Prediction of Across Wind Response of Tall Buildings: An Overview

B. Kiriparan, J. A. S. C. Jayasinghe, and U. I. Dissanayake

Abstract Wind induced lateral loading is one of the vital factors governing the design of tall buildings. Along wind, across wind and torsional responses are three important considerations in wind design of tall buildings. A well-established gust factor approach is adopted in most of the wind design codes to predict the dynamic response of tall buildings in the along wind direction. Along wind predictions using this approach is found to be with reasonable accuracy when the wind flow is not significantly affected by neighbouring buildings. However, the applicability of most of the wind design codes are restricted to regular shaped structures with limitation on height or natural frequency. Dynamic motion of tall and slender structures perpendicular to the direction of the wind is known as across wind excitation. This phenomenon can be resulted from three mechanisms and their higher time derivatives such as vortex shedding, incident turbulence mechanism and higher derivatives of cross-wind displacement (i.e., galloping, flutter and lock-in). Due to the complex nature of the wind, characteristics of vortices and its interaction with the structure, significant limitations are found among the provisions set out in different international standards for the prediction of across wind responses. Though most of the existing codes are capable of predicting the along wind loading to reasonable accuracy, only a few international standards provide provisions for across wind effects. Unlike the along wind responses significant discrepancies are found among the across wind responses estimated by different standards. This paper presents an overview of capabilities and limitations of design provisions available in seven international codes/standards such as BS 6399-2:1997, BS EN 1991-1-4:2005, AS/NZS1170.2:2011, AIJ: 2004, CNS: 2012, ASCE 7-10 and NBCC: 2005 for the prediction of across wind responses. Comparisons of predicted across wind induced response for different building configurations (range of plan aspect ratio form 1–2, height aspect ratio from 4 to 8 and height from 120 to 240 m) are used to explain the influence of methods adopted in each of those wind codes.

Keywords Tall buildings · Across wind responses · Vortex shedding · Wind design codes

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1 Introduction

Modern tall buildings are becoming more slender, flexible, light weight and low damping due to urbanization and advancement of technologies such as high strength concrete, light weight partitions etc. This makes modern tall buildings more vulnerable under wind induced dynamic excitations. Along wind, across wind and torsional responses (as shown in Fig. 1) are three important considerations in wind design of tall buildings. Wind design codes and standards are utilized in prediction of wind effect on tall buildings in the preliminary design stages.

Along wind predictions from the existing standards are found to be with reasonable accuracy when the wind flow is not significantly affected by neighbouring buildings. However, the applicability of most of the wind design codes are restricted to regular shaped structures with limitation on height or natural frequency. Dynamic motion of tall and slender structures perpendicular to the direction of the wind is known as across wind excitation. Due to the complex nature of the wind, characteristics of vortices and its interaction with the structure, significant limitations are found among the provisions set out in different international standards for the prediction of across wind responses. Though most of the existing codes are capable of predicting the along wind loading to reasonable accuracy, only a few international standards provide provisions for across wind effects. Unlike the along wind responses significant discrepancies are found among the across wind responses estimated by different standards [1].

This paper presents an overview of capabilities and limitations of design provisions available in seven international codes/standards such as BS 6399-2:1997, BS EN 1991-1-4:2005, AS/NZS1170.2:2011, AIJ: 2004, CNS: 2012, ASCE7-10 and NBCC: 2005 for the prediction of across wind responses. Comparisons of predicted across wind induced response for different building configurations (range of plan aspect ratio form 1–2, height aspect ratio from 4–8 and height from 120 to 240 m) are used to explain the influence of methods adopted in each of those wind codes.

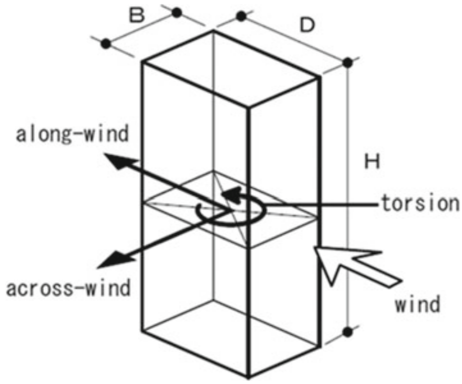

Fig. 1 Wind effects on tall buildings

Based on the comparison of predicted responses on selected building configurations; consistency of each wind codes in estimation of wind loading and accelerations are discussed. Capability of different wind codes and their limitations in across wind response estimation is outlined.

