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Wind Analysis of Tall Buildings Using Codal Provisions, Stochastic Approach and CFD – A Comparative Study

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ABSTRACT: Wind is dominant lateral loading on tall buildings and they govern the structural design of these tall buildings. Wind loads are estimated using codal provisions. In India, IS 875 (part 3) of 2015 gives procedure for calculating the wind loads on structures. For tall RC chimneys, wind load calculation procedure is given in IS 4998 of 2015. AS-NZS 1170-2 of 2015 and NBC, Canada of 2015 is the code to estimate wind loads on structures in Australia and Canada. Wind velocity fluctuation with time is random or stochastic in nature. Using PSD of wind velocity fluctuations, wind loads are estimated using RV approach and CFD is also been used to simulate the wind loads on the building. In recent years, application of CFD in making wind resistant design of tall buildings is increasing. CFD is used in place of wind tunnel study due to its ease and robustness over wind tunnel testing. In this paper, a tall building is considered and wind loads are obtained using codal provisions, using RV approach and using CFD. Along wind forces and across wind forces obtained using CFD are found to be very less compared to those obtained using codal provisions and RV approach. Wind forces obtained using Harris velocity PSD function, in RV approach are on higher end compared to the forces obtained using other velocity PSD functions. A broad comparison is made and findings of this paper are presented.

KEYWORDS: Computational Fluid Dynamics, ANSYS Fluent, Wind, Power Spectral Density function, Random vibration, Stochastic process, Drag, Lift, Tall buildings

I. INTRODUCTION

Growing population and limited buildable area in urban areas resulted in building vertically towards the sky. Tall buildings are the advancement of the multi- story buildings. According to IS 875 (part 3) of 2015, high rise or tall buildings are those whose height is greater than 50m or whose ratio of height to minimum lateral dimension greater than ‘5’. For tall buildings, wind is the governing structural design load and these tall buildings are to be properly designed for wind loads. For this purpose, estimation of wind load is to be done. Then, suitable structural design is to be executed. Different countries have different codal provisions for estimating wind loads on structures and in India, IS 875 (part 3) (2015) is the relevant code. Amongst other countries, Australia has AS-NZS 1170-2 (2011) and Canada has National Building code of Canada (2015) for estimating wind loads.

Along with, IS 875 (part 3), in India, IS 4998 (2015) is used for estimating wind loads on concrete chimneys and IS 16700 (2017) deals with criteria for structural safety of tall concrete buildings. In IS 875 (part 3), static and dynamic wind analysis methods are specified. In static analysis method, pressure coefficient approach and force coefficient approach is given. Pressure coefficients are given for a particular surface or part of particular surface of the building. Using these, wind loads on individual members such as, on walls of the buildings, on cladding system, on different types of roofs of the buildings, on frames etc can be worked out. Further, force coefficients are also specified to calculate the forces on the building as a whole in the direction of applied wind. Force coefficients are given for different orientation and plan shapes of the building and also clause on wind interference effects on low rise and high rise buildings are also given. IS 4998 is the code for tall RC chimneys [5]. However in this paper, wind forces on building are also obtained using this chimney code.

Wind analysis is basically an exercise in fluid mechanics. The wind analysis is based on the stochastic or random modeling of wind velocity fluctuations. Fig. 1 shows the typical wind velocity time history. Since, 1900, random vibration approach has been used to obtain wind forces. The wind forces are random in nature, as wind flow is turbulent in nature. Wind velocity variation is modeled as stochastic process. Wind flow profile is assumed as a stationary random process. So, wind load can be decomposed as mean wind and turbulent wind fluctuations carried by mean wind [14]. Thus the turbulence about the mean wind can be considered as summation of eddies (harmonics) of different angular frequencies. These eddies are designated with their angular wave number. Velocity per unit wave number of eddy is called velocity power spectral density (PSD) function. Mathematically, it is the spectrum of power of Fourier coefficients of velocity fluctuations for different frequencies [12]. Many of the codal provisions are based on stochastic modeling of wind velocity. Subsequently, Computational fluid dynamics (CFD) has also made inroads in wind analysis. Particularly, after the development of finite element method for fluid flow modeling, new tolls are available to perform wind analysis using CFD. Computational fluid dynamics (CFD) is a branch of fluid dynamics which is numerical analysis software that solves the partial differential equations of flow continuity, flow momentum equations and energy equations of the fluid flow.CFD can generate turbulent fluid flows. CFD is a virtual wind tunnel testing facility that is a lot flexible and efficient compared to classical wind tunnel testing. CFD also gives along wind pressure coefficients, across wind pressure coefficients, many other flow parameters etc. CFD gives clear visualization of flow field, flow separation, wake zone, pressure contours, velocity contours etc. But CFD doesn’t consider flexibility of the body under testing. ANSYS FLUENT, one of the applications provided by ANSYS work bench, for performing CFD is used for wind analysis.

