Cross-wind force spectra for low values of reduced velocity commonly required for New Zealand buildings

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ABSTRACT: The paper describes recent work carried out in New Zealand to measure the generalised wind force spectrum on models of buildings using a high frequency force balance. Structural engineers have found that some of the medium-rise high aspect ratio buildings that are being proposed for Auckland and Wellington at present have reduced velocities that are less than 2, and therefore are beyond the scope of the graphs available in AS1170.2: 1989 and 2002 to determine the cross-wind force spectral density. Wind tunnel tests have been carried out with the aim of extending the low frequency range of such graphs. In addition, tests have been done on an extended range of aspect ratios, and for oblique wind directions. It has been found that in general the measurements agree with the graphs in the standard. It has also been found that the existing cross-wind spectral density curves can be extrapolated to lower values of reduced velocity in a linear fashion on a log-log plot.

KEYWORDS: cross-wind excitation, spectral density, high aspect ratio building, human comfort, horizontal accelerations, human comfort, serviceability limit state.

1 INTRODUCTION

In the design of modern medium-rise and high-rise buildings, the cross-wind response often dominates over the along-wind response of buildings. Most existing codes and standards provide reliable procedures for calculating floor accelerations generated by along-wind excitation. The accelerations induced by cross-wind excitation mechanisms have proved to be much more complex to predict. Although there have been significant advancements in the understanding of the excitation mechanisms, no generalised analytical method is available to calculate the cross-wind response with a sufficient degree of reliability for design purposes. Recently it has been observed in New Zealand that buildings of moderate heights but with high aspect ratios have been proposed. Such buildings often operate at very low reduced velocities at the serviceability limit state, and the current data available in the appropriate wind loading standards are not sufficient. This is rather important, because adoption of the codified methods often results in acceleration predictions which are near or above acceptable levels. Hence it was decided to embark on the present study.

1.1 *Example of a building with a low value of reduced velocity*

A building recently proposed for Auckland had approximately the following dimensions: breadth - 27 m, depth - 7.5 m, height - 50 m. The structural engineer gave the uncracked natural frequencies for sway about the major and minor axes as 0.72 and 0.94 Hz respectively. The ratio H:B:D (50:27:7.5) is 6.7:3.6:1, which is not untypical for some recently proposed hotels and apartment buildings. If we take the one year return period mean wind speed as say 20 m/s (typical) then the reduced velocities for wind onto the narrow and wide faces are as shown in Table 1.

Table 1 Parameters for building example

Windward Face	**Return period, Years**	**V_h m/s**	**Width facing wind, b, m**	**n_{along} Hz**	**n_{across} Hz**	**$V_h/(n_c*b)$**
Wide	1	20	27	0.72	0.94	0.79
Narrow	1	20	7.5	0.94	0.72	3.7

Hence it is evident that low values of reduced velocity can be obtained for relatively small buildings, and the study was aimed at obtaining further information to help with such buildings.

1.2 *Main objectives of the study*

The main objective of this study was to gain\further understanding of the cross-wind response of medium to high-rise buildings in the lower region of reduced velocity i.e. reduced velocities less than 2.

The scope of this study covered a number of areas. The main ones were:

- A study of published work on the subject to identify research areas which required further work and which are of practical significance for real buildings of various aspect ratios.
- A re-examination of the cross-wind force coefficient spectra given in the wind loading standard AS/NZS 1170:2002.
- Extending the spectra given in the wind loading standard AS/NZS 1170:2002 below reduced velocities of 2.
- The development of more cross-wind force coefficient spectra for various aspect ratio buildings which are not included in the wind loading standard AS/NZS 1170:2002 such as (H:B:D) 6:1:3. 6:1:1.5, 6:3:1, 6:1.5:1, 3:1:0.75, 3:1:1.5, 3:0.75:1, 3:1.5:1.

1.3 *Background*

Two kinds of wind tunnel based procedures have been introduced in some of the existing codes and standards to treat the cross-wind and torsional response. The first is an empirical expression for the wind induced acceleration, such as that found in the National Building Code of Canada (NBCC) (NRCC 1996) [1], while the second is an aerodynamic load-based procedure such as those in Australian/New Zealand Standard (AS/NZS 1170.2:2002) [2] and the Architectural Institute of Japan (AIJ) Recommendations (AIJ 1996) [3]. The latter approach offers more flexibility as the aerodynamic load provided can be used to determine the response of any structure having generally the same architectural features and turbulence environment as the tested model, regardless of its structural characteristics.

