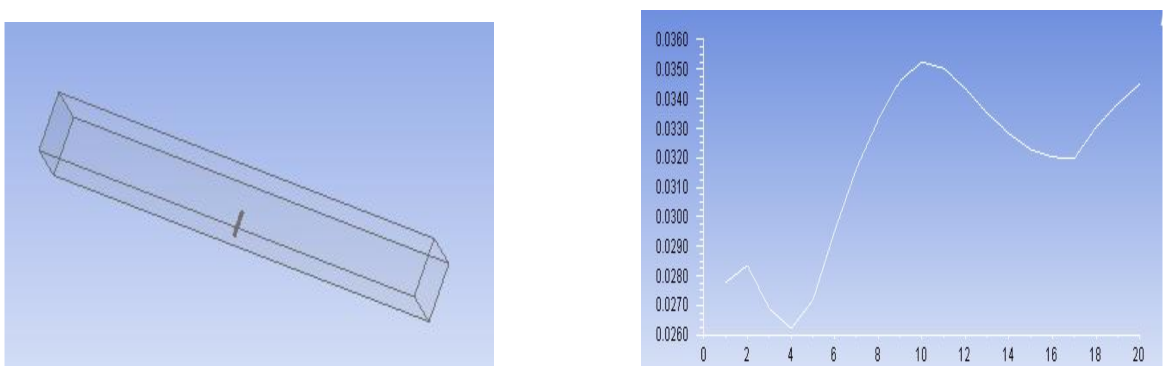


Fig. 2. Geometry of model along with response of the square prism as per paper retrieved when natural frequency(n) =.05

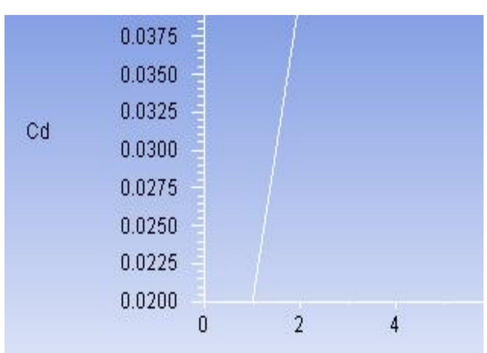


Fig. 3. Natural Frequency(n) = .002

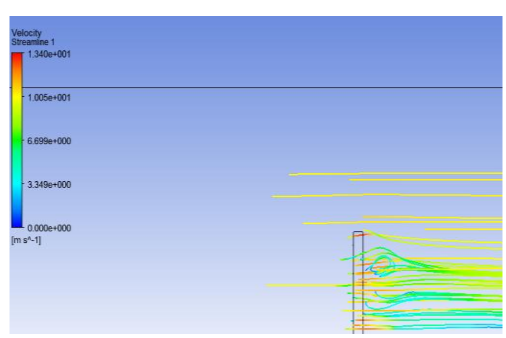


Fig. 4. Streamline Contour

CHAPTER 4

RESULT AND DISCUSSION

4.1 GENERAL

Across wind and along wind response i.e. drag and drift in ANSYS fluent gives an idea of cluster having minimum response when wind at high speed and with changed direction are simulated.

Tests were simulated in ANSYS, following are the three clusters arrangement that were used are as follows:-

1) Octagonal cluster

2) Rectangular Cluster

3) Triangle cluster

To determine the optimum configuration of building cluster corresponding to least Aerodynamic instability across-wind and along-wind responses along with pressure and moments were calculated on a single building surrounded by various clusters and changed direction of wind. Building height was kept 50 cm as per **H. Kwai (2012)** model which was validated before these tests were conducted. Length and breadth of model that was tested are also same as that of paper retrieved i.e. 50 mm. Cluster blocks which are surrounding the main block was tested with change in their height i.e. the height of cluster blocks that surrounds our main block was taken 50 mm, 100 mm, 150 mm, 200 mm, 250 mm, 300 mm, 350 mm, 400 mm, 450 mm, 500 mm and various responses were calculated as three types of clusters were tested. Wind angle was first kept at 0 than 15 , 30 and 45 degrees so as to get drag and drift responses from each angle to get crucial point where minimum drag and drift responses were seen.

4.2 RESULTS

1) Zero degree air flow

a) Octagonal cluster zero degree air flow

Following are the drift and drag values for octagonal cluster at different heights for zero degree air flow.