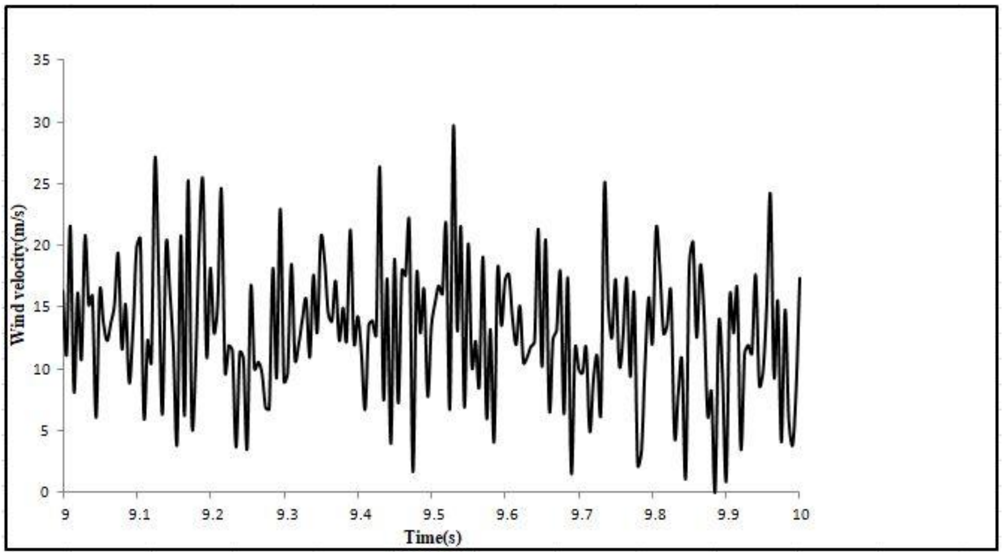

Fig. 1 Typical wind velocity time history

Thus, one finds that a typical exercise of wind load calculation can be done using, codal provisions, stochastic approach and using CFD. In this paper, for a typical tall building (Zhou et al. 2002), all the mentioned three approaches are used to obtain the wind loads. Conclusions are made and inferences are drawn.

In the next section, along wind analysis and across wind analysis of a tall building, using various codal standards is discussed. Followed by that, there will be discussion on Random vibration theory and its application in wind analysis. Then, wind analysis using CFD is presented. At last, there will be comparison of results and then finally conclusions are presented.

Wind analysis using various international standards

A 200m tall building from Zhou et al., 2002 [16], is considered. Along wind analysis and across wind analysis is performed using IS 875 (part 3) – 1987, IS 875 (part 3) – 2015, AS-NZS 1170-2 – 2011, NBC, CANADA – 2015, IS 4998 – 2015 (Chimney code). The details of the building are given in Table 1.

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Along wind analysis

All the codes have specified similar kind of formulations for along wind load calculations on the tall buildings. Gust factor method is specified by IS 875 (part 3) of 1987 and Dynamic response factor method is specified by IS 875 (part 3) of 2015 for determining dynamic wind forces on the building. Australian code in similar to Indian code, also used dynamic response factor for along wind analysis whereas, Canadian code used gust effect factor. The drag coefficient that is required for force calculation is a function of building configuration

Table 1 Details of the building

1.	Height (H)	200m
2.	Width (b)	33m
3.	Depth (d)	33m
4.	Basic Wind Speed (V_b)	40m/s
5.	Fundamental Frequency (f)	0.2Hz
6.	Building Density (ρ_b)	180(Kg/m^3)
7.	Damping Ratio (ξ)	0.01
8.	Terrain Category	IV

and height. Basically, drag coefficients were obtained from various wind tunnel tests and are different in different codes. For our building configuration, the drag coefficients obtained from various codes are given in Table 2. It is to be noted that, IS 4998 is the code for design of RC chimneys. However, here, this code is used to obtain wind forces on buildings. As per IS 4998 (2015), the aerodynamic roughness length (Z_0) is 0.02m for all the terrains though it's varying with different terrains in other codes.

Table 2 Drag coefficients from different codes

Code	IS 875 (1987)	IS 875 (2015)	Australian code	Canadian code	IS 4998
Drag coefficient	1.5	1.5	2.2	0.8	0.8

All these codal standards have mentioned gust effect factor or gust factor or dynamic response factor for force calculation which in common represents the ratio of peak response to the mean response of the building. Different expressions were given by these codes for gust factor and are shown is Table 3.