2 Background of Across Wind Loading

Wind is a very complicated phenomenon as the movement of air particles are turbulent due its low viscosity. Fluctuation of the wind speed shown in Figs. 2 and 3 illustrate the random nature of wind with both time and along building height respectively.

Due to this fluctuation in wind speed flexible structures like tall buildings are subjected to dynamic excitation under the wind loading. Generally, a structure is considered to be dynamically sensitive under wind loading if first natural frequency is less than 1 Hz (ASCE-7-10). Dynamic interaction of wind with structural system of a flexible structure leads amplification of wind induced responses. Aerodynamic loads acting on flexible tall buildings are magnified based on their dynamic characteristics. A well-defined peak factor method originally established by Davenport [2] used widely to predict dynamic amplification of along wind loading caused by the pressure fluctuation between wind ward and leeward faces. Predicted along wind buffeting

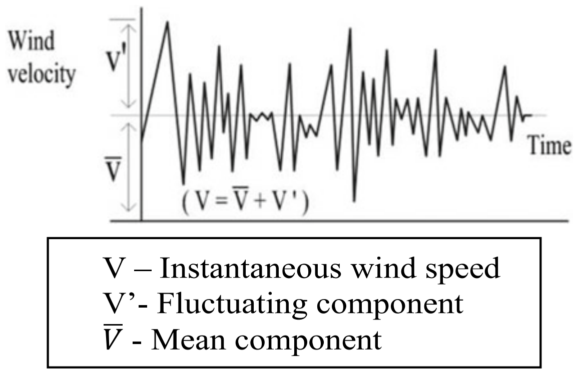

Fig. 2 Wind speed variation with time

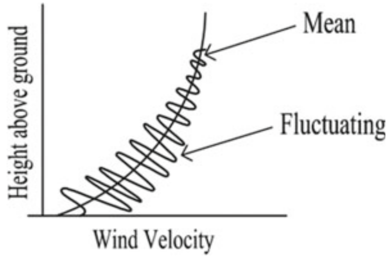

Fig. 3 Wind speed variation along height

loads using this theoretical method employed in most of the international wind codes are found to be within reasonable accuracy [3].

In dynamically sensitive tall buildings wind induced motion in the across wind direction caused by alternative shedding of vortices is an important phenomena to be considered in the design. A dimensionless parameter called 'Strouhal number' is used to identify the potential of particular structure, to the influence of vortices shedding. Figure 4 illustrates different factors associated with the across wind loading.

If the natural frequency of the structure coincides with the shedding frequency of the vortices, large amplitude displacement response may occur due to the resonance. This condition is referred as lock-in phenominon which can generally occurs within 10% range of building's natural frequency. Based on the geometry of the building Strouhal number is determined from wind tunnel testing.

A measured spectra of along-wind and across-wind load components of a flexible tall building reported in [4] reproduced in Fig. 5 to demonstrate the vortex shedding.