Table 1

h/H	Drag	Drift
0.1	2.012	0.103
0.2	1.98	0.043
0.3	1.8	0.06
0.4	1.6	-0.027
0.5	1.7	-1.01
0.6	1.5	0.115
0.7	**1.24**	**0.173**
0.8	1.31	-0.238
0.9	1.37	0.061
1	1.17	0.051

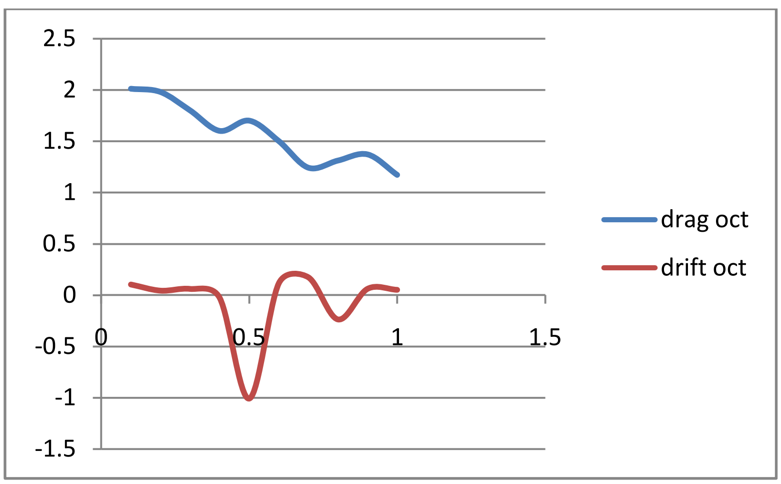


Fig. 5. Drift and Drag values zero degree air flow for octagonal cluster

b) Rectangular cluster zero degree air flow

Following are the drift and drag values for rectangle cluster at different heights for zero degree air flow.

TABLE 2 :-

h/H	**drag**	**drift**
0.1	1.94	-0.024
0.2	1.88	0.0432
0.3	1.85	0.021
0.4	1.6	-0.62
0.5	1.48	0.007
0.6	1.52	-0.25
0.7	1.5	-0.14
0.8	**1.3**	**0.018**
0.9	1.08	-0.062
1	1.33	-0.033

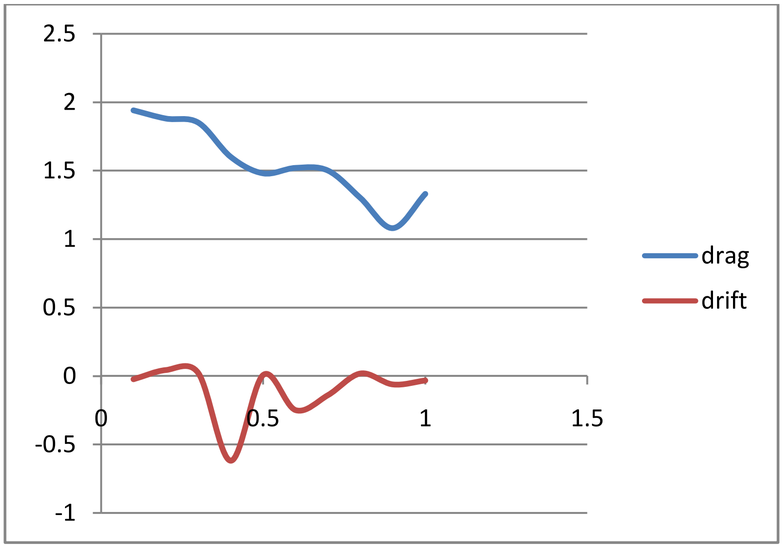


Fig. 6. Drift and Drag values zero degree air flow for rectangle cluster

c) Triangular cluster zero degree air flow

Following are the drift and drag values for triangular cluster at different heights for zero degree air flow.