Table 3 Gust Response Factor (or) Dynamic Response Factor from Various Codal Provisions

Code	G (or) C_{dy}
1. IS 875 (Part 3) - 1987	$G = 1+g_f\sqrt{\left[B(1+\o)^2+\frac{SE}{\beta}\right]}$
2. IS 875 (Part 3) – 2015	$C_{dy} = \frac{1+2I_h\left[{g_v}^2B_s+\frac{H_s {g_R}^2 SE}{\beta}\right]^{0.5}}{1+2g_v I_h}$
3. AS-NZ 1170-2 – 2011	$C_{dy} = \frac{1+2I_h\left[{g_v}^2B_s+\frac{H_s {g_R}^2 SE}{\xi}\right]^{0.5}}{1+2g_v I_h}$
4. NBC, Canada – 2015	$G = 1+g_p\sqrt{\frac{K}{C_{eH}}\left(B+\frac{sF}{\beta}\right)}$
5. IS 4998 – 2015	$G = 1+g_f r_t\sqrt{B+\frac{sE}{\beta}}$

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Fig. 2 shows the variation of gust factor or dynamic response factor, calculated for this building, with height. It is seen that the gust factor from IS 875 of 1987 and Canadian code are very high compared to the dynamic response factor obtained from IS 875 of 2015 and Australian code. The reason being that the gust factor is based on hourly mean wind speed whereas, the dynamic response factor is based on 3-sec gust speed. The gust factor obtained from IS 875 (part 3) of 1987 and NBC, Canada of 2015 are almost equal to each other (~2.7). Whereas, the dynamic response factor obtained from AS-NZS 1170-2 of 2011 and IS 875 (part 3) of 2015 are almost similar to each other (~1.2). At the tip of the building, the gust factor obtained using IS 4998 of 2015 is highest (~2.8) compared to other codes.

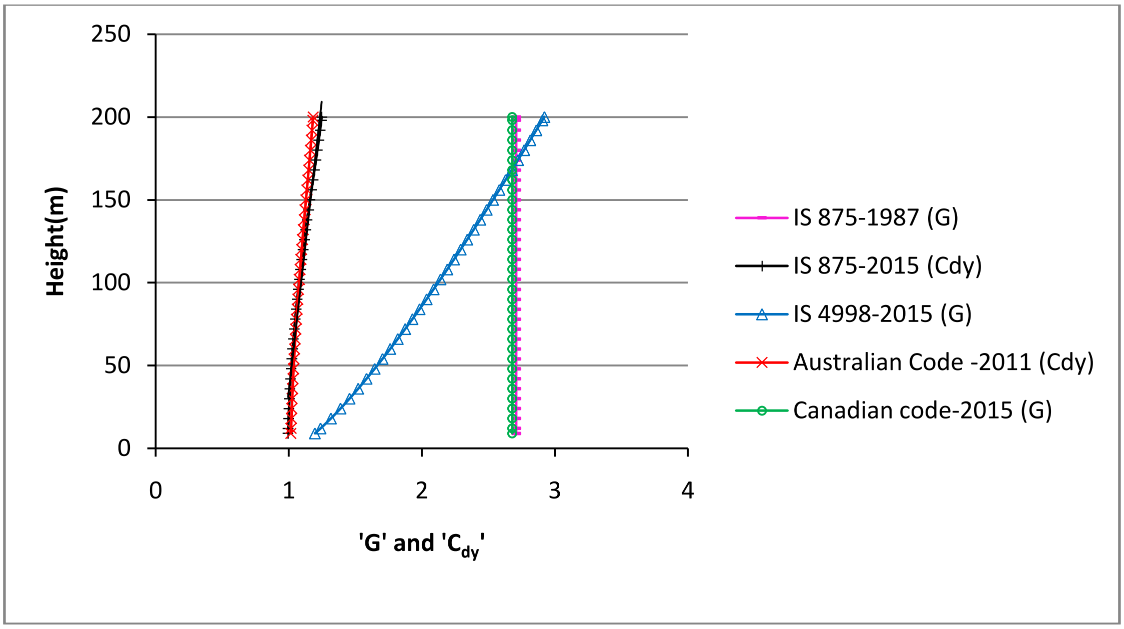

Fig. 2 Variation of 'G' and 'C_{dy}' with Height

Across wind analysis

Expressions for calculating across wind forces due to wake excitation are specified in various codal provisions. However, IS 875 (part 3) of 1987 does not specify any expression for calculating across wind forces. Even National Building code of Canada does not specify any expression for calculating across wind forces. Rather, they have suggested to perform wind tunnel studies to study the across wind behavior of tall buildings. The across wind analysis is based on two assumptions. (1) The shape of fundamental mode shape is linear and (2) The response to wind loading is generally dominated by the fundamental mode [14]. The second assumption holds if the ratios of natural frequencies in the second and higher modes to the fundamental frequency are sufficiently large. Various expressions were provided by codes for determining peak across wind forces at various heights of the building.

Wind analysis using Theory of Random Vibrations

Codal provisions are evolved based on analytical/numerical and wind tunnel studies. Variation of wind velocity with time is highly random or stochastic, hence random vibration analysis is useful for finding wind forces. Random vibration is a non-deterministic vibration, where the variation of physical variable will be random in nature with fluctuations, so as wind. Along wind analysis and across wind analysis is done using the procedure specified by Simiu and Scanlan, 1996.