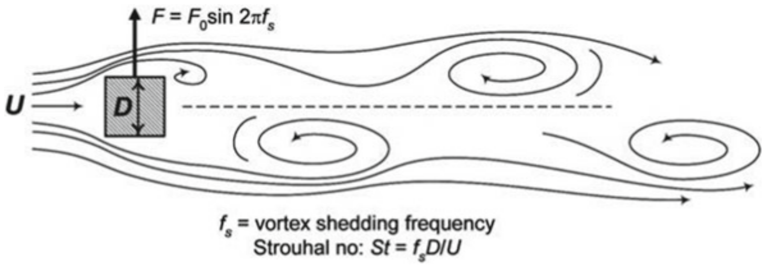

Fig. 4 Vortex shedding

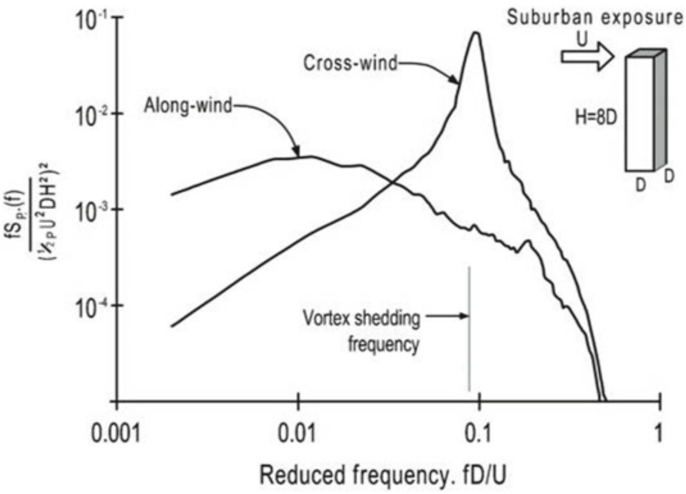

Fig. 5 Comparison of along and across wind spectra measured on a wind tunnel model [4]

Along wind dynamic response decrease when frequency increase whereas across-wind spectra has an intermediate peak resulted from vortex shedding, that highly affect the resonant response.

The magnitude of across wind response resulted from vortex shedding highly depends on building geometry. Buildings with regular geometries and sharp corners highly susceptible for cross wind effects. Aerodynamic shaping of buildings to minimize the across wind loading is a well-established exercise performed during the conceptual design stage to optimize the structural scheme against across wind effects.

Unlike along wind buffeting forces induced by the pressure fluctuations, strip and quasi-steady theories are not capable of predicting across wind excitation due to the complex nature of vortex shedding. Wake dynamics theories are used to explain the across wind excitation [5].

3 Overview of Codal Provisions for Prediction of Across Wind Effects

Many international design standards/guidelines are available for the prediction of wind response of tall buildings. Scope of most of the wind design codes are limited to regular shaped structures and due to the governance of dynamic responses again the limitations are imposed either based on building height or natural period. Still, for the buildings falls in the scope of the design codes inconsistences are found in the results obtained from different design codes [1]. Capabilities and limitations of seven major intentional codes: British Standard (BS 6399-2:1997), Australian Standard (AS/NZS1170.2:2011), Euro Code (EN1991-1-4:2005), Japanese Code (AIJ 2004), National Building Code of Canada (NBCC 2005), ASCE Minimum Design Loads for Buildings and Other Structures (ASCE 7:10) and China National Standard (CNS: 2012) are summarized in Table 1.

All seven standards considered set out provisions for the prediction of along wind loading. Provisions for calculation of across wind loading is provided in only five standards namely AS/NZS1170.2:2011, AIJ 2004, NBCC 2005, ASCE 7-10, and CNS: 2012. Further, across wind effects are only introduced very recently in many of those codes (e.g. included in CNS: 2012 while upgrading from CNS: 2006). In addition, BS 6399-2:1997 does not provide any guidelines for the calculation of wind induced accelerations whereas only along wind acceleration calculations are presented in EN1991-1-4:2005 and ASCE 7-10. In most of the cases across wind vibrations induced due to the vortex shedding is more critical than the along wind vibration. AS/NZS 1170.2:2011, AIJ 2004, NBCC 2005 and CNS 2012 provides guidelines for the calculation of both along wind and across wind accelerations. Procedures given for the across wind loading and accelerations are only discussed in this paper. A detailed comparison of expressions provided in those international standards for across wind load calculation are summarized in Table 2.