TABLE :-

h/H	**drag**	**drift**
0.1	2.062	-0.006
0.2	1.976	0.114
0.3	**2.02**	**0.04**
0.4	2.07	0.083
0.5	2.06	-0.03
0.6	2.03	0.047
0.7	2.09	0.007
0.8	2.09	0.019
0.9	2.06	0.05
1	2.004	-0.02

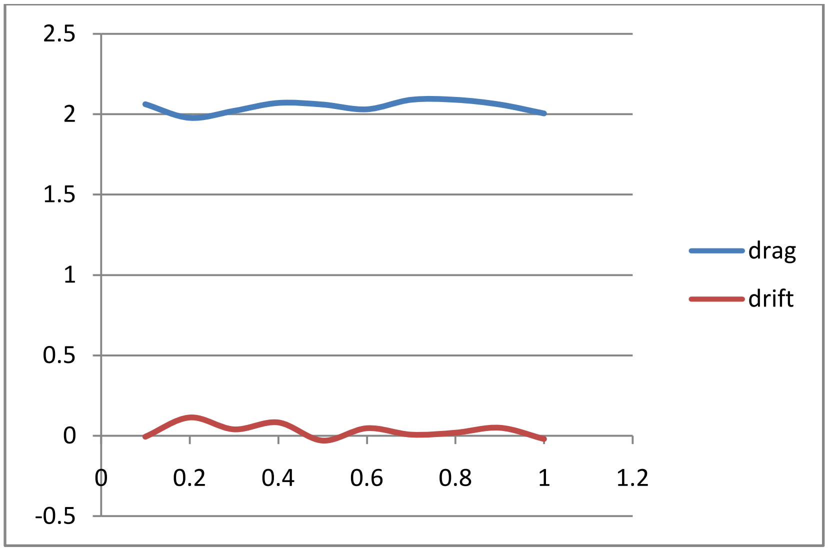


Fig. 7. Drift and Drag values zero degree air flow for triangular cluster

2) 15 degree air flow

a) Octagonal cluster with 15 degree air flow

Following are the drift and drag values for octagonal cluster at different heights for 15 degree air flow.

TABLE 4:-

h/H	Drag	Drift
0.1	1.92	-0.14
0.2	1.9	-0.04
0.3	1.94	-0.061
0.4	**1.89**	**-0.03**
0.5	1.91	-0.13
0.6	1.89	-0.11
0.7	1.94	-0.018
0.8	1.96	-0.24
0.9	1.98	-0.12
1	1.9	-0.1

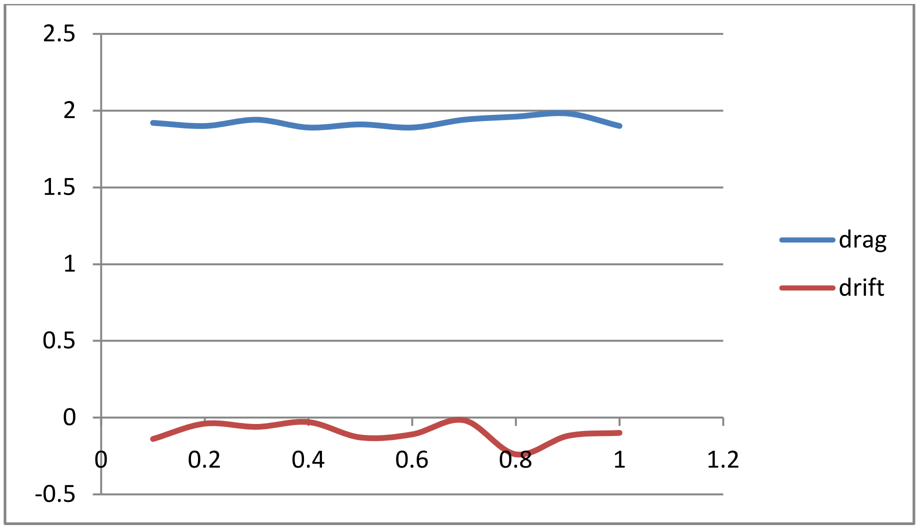


Fig. 8. Drift and Drag values 15 degree air flow for octagonal cluster

b) Octagonal cluster with 15 degree air flow

Following are the drift and drag values for octagonal cluster at different heights for 15 degree air flow

TABLE 5 :-

h/H	Drag	Drift
0.1	1.9	0.03
0.2	1.84	0.07
0.3	1.89	-0.11
0.4	1.95	-0.13
0.5	1.966	-0.19
0.6	1.87	-0.15
0.7	1.89	-0.11
0.8	1.988	-0.087
0.9	**1.84**	**-0.06**
1	1.9	-0.104