Along wind analysis

Since the wind velocity profile is decomposed as mean wind speed and turbulent wind speed, from Simiu and Scanlan, 1996, the total force exerted by the wind on the structure can be written as,

$$F_{Total} = F_{mean} + F_{fluctuating} \quad (1)$$

The mean force component is given by,

$$F_{mean}=\frac{1}{2}\rho u_m^2 A_e C_d \quad (2)$$

Where,
'ρ' is the density of atmosphere under standard conditions ($1.25\frac{Kg}{m^3}$)
'u_m' is the hourly mean wind speed
'A_e' is the effective frontal area
'C_d' is the drag coefficient

The fluctuating force component is given by,

$$F_{fluctuating}=\rho u_m u' A_e C_d \quad (3)$$

Where,
'u'' is the fluctuating component of wind velocity
'ρ' is the density of atmosphere under standard conditions ($1.25\frac{Kg}{m^3}$)
'u_m' is the hourly mean wind speed
'A_e' is the effective frontal area
'C_d' is the drag coefficient

The peak fluctuating velocity component is given by,
$$u' = k\sigma \quad (4)$$

Where, 'σ' is the root mean square velocity with respect to mean. It is also called as standard deviation with respect to mean value. 'k' is the peak factor for fluctuating velocity component as shown in Fig. 3. The peak factor and standard deviation are obtained using velocity power spectral density function given in Simiu and Scanlan and the drag coefficient for our building configuration is obtained as '1.3'.

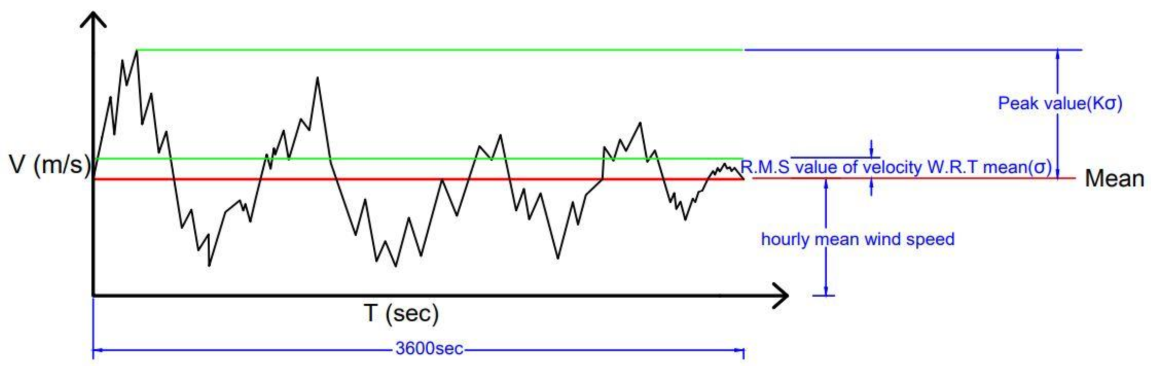

Fig. 3 Turbulent wind velocity profile

Across wind analysis

Across wind oscillations due to wake excitation is obtained using expression given in Simiu and Scanlan (1996). The peak value of the acceleration at the tip of the building is given by,

$$\ddot{Y} = k \times \sigma_{\ddot{y}}(h) \quad (5)$$

Where,
'$\sigma_{\ddot{y}}(h)$' is the rms value of acceleration at the zenith.
'k' is the peak factor for across wind accelerations = 4.

Expression for finding '$\sigma_{\ddot{y}}(h)$' is given in Simiu and Scanlan, 1996. The mass of the building is 288000 kg/m. Thus the peak tip across wind force due to wake excitation can be obtained by making up mass times acceleration for a linear mode shape. Now, by applying mode shape correction factor actual forces are obtained.

Wind analysis using Computational Fluid Dynamics

For wind analysis using CFD, there is a module in ANSYS software. That module is called ANSYS- FLUENT. Simulation in CFD involves Modeling, Meshing, Solution and finally extracting results. Our building is injected into a computational domain. Computational domain is wind fluid flow zone where flow equations are solved using finite element operations. The size of computational domain adopted here to capture

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Table 4 Modeling Parameters

1.	Length scale	1:400
2.	Velocity scale	1:5
3.	Upstream length(l_u)	5H
4.	Downstream length(l_d)	15H
5.	Side clearance(b)	5H
6.	Height of the domain(h)	6H
7.	Dimensions of the domain	10.1m × 5.1m × 3m

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the fluid flow accurately and other modeling parameters are given in Table 4 [8]. Structured meshing is done with a total of 1.3 Million hexahedral elements with a Y_+ value of 100 and using 15 inflation layers. Inflation layers are used to capture the boundary layer flow accurately [7]. Very fine meshing is done around the building fluid interface to capture the fluid interaction accurately. Fig. 4 shows the wireframe computational