In AS/NZS 1170.2:2002 [2], the cross-wind base overturning moment and peak cross-wind acceleration for serviceability can be found using equations (1) and (2) respectively.

$$Mc = 0.5 g_R b \left[\frac{0.5 \rho (V_{des,\theta})^2}{(1 + g_v I_h)^2} \right] h^2 \left(\frac{3}{k+2} \right) K_m \sqrt{\frac{\pi C_{fs}}{\xi}} \qquad (1)$$

$$\ddot{y}_{\max} = \frac{1.5 b g_R}{m_0} \left[\frac{0.5 \rho (V_{des,\theta})^2}{(1 + g_v I_h)^2} \right] K_m \sqrt{\frac{\pi C_{fs}}{\xi}} \qquad (2)$$

In equations (1) and (2), C_{fs} is the spectral density of cross-wind moment generalised for a linear mode shape which is based on wind tunnel testing various models. The spectra of cross-wind moment versus reduced velocity ($V_h/n_c b$) for various aspect ratios and turbulence intensities are published in AS/NZS 1170.2:2002. A similar approach was also used in the previous version of this standard AS/NZS 1170.2:1989 [4].

Studies on cross-wind response of rectangular buildings have appeared frequently in the literature. However, most of these studies have reported results for the reduced velocity in the range from 2 to 18 and for limited aspect ratio (H:B:D) buildings, where B and D are of similar size.

The importance of determining wind induced cross-wind load using wind tunnel techniques was recognised long ago, e.g. Saunders and Melbourne [5]. In these studies it is shown from an analysis using non-dimensional cross-wind force spectral densities of tall prismatic model buildings that the aerodynamic input into model buildings is insensitive to the level of cross-wind motion of the models, and that the cross-wind motion is primarily due to wake excitation. The use of these spectral densities then permits the prediction of the cross-wind response and loads on the buildings. The cross-wind displacement spectral densities were measured from dynamic models which simulated tall buildings. The model scale was 1/400 for which the full scale height corresponding to the 0.552 m model would be 221 m (724 ft). The cross-wind force spectra were deduced from the measurements of the cross-wind displacement spectrum by dividing by the mechanical admittance function. These results are the basis of the design curves in the wind loading Standards [2,4].

A recent study [6] has been carried out by Central Laboratories, Opus International Consultants Limited, New Zealand sponsored by the New Zealand Heavy Engineering Research Association (HERA) to provide better information for calculating the dynamic wind motion of low aspect ratio medium-rise buildings. The aim was to provide information to help designers better assess the dynamic wind motion of low aspect ratio designs, which are typical of some medium-rise buildings presently being constructed in New Zealand. Four different models with aspect ratios of 3:1:1, 1.5:1:1, 2:2:1, 2:1:2 were tested using the high frequency force balance (HFFB) technique which is briefly described in Section 2. The models were all rectangular prisms 200 mm high, corresponding to a full scale height of 30 m using the model scale of 1:150.

Further studies have been carried out by other researchers, as documented in [7, 8, 9, 10, 11]. Most of these studies reported results for the reduced velocity ($V_h/n_c b$) in the range 2 to 18.

Because of the recent trend in New Zealand towards high aspect ratio slab-like buildings of moderate height, it has been found that increasing numbers of buildings have reduced velocities less than 2, particularly for one-year return period winds which are often used to estimate the annual peak accelerations. It has also been found that the building geometry is often quite different, and less compact than the building shapes for which C_{fs} can be found in the wind loading Standard.

From this survey, it is clear that there is need to conduct further studies to provide better information for calculating the response of a greater range of aspect ratio buildings, as well as extending the data to lower values of reduced velocity in order to improve the design of medium-rise and high-rise buildings. Furthermore, it would be of some interest to investigate the excitation of buildings subject to oblique winds to ensure that the excitation under those conditions is not more onerous than the codified cases where the wind is normal to one of the faces.