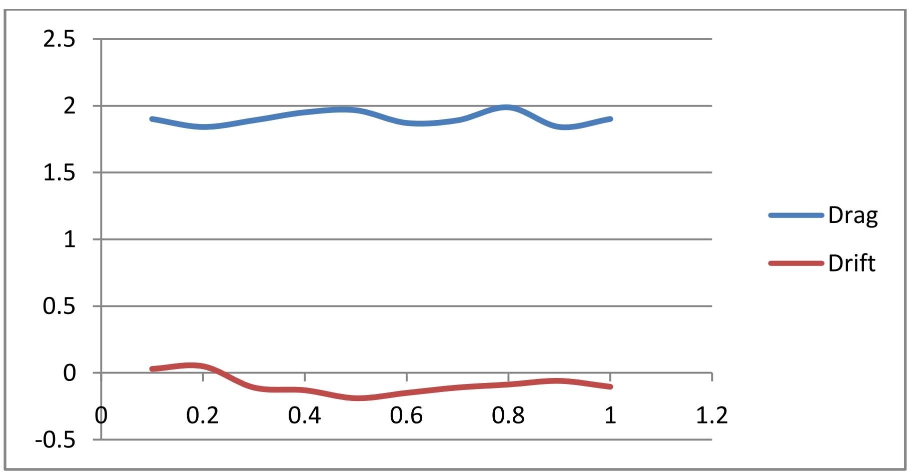


Fig. 9. Drift and Drag values 15 degree air flow for rectangular cluster

c) Triangular cluster with 15 degree air flow

Following are the drift and drag values for triangular cluster at different heights for 15 degree air flow

TABLE 6 :-

h/H	Drift	Drag
0.1	1.94	-0.13
0.2	1.91	0.011
0.3	1.9	-0.06
0.4	1.86	-0.05
0.5	1.89	-0.06
0.6	**1.86**	**-0.03**
0.7	1.89	-0.011
0.8	1.9	-0.044
0.9	1.9	-0.048
1	1.94	-0.13

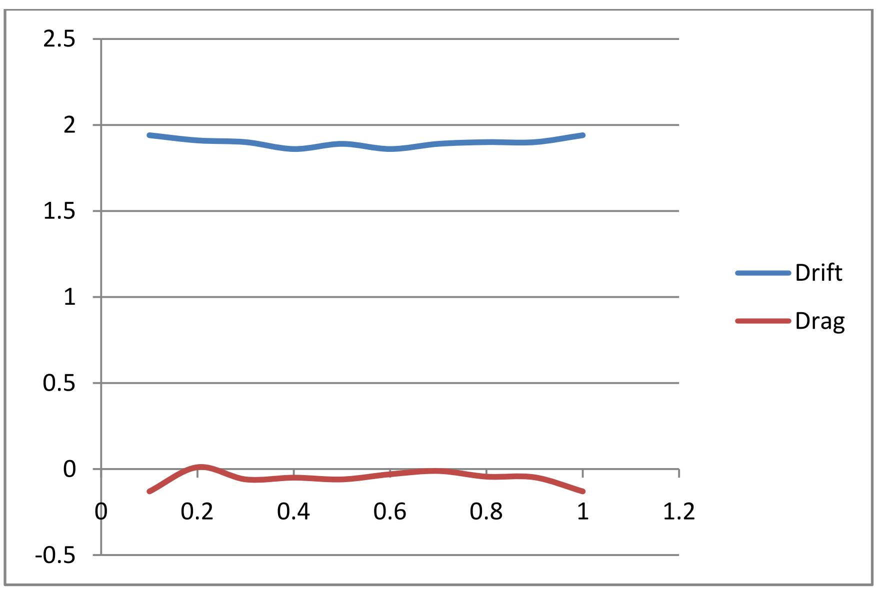


Fig. 10. Drift and Drag values 15 degree air flow for triangular cluster

4.3 DISCUSSIONS

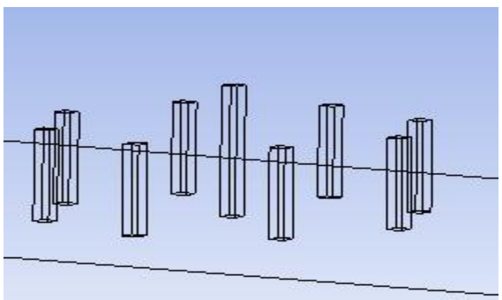
1) Zero degree wind flow

With zero degree wind flow, building interaction was different for 3 clusters ,values were obtain above can be used to predicted following:-

1) When block cluster are kept at 350 mm height minimum values of drag and drift are obtained for octagonal pattern.