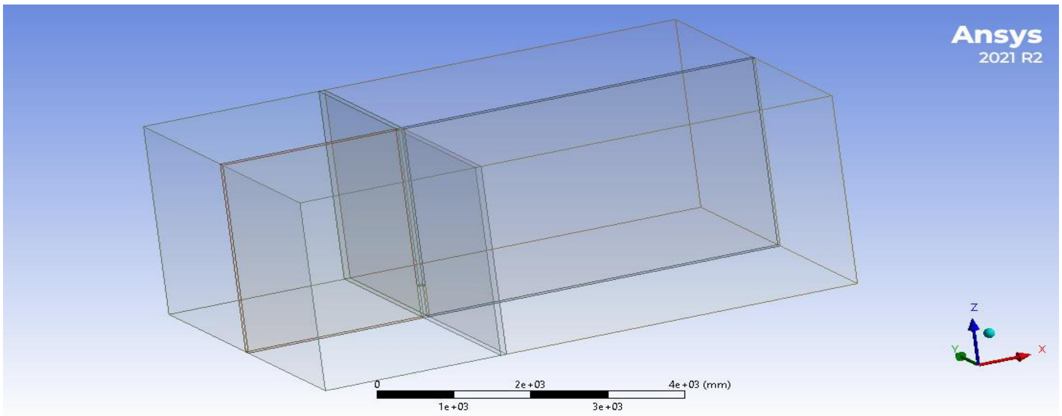

Fig. 4 Wire frame of computational domain

domain and Fig. 5 shows the meshed computational domain. Table 5 provides the solver settings used in the simulation. Finally, results of simulation are obtained after 5hrs of simulation activity. The Fig. 6 shows drag coefficient time history and Fig. 7 shows Lift coefficient time history obtained from after simulation.

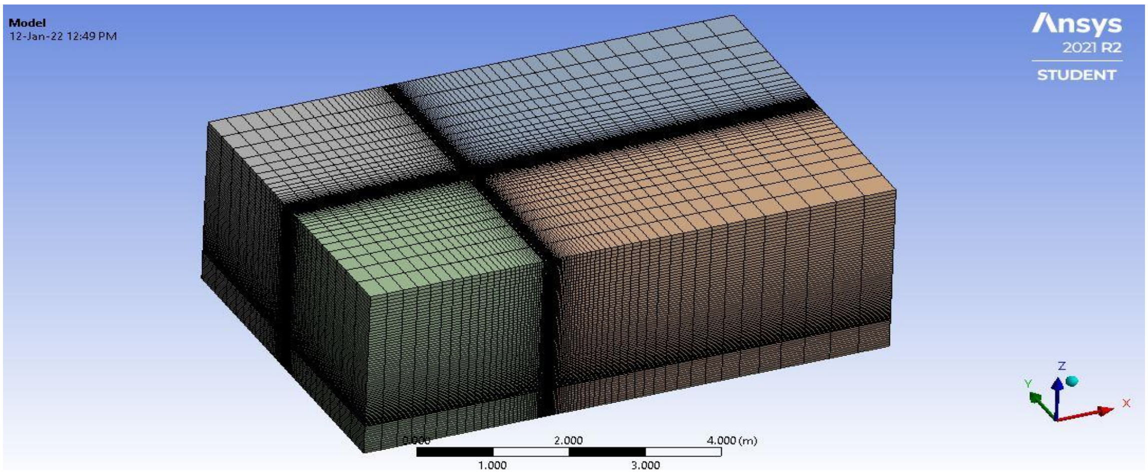

Fig. 5 Meshed computational domain

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Table 5 Solver Settings

1.	Simulation model	Transient large eddy simulation model
2.	Inlet boundary condition	Velocity inlet
3.	Outlet boundary condition	Pressure outlet
4.	Solution scheme	Pressure-velocity coupled scheme
5.	Spatial discretisation	Second order-upwind
6.	Gradient discretisation	Least square cell based method
7.	Time step size	0.005 s
8.	Iterations per time step	20
9.	Total number of iterations	4500

From above Fig. 6, it is clear that, the maximum turbulent drag coefficient is equal to 2.35 and average drag coefficient is 1.69. Fig. 7 shows that the maximum turbulent lift coefficient is 1.34. The along wind forces are obtained from drag coefficient as,