Table 1 Applicability of different international wind codes

<table>
<tr><td rowspan="2">Criteria</td><td colspan="7">Code</td></tr>
<tr><td>BS 6399</td><td>EN1991-1-4:2005</td><td>AS/NZS 1170.2:2011</td><td>AIJ2004</td><td>ASCE 7-10</td><td>CNS:2012</td><td>NBCC:2005</td></tr>
<tr><td>Height</td><td>No provisions for h > 300 m</td><td>No provisions for h > 200 m</td><td>No provisions for h > 200 m</td><td colspan="2">No explicit limit specified</td><td>No provisions for h > 550 m</td><td>No explicit limit specified</td></tr>
<tr><td>Frequency</td><td></td><td>No provisions for f < 0.2 s</td><td>No provisions for f < 0.2 s</td><td colspan="4">No explicit limit specified</td></tr>
<tr><td>Geometry</td><td colspan="7">No provisions for buildings with complicated shapes</td></tr>
<tr><td>Along wind loading</td><td colspan="7">Geometrical and height restrictions in along wind load calculations Geometrical</td></tr>
<tr><td>Across wind loading</td><td>No provision for given</td><td colspan="3">Geometrical and height restrictions in across wind load calculations</td><td>No provisions</td><td colspan="2">Geometrical and height restrictions in across wind load calculations</td></tr>
<tr><td>Torsional loading</td><td>No provision for given</td><td colspan="2">Nominal eccentricities specified</td><td>Detailed provision</td><td colspan="3">Nominal eccentricities specified</td></tr>
<tr><td>Along wind accelerations</td><td>No provision for given</td><td colspan="6">Provision are given</td></tr>
<tr><td>Cross wind accelerations</td><td>No provision for given</td><td>No provision for given</td><td colspan="2">Provision are given</td><td>No provision for given</td><td colspan="2">Provision are given</td></tr>
<tr><td>Torsional accelerations</td><td colspan="3">No provision for given</td><td>Provision given</td><td colspan="3">No provision for given</td></tr>
</table>

Table 2 Comparison of across wind prediction by international wind codes

Standard	Formula for across wind loading
AS/NZS1170.2:2011	$W_{eq}(z) = 0.5\rho_{air} V_{des,\theta}^2 d C_{fig} C_{dyn}$ $V_{des,\theta} =$ design velocity at building height d = horizontal depth of the building parallel to the wind stream C_{fig} = aerodynamic shape factor C_{dyn} = dynamic response factor $C_{fig} C_{dyn} = 1.5 g_R \left(\frac{b}{d}\right) \frac{K_m}{(1+g_v I_h)^2} \left(\frac{z}{h}\right)^k \sqrt{\frac{\pi C_{fs}}{\int}}$ b = width of the building normal to the wind direction h = building height z = height of interest K_m = mode shape correction factor I_h = turbulence intensity factor C_{fs} = across wind spectrum generalized for linear mode ϵ = critical damping ratio
AIJ-RLB-2004	$W_L(z) = 3 q_h C_L^{'} A \frac{z}{h} \sqrt{1 + \O_L^2} R_L$ $C_L^{'} = 0.0082\left(\frac{d}{b}\right)^3 - 0.071\left(\frac{d}{b}\right)^2 + 0.22\left(\frac{d}{b}\right)$ q_h =velocity pressure at roof level A = projected area z = height of interest h = building height $\O_L$ = correction coefficient for vibration mode R_L = resonance factor

(continued)

Table 2 (continued)

Standard	Formula for across wind loading
NBCC (2005)	$M_c = f_c^2 g_R (BD)^2 \left(\frac{78.5\times10^{-3}}{g\sqrt{\varepsilon}}\right)\left[\frac{V_H}{f_c\sqrt{BD}}\right]^{3.3} \frac{H^3}{3}$ $H =$ average height to the roof top $B =$ Breadth of the structure normal to the wind $D =$ Depth of the structure parallel to the wind $V_H =$ Mean wind speed, in $\frac{m}{s}$ at the building height, H $f_c =$ First mode natural frequency of vibration of a structure in across wind direction (in Hz) $g_R =$ Peak factor for across wind, taken as 3.75 $\varepsilon =$ Critical damping ratio in across wind direction
GB5009-2012	$M_c = g_R w_0 \mu_z (2+2\alpha)\gamma_{CM}\sqrt{1+R_L^2} B_z d_z,\ \gamma_{CM} = C_R - 0.019\left(\frac{D}{B}\right)^{-2.54}$ $R_L = \frac{1.4}{(\alpha+0.95)}\left(\frac{z}{H}\right)^{-2\alpha+0.9}\sqrt{\frac{\pi S_{FL}}{4\varepsilon\gamma_{CM}^2}}$ $w_0 =$ Reference wind pressure $g_R =$ Peak factor for across wind, taken as 3.0 $\mu_z =$ Exposure factor of a 10 -minute mean wind pressure profile $\mu_z = C_E\left(\frac{z}{H}\right)^{-2\alpha}$, C_E is terrain roughness $\alpha =$ Wind speed profile index $S_{FL} = f S_{ML}(f)/qHBH^2$ =Power spectrum of non -dimensional across wind generalised force