2 REVIEW OF CURRENT EXPERIMENTAL WIND TUNNEL TESTING TECHNIQUES FOR BUILDINGS

Physical modelling of wind structure/building interaction using a wind tunnel is currently the most accurate and practical means of relating the aerodynamic loading of a building to the local wind structure. To determine the overall structural loads and response, there are currently three main approaches to wind tunnel tests on building models. These are briefly described in the following sections.

2.1 *High Frequency Force Balance Technique*

The high frequency force balance (HFFB) technique has been used to determine the wind induced response of many high-rise buildings since its development around 1980 [12]. The main requirements for a force balance are high stiffness and good sensitivity. The force balance technique involves testing a lightweight, rigid and geometrically scaled model of the subject building on an ultra sensitive balance. Since the main component of the response of buildings is primarily due to the excitation in the fundamental modes by the modal forces, these forces can be measured directly by a suitable balance by measuring the overturning moments.

2.2 *Instantaneous Pressure Measurement Technique*

The second approach is to carry out a direct pressure study on a stationary, rigid pressure model. This approach does not include any aeroelastic effects (like the HFFB approach described above) which change the dynamic response of the building. In the past, pressure model studies were primarily used to obtain the peak loads for the design of glass and cladding and to determine the overall mean loads by integrating local mean pressures from asynchronous sampling records. It is now possible to integrate simultaneously occurring local pressures to determine wind induced loads. Detailed descriptions of this method can be found in a number of publications, e.g. [13]. Recently, the University of Auckland, New Zealand has developed a high speed electronically synchronously scanned pressure measurement system [14]. This enables all pressures at up to 512 locations, to be sampled at a rate up to 1000 Hz. From such data forces moments, modal forces etc can be determined with relative ease.

2.3 *Aeroelastic model Testing Technique*

It can be shown from dimensional analysis that if all or most of the relevant similarity requirements are fulfilled then the results of tests on scaled models can be applied to a full scale structure. The important requirements include the modelling of the oncoming flow (velocity, turbulence etc.) as well as the dimensions, stiffness, mass and damping characteristics of the wind tunnel model. This is called aeroelastic model testing. The disadvantages of the aeroelastic model testing technique are that the model making is time consuming and expensive. The model is also designed for a single set of dynamic properties and approximations must be made if these change. Because of these factors, its use is becoming less common.

3 EXPERIMENTAL STUDIES

3.1 *Experimental studies using the electronically scanned multi-channel pressure system*

Spectra of forces and moments in the along and across-wind directions were determined from pressure measurements on 1:100 scale models of the subject buildings. These tests were carried out in the Twisted Flow Wind Tunnel in its 3.5m * 3.5m open jet configuration. The digital pressure scanning system developed by the University of Auckland was used for the tests. The measured time histories were checked for data integrity, corrected for the tubing response attenuation using a recursive filter, and then time histories of the force and overturning moment coefficients were determined. To save space, the results from the pressure study which used large 1:100 scale pressure tapped models will not be presented here.

3.2 *Experimental studies using the high frequency force balance (HFFB)*

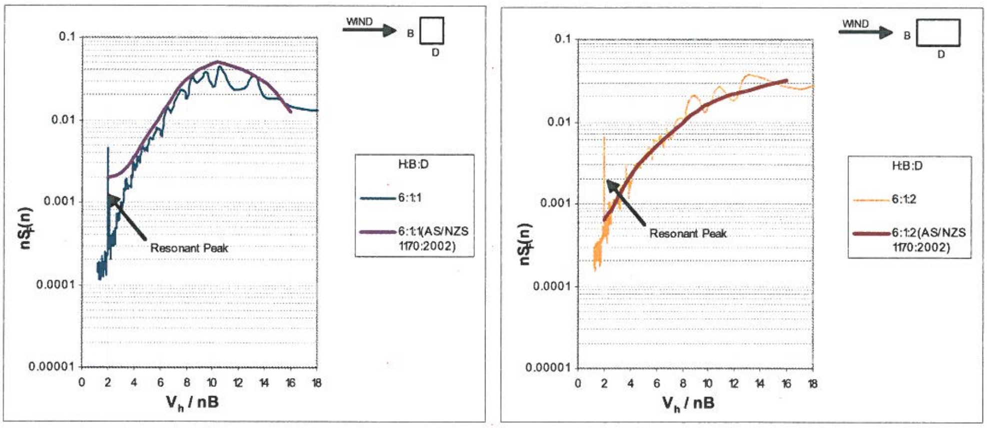
The force balance tests were carried out in the de Bray wind tunnel which has a test section 1.8 m wide and 1 m high. The models were built to a 1:250 scale and were all rectangular prisms 240 mm high corresponding to 60 m in full scale. Models with the following aspect ratios were tested: (height: width: depth) 6:1:1, 6:1:1.5, 6:1.5:1, 6:1:2, 6:2:1, 6:1:3, 6:3:1, and 3:1:0.75, 3:0.75:1, 3:1:1, 3:1:1.5, 3:1.5:1. The wind tunnel flow was set up using blocks, trip barriers etc. to simulate Terrain Category 3 conditions, as set out in [2,4]. The velocity and turbulence intensity profiles showed excellent agreement with the target values, and this resulted in a turbulence intensity of 20% at 2/3rds of the height of the building models.