$$F = \frac{1}{2}\rho A u^2 C_d \tag{6}$$

and the across wind forces are obtained from lift coefficient as,

$$F = \frac{1}{2}\rho A u^2 C_L \tag{7}$$

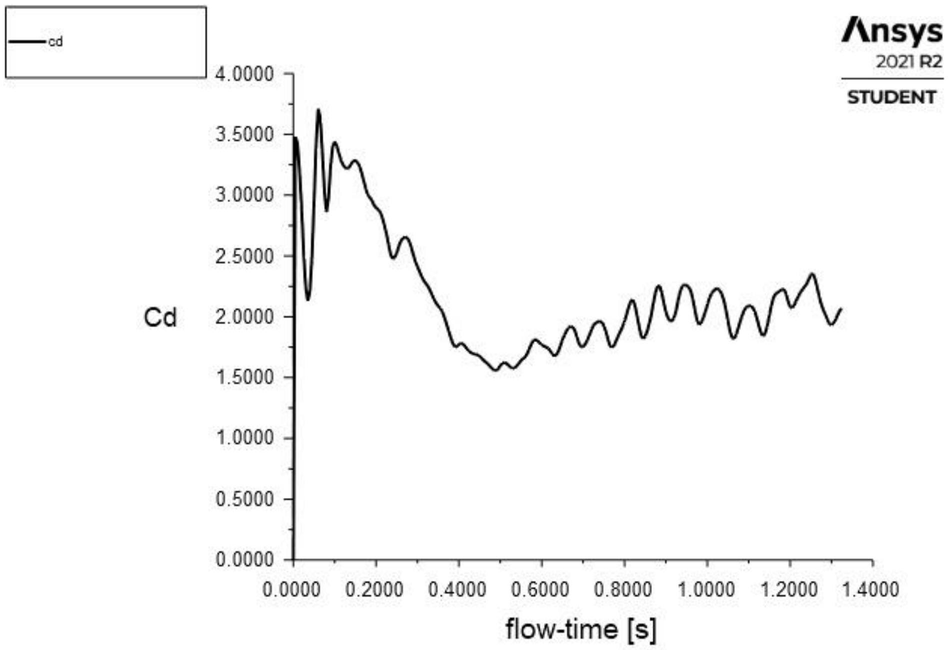

Fig. 6 Drag Coefficient Time History

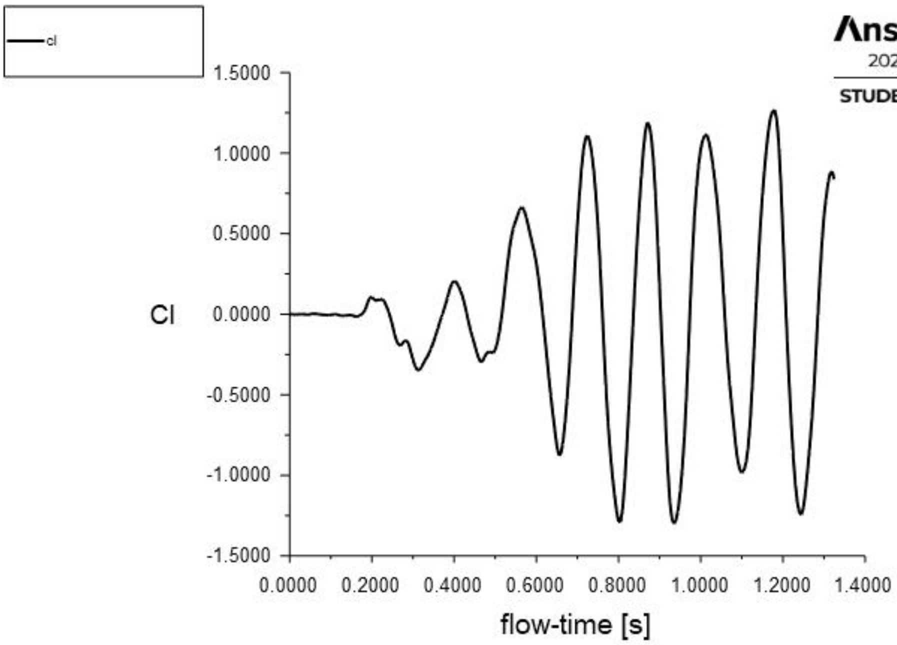

Fig. 7 Lift Coefficient Time History

Where,

'ρ' is the density of air

'u' is the far upstream velocity

'A' is the effective frontal area

'C_d' is the drag coefficient

'C_L' is the lift coefficient

From the above figures we can observe that, the lift coefficient variation and drag coefficient variation with time is oscillating about a mean value. The mean values produce steady state displacement. Whereas these oscillations are having definite frequencies. If the frequencies of these oscillations are in line with frequency of our building, it produces amplified displacements which is called resonance phenomena. Thus the building will be oscillating about mean displacement. But, CFD doesn't consider the flexibility of the body. It treats the body as rigid. Thus we cannot get the response of the structure from CFD.

II. RESULTS

The along wind forces and across wind forces are obtained from various international codes, RV approach and from CFD analysis. For calculating along wind forces using RV approach, various velocity power spectral density functions are used such as Simiu's PSD, Haris PSD and Kaimal PSD. As mentioned earlier, Canadian code and IS 875 (1987) has not mentioned any formulations for calculating the across wind forces on the building.