Table 3 Building configurations used for comparison of wind response predictions

Building ID	B × D × H	D/B	H/B	f_0
$M_{3030120}$	30 × 30 × 120	1.0	4	0.30
$M_{3030183}$	30 × 30 × 183	1.0	6	0.20
$M_{3046183}$	30 × 46 × 183	1.5	6	0.20
$M_{3060183}$	30 × 60 × 183	2.0	6	0.20
$M_{3030240}$	30 × 30 × 240	1.0	8	0.15

Table 4 Design wind speeds (m/s)

Averaging time	Ultimate limit states	Serviceability limit state
3-s	59	35
10-min	41	25
1-h	37	22

4 Numerical Example

Wind induced response of five building configurations as tabulated in Table 3, (including a benchmark building called CAARC) were determined using the seven wind design codes discussed.

All the buildings were assumed to be with uniform mass of 160 kg/m^3 throughout the height. Natural frequency of the building in along wind and across wind direction was considered as 36/H. This relationship is selected based on structural engineer's data provided for several wind tunnels including the benchmark building considered [6].

Calculations to predict along wind force, across wind force, along wind and across wind accelerations were carried out using different wind loading codes. Wind speeds shown in Table 4 were considered for the calculations [7].

5 Results and Discussion

Along wind and across wind base shears calculated based on different standards are presented in Tables 5 and 6. The Coefficient of Variation (CoV) are calculated to represent the discrepancies between predicted wind responses by different design standards. Along wind forces predicted using seven international standards are found to be consistent with a Coefficient of variation less than 15%. However, when the building height and natural period of the building increases, coefficient of variations are increasing due to the significance of dynamic responses. Variation of along wind base shear with height aspect ratio is shown in Fig. 6. The prediction of CNS: 2012 is

Table 5 Comparison of along wind base shear (kN)

	$M_{3030120}$	$M_{3030183}$	$M_{3046183}$	$M_{3060183}$	$M_{3030240}$
BS	11,525	17,292	17,292	17,292	21,868
EC	14,256	21,866	21,866	21,866	29,425
AS	13,967	20,979	20,979	17,525	28,925
AIJ	13,852	21,548	23,837	23,837	29,838
ASCE	11,318	17,053	17,053	17,053	24,585
CNS	10,895	16,580	16,580	16,580	21,015
NBCC	10,928	16,855	16,568	16,568	21,456
CoV (%)	12	13	14	15	16

Table 6 Comparison of across wind base shear (kN)

	$M_{3030120}$	$M_{3030183}$	$M_{3046183}$	$M_{3060183}$	$M_{3030240}$
BS	–	–	–	–	–
EC	–	–	–	–	–
AS	12,515	18,927	28,805	36,007	33,650
AIJ	17,013	24,936	40,862	58,796	49,196
ASCE	–	–	–	–	–
CNS	13,855	23,680	32,645	54,620	38,967
NBCC	11,800	17,424	26,253	39,568	27,950
CoV (&)	17	17	20	24	24

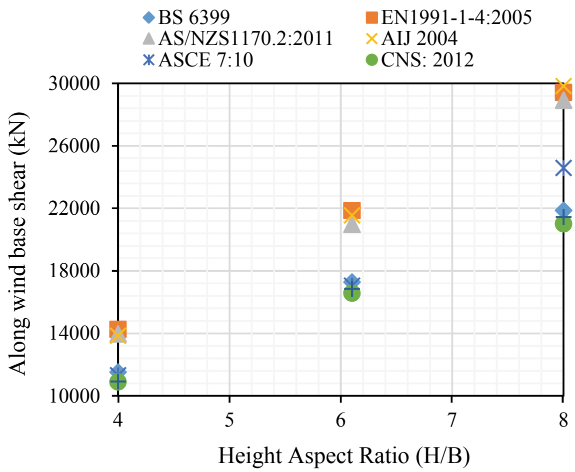

Fig. 6 Variation of along wind response with height aspect ratio

observed to be as lower bound for all the cases considered. EN1991-1-4:2005 estimations give higher value for lower height aspect ratios whereas AIJ: 2004 prediction for more slender and flexible buildings are found to be higher than all other standards. Different velocity profiles adopted by each codes and variations in the calculations of peak factors cause such inconsistences in the along wind predictions.