2) When block cluster are kept at 400 mm height minimum values of drag and drift are obtained for rectangular pattern.

3) When block cluster are kept at 150 mm height minimum values of drag and drift are obtained for triangular pattern.



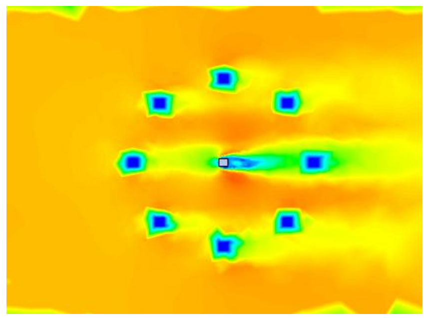
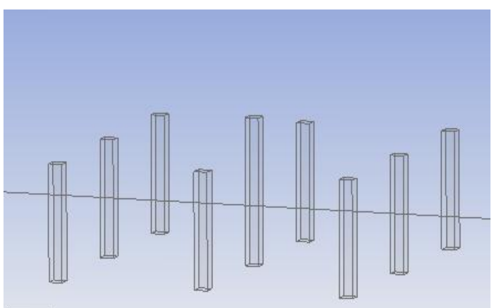


Fig. 11. Octagonal Pattern Geometry and Velocity Contour at 350 mm height



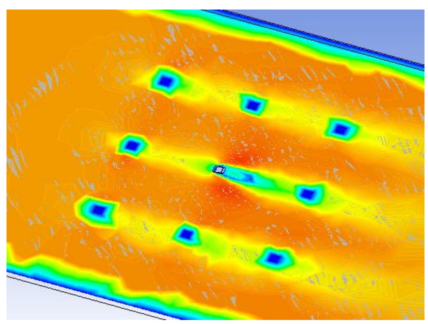
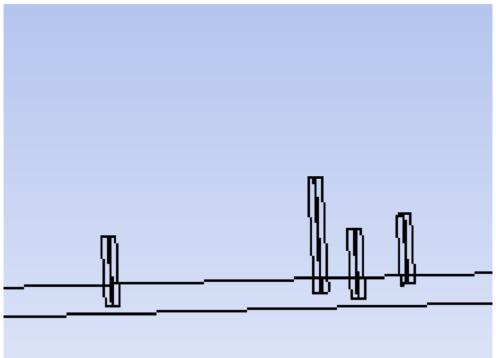


Fig. 12. Rectangular Pattern Geometry and Velocity Contour at 400 mm height



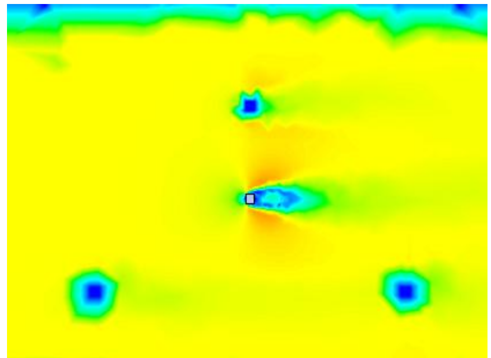


Fig. 13. Triangular Pattern Geometry and Velocity Contour at 150 mm height

2) 15 Degree air flow

With 15 degree air flow, building interaction was different for 3 clusters ,values were obtain above can be used to predicted following

1) When block cluster are kept at 200 mm height minimum values of drag and drift are obtained for octagonal pattern.

2) When block cluster are kept at 450 mm height minimum values of drag and drift are obtained for rectangular pattern.

3) When block cluster are kept at 300 mm height minimum values of drag and drift are obtained for triangular pattern.