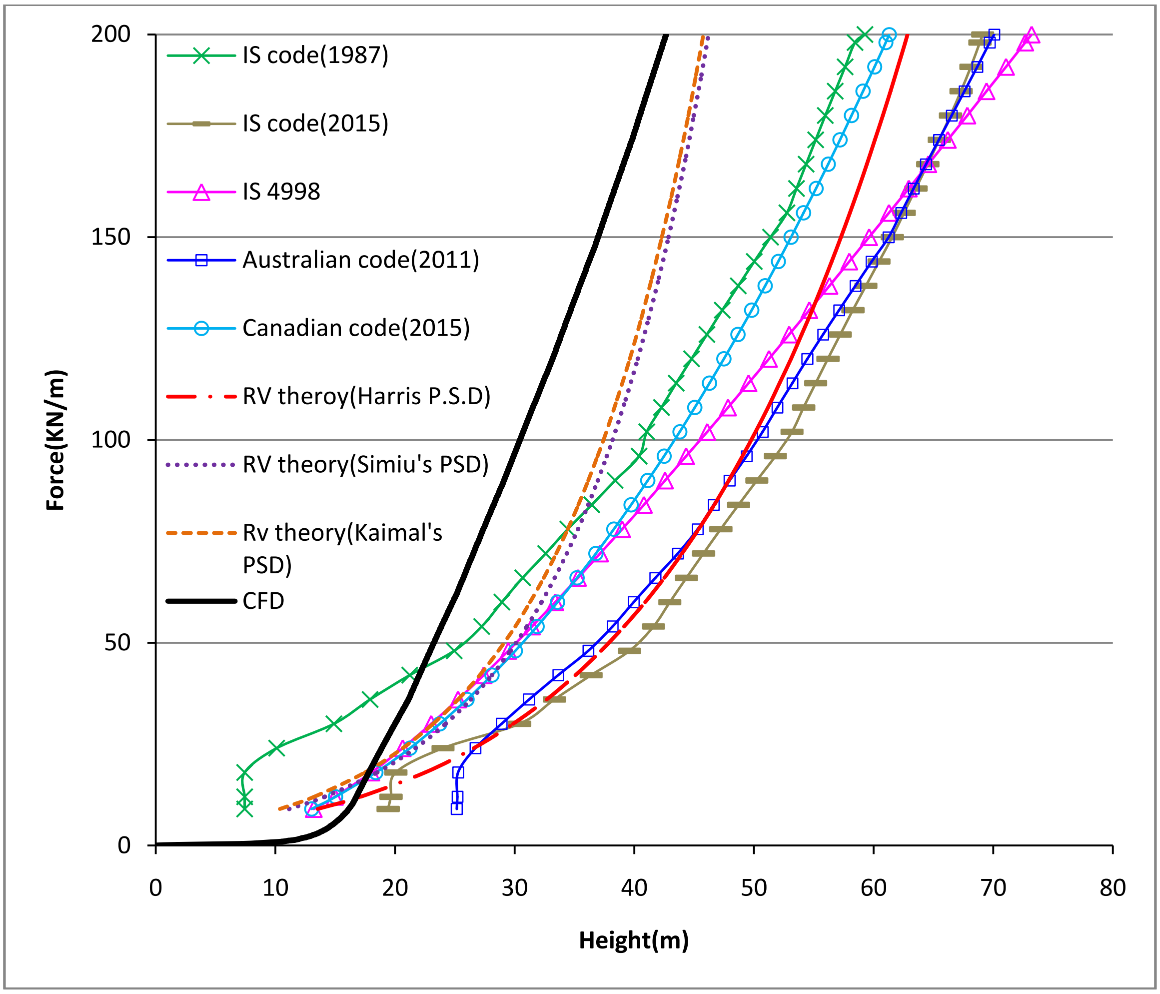

Fig. 8 Variation of Along Wind Forces with Height

Fig. 8 shows the variation of along wind forces with height of the building. It is seen that the along wind forces obtained from CFD analysis are almost closer to the along wind forces obtained using Simiu's and Kaimal's velocity power spectral density function. The along wind forces from CFD analysis are almost lesser by 40% compared to the forces obtained using codal provisions. Fig. 9 shows the variation of across wind forces with height of the building. The across wind forces obtained using CFD analysis are lesser by 50% compared to the forces obtained using RV approach and are lesser by 70% compared to the forces obtained using IS 875 (part 3) of 2015 and lesser by 60% compared to the forces obtained using IS 4998 of 2015. From both the plots, we can observe that, the along wind and across wind forces obtained from CFD are on very less side. The reason behind that is the missing of gust factor or dynamic response factor in CFD force calculation. CFD doesn't consider the flexibility of body under consideration. It assumes the body as a rigid, which is the short coming of CFD. Whereas forces obtained from codes or RV approach are displacement based wherein the response of the structure is considered in the form of gust factor or dynamic response factor. The forces obtained from codes are those that are based on peak displacement of the structure under resonant amplification. That is why code takes, stiffness, mass and damping ratio of the structure under consideration.