Coefficient of variation for across wind loading predictions are found to be significantly high (>15%). Unlike along wind loadings, crosswind spectra-based methods set out in the design standards for across wind loadings are derived from different wind tunnel sources. This may be the important reason for such higher discrepancies. With the increment of height and plan aspect ratios the deviations are further increasing as presented in Figs. 7 and 8 respectively. Prediction of NBCC and

Fig. 7 Variation of across wind response with height aspect ratio

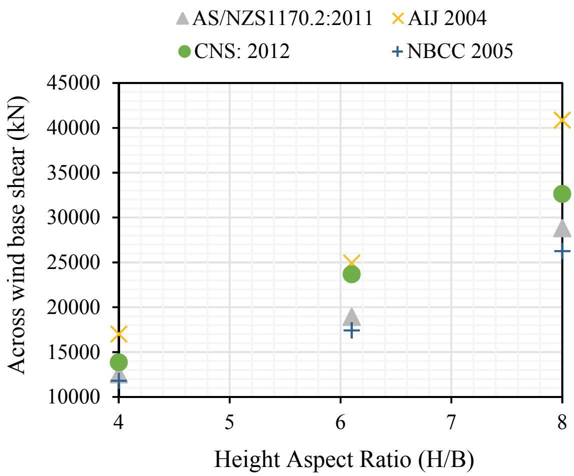

Fig. 8 Variation of across wind response with plan ratio

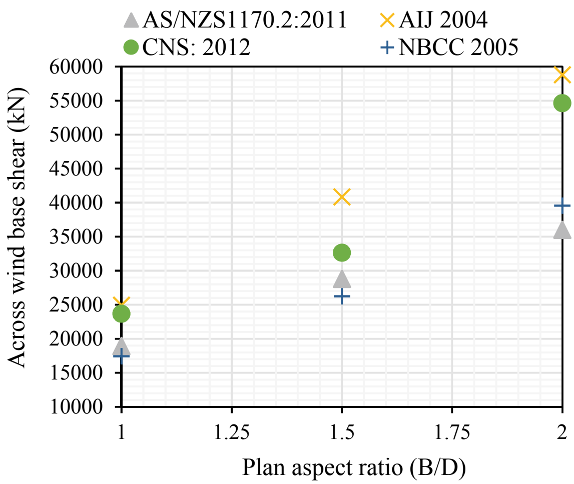

Table 7 Comparison of along wind accelerations (milli-g)

	$M_{3030120}$	$M_{3030183}$	$M_{3046183}$	$M_{3060183}$	$M_{3030240}$
BS	–	–	–	–	–
EC	10	14	11	8	15
AS	13	16	13	11	18
AIJ	11	15	10	10	16
ASCE	8	10	8	7	11
CNS	9	11	10	8	12
NBCC	12	14	13	10	17
CoV (%)	18	18	18	17	19

Table 8 Comparison of across wind accelerations (milli-g)

	$M_{3030120}$	$M_{3030183}$	$M_{3046183}$	$M_{3060183}$	$M_{3030240}$
BS	–	–	–	–	–
EC	–	–	–	–	–
AS	44	51	36	28	61
AIJ	36	42	28	24	51
ASCE	–	–	–	–	–
CNS	40	44	30	27	53
NBCC	41	48	33	26	56
CoV (%)	8	9	11	7	8

AS/NZS are laying at the lower side, on the other hand AIJ estimations provides relatively higher crosswind loading compare to all other standards.

Along wind and across wind peak accelerations calculated based on each standard are presented in Tables 7 and 8. Inconsistencies in the along wind acceleration predictions are increasing with building height and height aspect ratios. The influence of mass to minimize the building motion can be clearly seen from this results. Only four standards considered are capable of predicting the across wind accelerations. Coefficient of variation among those few available provisions are found less than along wind cases. Variation of along wind and across wind accelerations are with height aspect ratio are shown in Figs. 9 and 10.