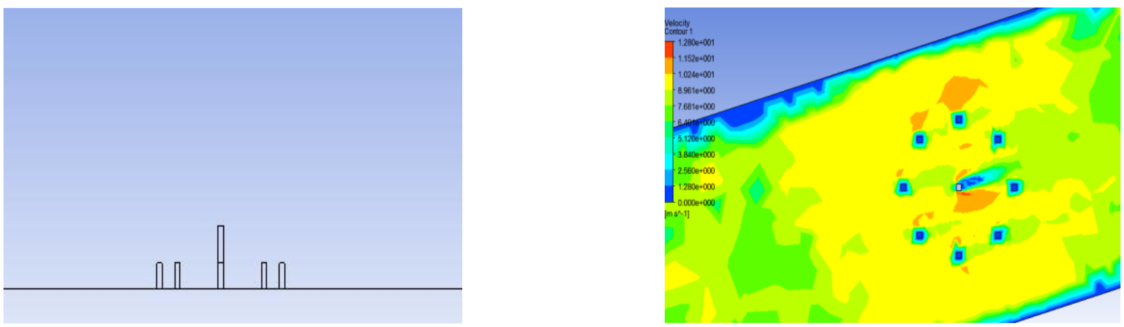


Fig. 14. Octagonal Pattern Geometry and Velocity Contour at 200 mm height

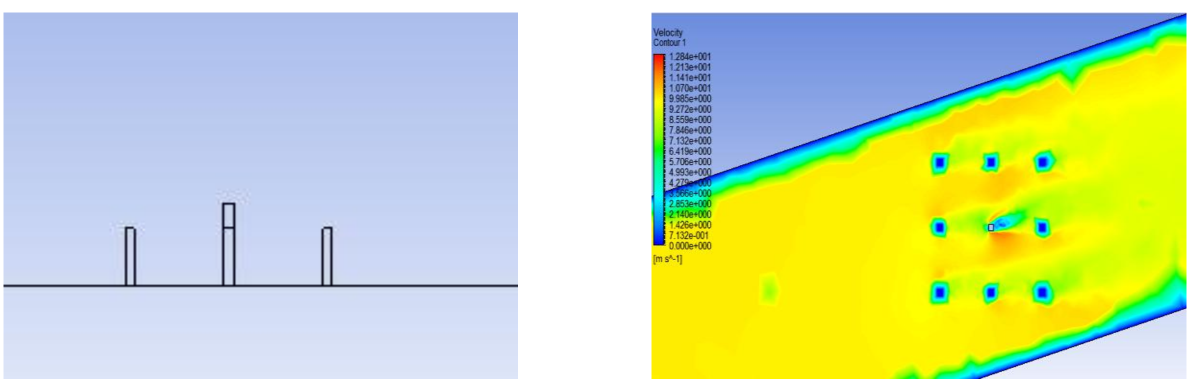


Fig. 15. Rectangular Pattern Geometry and Velocity Contour at 450 mm height

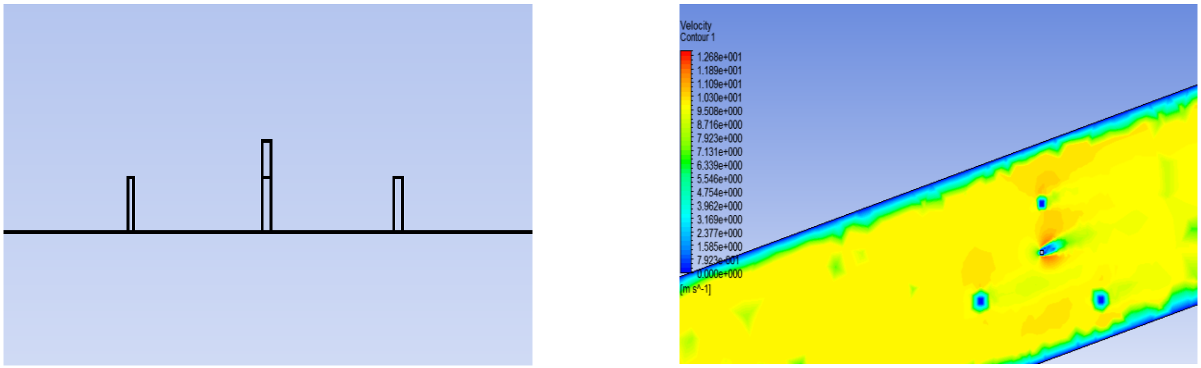


Fig. 16. Triangular Pattern Geometry and Velocity Contour at 300 mm height

4.4 CONCLUSION

In case of zero degree wind flow triangular cluster is most effective to suppress the aero-elastic instability. Height of block cluster and the main block (h/H)=.3 is the crucial point in this case. On the other hand clusters like octagonal and rectangular were effective at (h/H)=.7 and (h/H)=.8 respectively. Reduced drag and drift occurs due to formation of cluster around the main block which reduces the response at high velocity i.e. U/nB>10. Taking results from 15 degree wind flow sector octagonal cluster having height difference i.e. (h/H)=.4 is most effective to reduce the aeroelastic or aerodynamic instability .It can be stated that .4 is the crucial point in this sector. On the other hand(h/H)=.9 and (h/H)=.6 are the crucial points for rectangular pattern and triangular pattern respectively.

Where,

U = Reduced Velocity, B = Width of block , n = natural frequency

REFERENCES

[1].Ahmad, Shakeel, “Wind pressures on low rise hip roof buildings”. Ph.D. Thesis, Civil Engineering Department, University of Roorkee (Now Indian Institute of Technology Roorkee), May 2000.

[2.] Bailey, P.A., and Kwok, K.C.S., “Interference Excitation of Twin Tall Buildings”. Journal of Wind Engineering and Industrial Aerodynamics, Vol. 21, 1985, pp. 323–338.

[3.] Bayar, D.C., “Drag coefficients of latticed towers”. Journal of Structural Engineering, ASCE, Vol. 112, 1986, pp. 417–430.

[4.] Bowen, A.J., “The prediction of mean wind speeds above simple 2D hill shape”. Journal of Wind Engineering and Industrial Aerodynamics, Vol. 15, 1983, pp 259–220.

[5.] Cook, N.J., The designer’s guide to wind loading of building structures – Part 1”. Butterworths, London, 1985.