Spectra of the longitudinal and lateral velocity components were measured and showed good agreement with the von Karman form of the atmospheric turbulence spectral equations. Integral length scales were determined at the top of the model and converted to full-scale values. The u-component measured integral length scale was 75 m compared to a target value of 116 m, and the v-component integral length scale was 42 m, compared to the target value of 42.5m. Thus the wind tunnel flow was a good representation of full-scale.

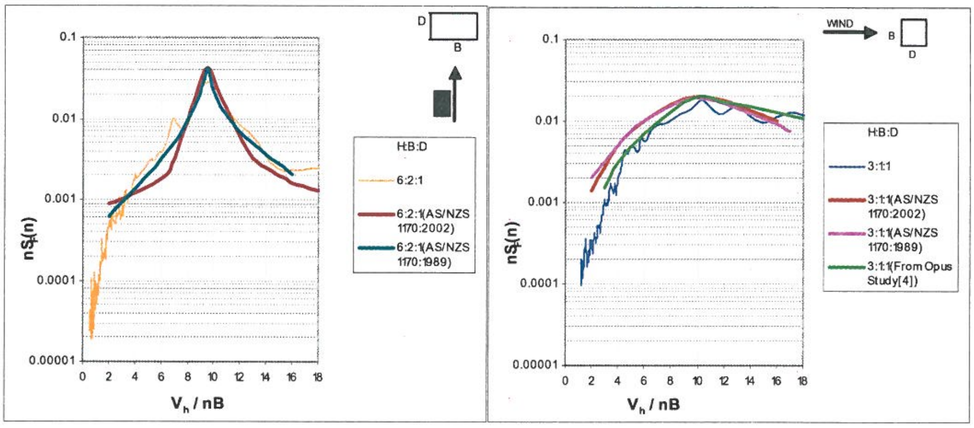
A six-component JR3 force balance [15] was used for the measurements. The JR3 force balance is a monolithic aluminium device instrumented with metal foil strain gauges which sense the loads imposed on the sensor. The strain gauge signals are connected to the external amplifier and signal conditioning equipment through the sensor cable. The electronic system connected to an analogue to digital converter card in a computer. The manufacturer's calibration was checked and found to be accurate, so it was used to convert the balance voltages to forces and moments. Models of the buildings were made of blue foam (trade name Styrofoam) glued to an aluminium alloy base and vertical spine. The natural frequency of the combined balance/model system was in the range 50 – 150 Hz, depending on the size of the model, which was lower than ideally desired, but acceptable for the present study.

3.3 *Results of force balance study*

Figure 1 compares the measured spectra with those given in the Australasian wind loading standard. It can be seen that the comparison is very good. However, in the case of the 6:2:1 model it is evident that the present measurements show better agreement with the 1989 version [4] of the codified spectra, rather than with the 2002 version of the standard [2].



(a) Generalised cross-wind force spectra (6:1:1) (b) Generalised cross-wind force spectra (6:1:2)



(c) Generalised cross-wind force spectra (6:2:1) (d) Generalised cross-wind force spectra (3:1:1)

Figure 1 Direct comparison of cross-wind force spectra measured in the wind tunnel and given in the wind load standard (Turbulence Intensity: 20% at (2/3) Height)

Figure 2 shows the effect on the spectra of varying the after-body length. It is evident that the spectra are fairly consistent at values of reduced velocity below the reduced velocity of the peak, but that there is a strong effect on the spectral density at high reduced velocities. The same effect of increasing after-body length is also evident in the low aspect ratio 3-series results shown in Figure 3. These and other figures also show some spikes at low values of reduced velocities. These are due to resonant frequencies of the balance/model system, and do not appear to have affected adjacent results. Hence they have not been filtered out.