Dynamic wind effect is one of the governing factor in the design of tall buildings. Thus, it is important to predict the wind effects precisely during the preliminary design in order to arrive at an optimum and safe structural scheme. Capabilities and limitations of different wind codes and consistency of their predictions were discussed in this study.

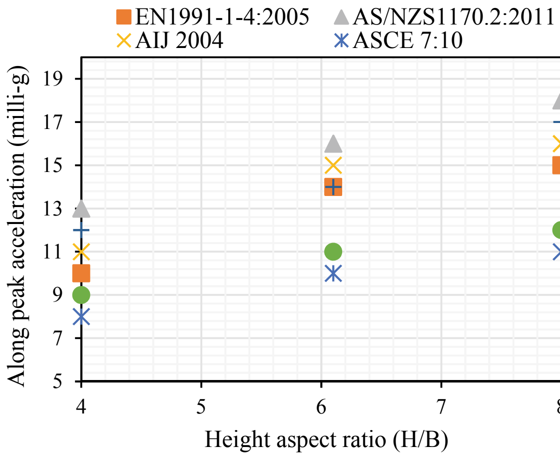

Fig. 9 Variation of along accelerations with height aspect ratio

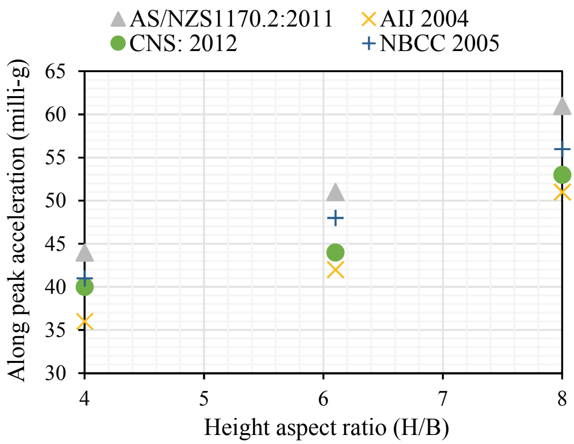

Fig. 10 Variation of across wind acceleration with height aspect ratio

6 Conclusion

This study presents an overview and importance of across wind loading in tall building design. The fundamentals associated with the across wind loadings and available provisions in seven international standards were discussed. Finally, a numerical comparison of predicted wind induced base shear and peak accelerations using those wind codes was carried out. The study shows consideration of across wind loadings is equally important as along wind loading in the design of tall buildings. Further, following observations were made from this study.

- When the plan aspect ratio is higher than unity across wind loading is increasing even beyond the along wind loading for few cases considered. Thus, for the

buildings with rectangular geometry across wind loading effect is higher than square geometries.
- Along wind loading predictions by all seven codes are within reasonable accuracy (CoV < 15%) for buildings up to 200 m and natural period not greater than 5 s. For building configurations considered beyond this limit variations are found to be increasing. CNS: 2012 provide lower bound along wind load among all seven standards, EN1991-1-4:2005 estimations gives higher value for lower height aspect ratios whereas AIJ: 2004 prediction for more slender and flexible buildings are found to be higher than all other standards.
- Significant discrepancies (CoV > 15%) in across wind loads estimated by different international standards are noticed. Prediction of NBCC and AS/NZS are laying at the lower side, whereas AIJ estimations provides relatively higher acrosswind loading compare to all other standards.
- Also, significant discrepancies (CoV > 15%) are observed in along wind acceleration predictions for more slender and flexible buildings.
- Only four international standards considered provide provisions for across wind accelerations predictions and their predictions are found to be consistent for the cases considered in this study. Similar source of limited aeroelasticity test results used to develop the across wind acceleration predictions by different wind codes may provide this consistency.

7 Recommendation for Further Work

Although similar comparative studies were conducted previously only few studies are available for the comparison of all these seven standards together. Further across wind predictions are very recently introduced in few of those standards such as CNS 2012. Significant inconsistencies are found in prediction of across wind loading estimations. Since across wind response is leading the along wind response for rectangular geometries an extensive parametric study may be performed to investigate this further. In addition, there are several models proposed by the researchers for the prediction of across wind responses a comparison with such predictions and existing wind tunnel test results will give more insight.

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