[6.] Davenport, A.G., “Gust loading factors”. Journal of the Structural Division, ASCE, Vol. 93, 1967, pp. 11–34.

[7.] Gumley, S.J., “A parametric study of extreme pressures for the static design of canopy structures”. Journal of Wind Engineering and Industrial Aerodynamics, Vol. 16, 1984, pp 43–56.

[8.] Gupta, Abhay, “Wind tunnel studies on aerodynamic interference in tall rectangular buildings”. Ph.D. Thesis, Civil Engineering Department, University of Roorkee (Now Indian Institute of Technology Roorkee), 1996.

[9.] Holmes, J.D., “Mean and fluctuating internal pressures induced by wind”. Proc. 5th International Conference on Wind Engineering, Fort Collins, 1979, pp. 435–450.

[10.] Holmes, J.D., “Recent development in the codification of wind loads on low–rise structures”, Proc. Asia–Pacific Symposium on Wind Engineering, Roorkee, India, December 1985, pp. iii–xvi.

[11.] Hussain, M., and Lee, B.E., "A wind tunnel study of the mean pressure forces acting on large groups of low rise buildings". Journal of Wind Engineering and Industrial Aerodynamics, Vol. 6, 1980, pp 207–225.

[12.] Krishna, P., "Wind loads on curved roofs", Proceeding of Second Asia Pacific Conference on Wind Engineering (APCWE-II), Beijing, China, 1989.

[13.]Kwatra, Naveen, "Experimental studies and ANN modelling of wind loads on low buildings". Ph.D. Thesis, Civil Engineering Department, University of Roorkee (Now Indian Institute of Technology Roorkee), February 2000.

[14]. Lakshmanan, N., Arunachalam, S. and Harikrishna, P., "Parameters of risk coefficients for structures located in cyclone prone regions". Proc. of the National Conference on Wind Engineering, 145–153, April 2002, Roorkee.

[15.] Letchford, C.W. and Holmes, J.D., "Wind loads on freestanding walls in turbulent boundary layers". Journal of Wind Engineering and Industrial Aerodynamics, Vol. 51, 1994, pp 1 to 27.

[16.] Macdonald, P.A., Holmes, J.D., and Kwok, K.C.S., "Wind loads on circular storage bins, silos and tanks. II. Effect of grouping". Journal of Wind Engineering and Industrial Aerodynamics, Vol. 34, 1990, pp. 77–95.