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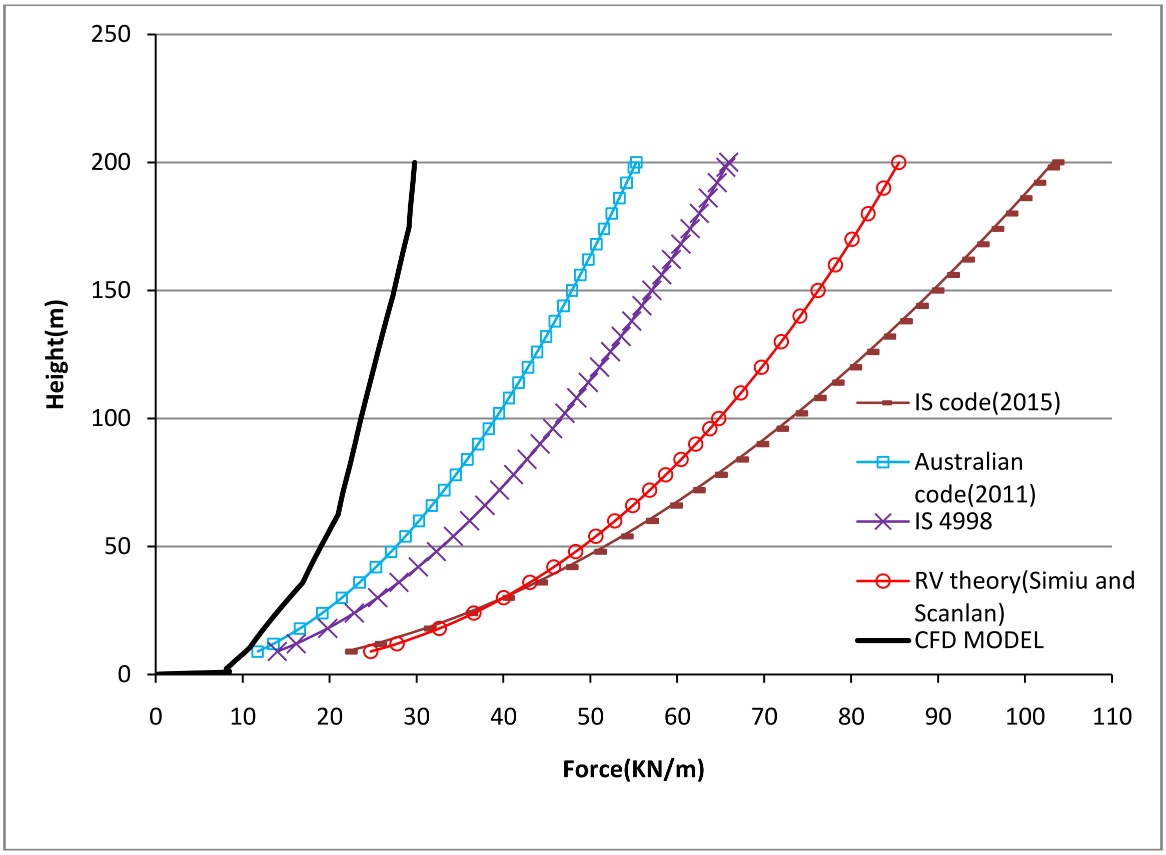

Fig. 9 Variation of Across wind Forces with Height

III. DISCUSSION

In this paper, a tall building from Zhou et al., 2002 is taken and along wind analysis and across wind analysis is performed according to various international codal standards, theory of random vibrations and finally using CFD. Based on this, the following are the findings of the paper.

1. The along wind forces from Australian code, IS 875 (part 3) of 2015 and IS 4998 of 2015 are higher than those obtained from Canadian code and IS 875 (part 3) of 1987 with a difference of almost 20%.
2. The across wind forces from IS 875 (part 3) of 2015 are higher compared to forces from Australian code and IS 4998 of 2015.
3. The along wind forces obtained using Harris velocity power spectral density function are 30% more than those obtained using Simiu's and Kaimal's velocity power spectral density function.
4. The across wind forces obtained using RV approach are greater by 25% compared to those obtained using AS-NZS 1170-2 of 2015 and IS 4998 of 2015 and lesser by 20% compared to the forces obtained using IS 875 (part 3) of 2015.
5. The along wind forces from CFD analysis are almost lesser by 40% compared to the forces obtained using codal provisions.
6. The across wind forces obtained using CFD analysis are lesser by 50% compared to the forces obtained using RV approach and are lesser by 70% compared to the forces obtained using IS 875 (part 3) of 2015

The forces obtained from the codes and RV approach is based on resonant displacements of the structure and can be termed as displacement based forces. Whereas, the forces obtained from CFD are not displacement based and hence wind forces from CFD analysis cannot be used for design. But CFD analysis is useful in generating drag coefficients, lifts coefficients that are used in design and gives a subtle visualization of the flow path, flow interaction and flow separations for any building configuration.

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