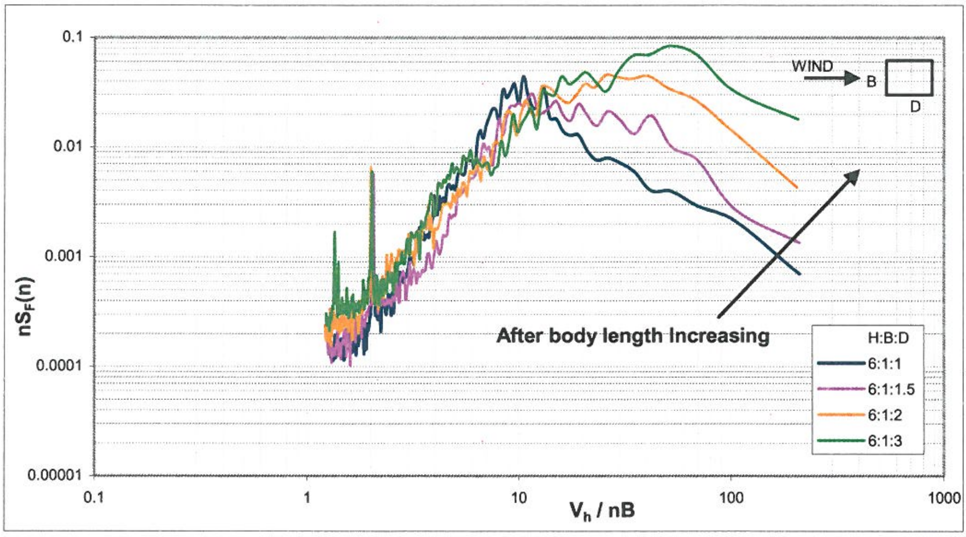


Figure 2 Generalised cross-wind force coefficient spectra of 6-series building models - afterbody increasing in length (Turbulence Intensity: 20% at (2/3) Height)

Figure 3 Generalised cross-wind force coefficient spectra of 3-series building models - afterbody increasing in length (Turbulence Intensity: 20% at (2/3) Height)

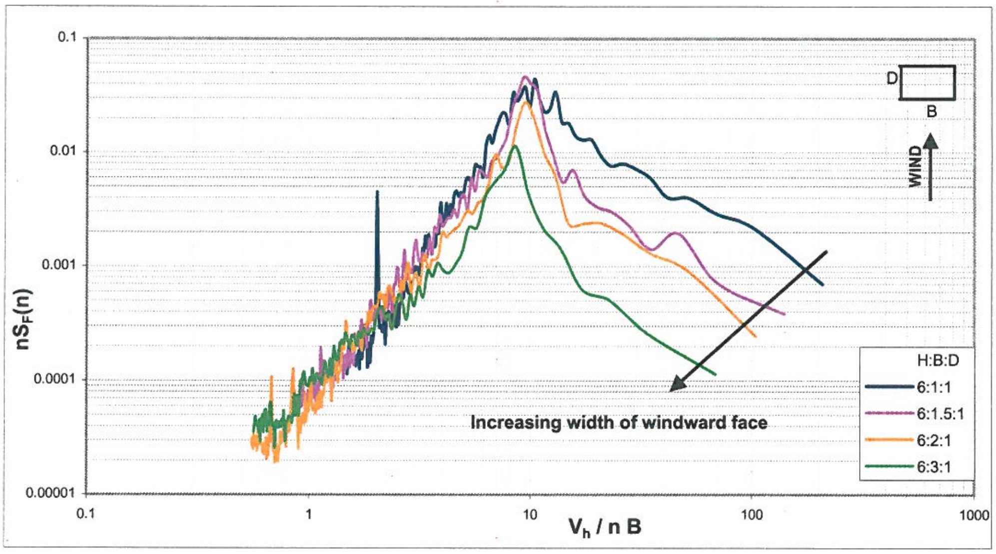


Figure 4 Generalised cross-wind force coefficient spectra of high aspect ratio buildings-width of windward face increases (Turbulence Intensity: 20% at (2/3) Height)

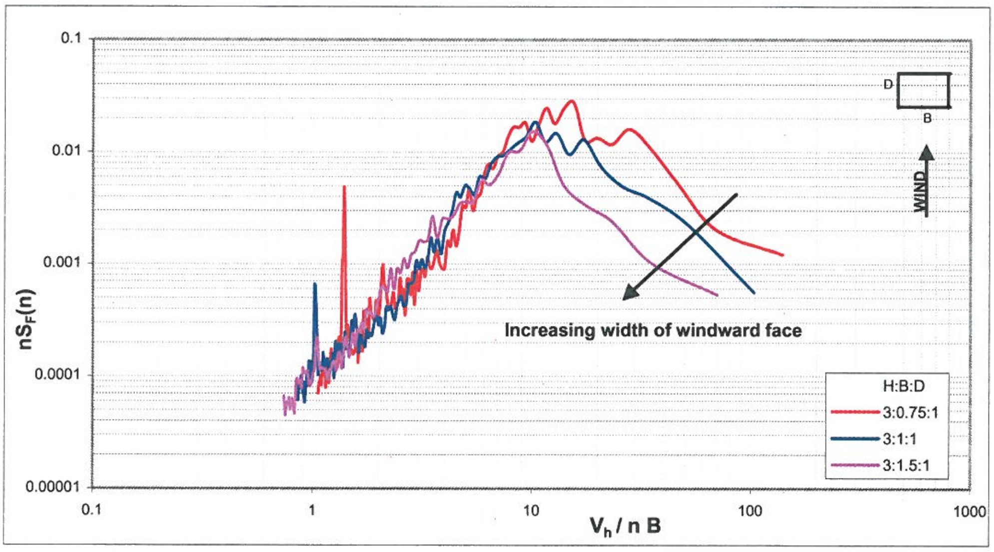
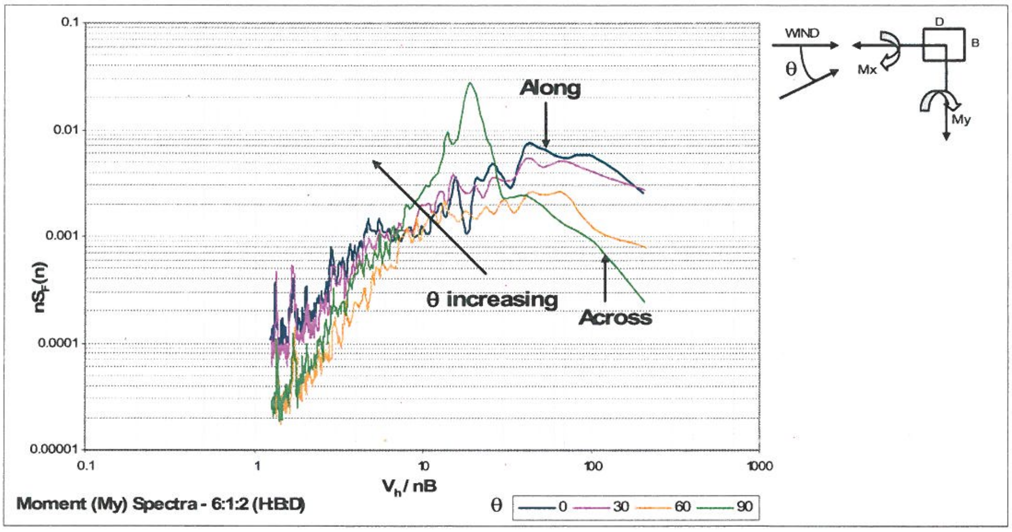
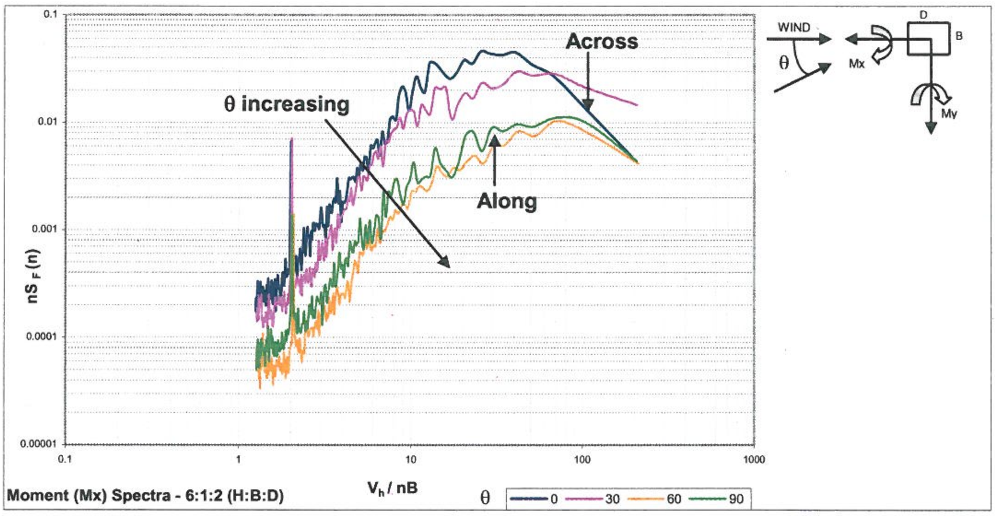


Figure 5 Generalised cross-wind force coefficient spectra of low aspect ratio buildings-width of windward face increases (Turbulence Intensity: 20% at (2/3) Height)

Figures 4 and 5 show cross-wind force spectra when the wind is normal to the wide face. Again the spectra are fairly consistent at reduced velocities below the reduced velocity of the peak, but there is a strong affect of the width of the windward face at high reduced velocities.



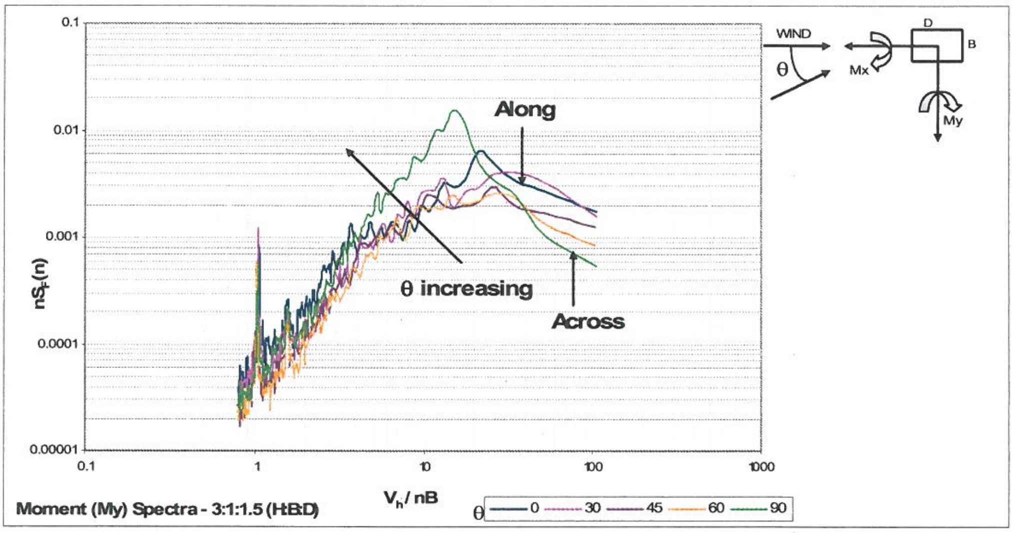
(a) Generalised base moment (My) spectra for 6:1:2 model



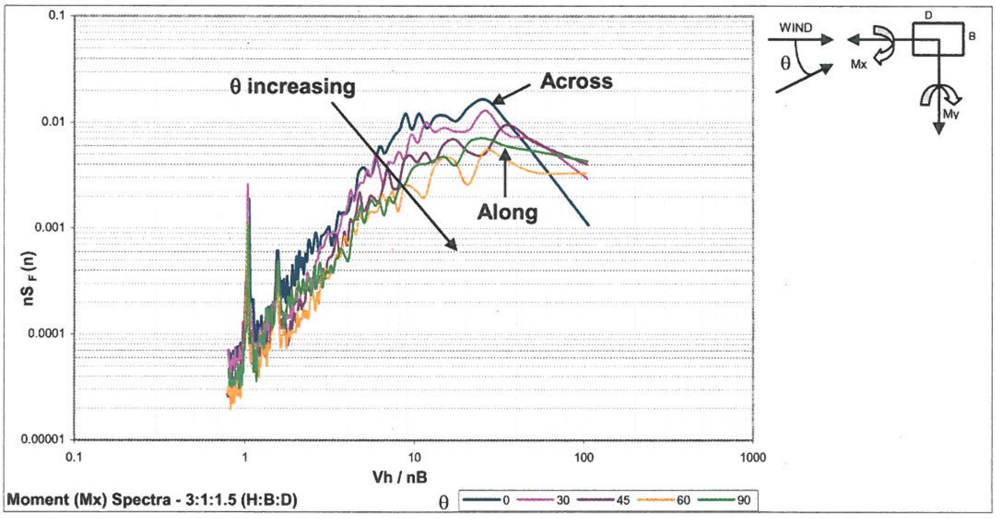
(b) Generalised base moment (Mx) spectra for 6:1:2 model

Figure 6 Generalised Moment Spectra of Building with an Aspect Ratio of 6:1:2 for Different Wind Directions (θ) (Turbulence Intensity: 20% at (2/3) Height)

Figure 6 shows the effect of wind direction on the cross-spectrum for a 6:1:2 model. Figure 6(a) shows the overturning moment *My*, which goes from along-wind for $\theta = 0$, to across-wind when $\theta = 90°$. Figure 6(b) shows the overturning moment *Mx*, which goes from across-wind for $\theta = 0$, to along-wind when $\theta = 90°$. It is interesting to observe that there are two groups of results in this figure. The results for $\theta = 0$ and 30° behave similarly, as do the results for $\theta = 60$ and 90°.



(a) Generalised base moment (My) spectra for 3:1:1.5 model



(b) Generalised base moment (Mx) spectra for 3:1:1.5 model

Figure 7 Generalised Moment Spectra of Building with an Aspect Ratio of 3:1:1.5 for Different Wind Directions (θ) (Turbulence Intensity: 20% at (2/3) Height)

Similar results for the effect of wind direction on the cross-spectrum of the 3:1:1.5 model are evident for this lower aspect ratio model shown in Figure 7 as for the results in Figure 6, except that they are less pronounced presumably because the flow is more three-dimensional for this lower aspect ratio model. Figure 7(a) shows the overturning moment *My*, which goes from along-wind for $\theta = 0$, to across-wind when $\theta = 90°$. Figure 7(b) shows the overturning moment *Mx*, which goes from across-wind for $\theta = 0$, to along-wind when $\theta = 90°$.

It is clearly evident in all the figures that when plotted in a log-log format, the spectra can be extrapolated to lower values of reduced velocity with a straight line. This is a very significant and useful result, as it means that the curves in the standards can be extrapolated to values of reduced velocity below 2 using this method.

The additional results obtained for the other building configurations are not included herein due to space, but are available in the masters thesis [16].

4 CONCLUSIONS

This research is mainly concerned with the cross-wind excitation of medium-rise buildings at the lower values of the reduced velocity i.e. reduced velocities less than 2. Based on the work carried out in these studies, the following conclusions can be deduced:

Cross-wind force coefficient spectra for various aspect ratio buildings, namely 6:1:3, 6:1:1.5, 6:3:1, 6:1.5:1, 3:1:0.75, 3:1:1.5, 3:0.75:1, 3:1.5:1 which are not included in the wind loading standard AS/NZS 1170:2002 were measured.

Cross-wind force coefficient spectra obtained from the force balance showed good agreement with spectra given in the wind loading standard for the building models with aspect ratios of 6:1:2, 6:2:1, 6:1:1, 3:1:1. This good agreement provides confidence that the other spectra measured for building models with aspect ratios of 6:1:3, 6:3:1, 6:1:1.5, 6:1.5:1, 3:1:1.5, 3:1.5:1, 3:1:0.75, 3:0.75:1 can be used for the structural design purposes.

The spectrum measured from the model with an aspect ratio of 6:2:1 showed good agreement with the corresponding spectrum given in AS/NZS 1170:1989 but did not agree with the spectrum given in AS/NZS 1170:2002. It is suggested that the spectrum in AS/NZS 1170:1989 is more appropriate for this building shape.

5 ACKNOWLEDGEMENTS

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