New Zealand Economy Report on Wind Engineering Activities for APEC-WW 2012

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ABSTRACT: This paper summarises the major wind engineering activities that have been undertaken in New Zealand over the past two years. Wind Engineering activities are carried out by universities, government organizations, and also by private companies. In the past two years three major activities that have continued. The wind speedup over hills project, funded by the NZ Natural Hazards Platform is continuing. It is a collaboration among GNS Science, NIWA, Opus International Consultants, and the University of Auckland. Two of the continuing projects are full-scale building monitoring projects. The first project is a collaboration among GNS Science, NIWA and the University of Auckland. The second project is a collaboration between Opus International Consultants and the University of Auckland. Another major activity is the Riskscape project being carried out by GNS and NIWA. In addition there are a number of smaller research projects that are underway at the University of Auckland, being done by faculty and students, such as cross-wind excitation of buildings, internal pressures, damage from wind-blown debris.

KEYWORDS: New Zealand, cross-wind excitation, internal pressures, CFD, wind turbine, riskscape, natural hazards, wind speed-up over hills, windborne debris.

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1 INTRODUCTION

This report summarises research and other work carried out in New Zealand over the period 2011 - 2012 since the previous APEC-WW 2010 [1] meeting at Kwandong University, Institute of Environmental Research (DAEWON), 522, Naegok-dong, Gangneung-city, Gangwon-do 210-701, South Korea. It is based on information received from active Wind Engineers in various organisations in New Zealand. Because it is a report on various wind engineering activities, it is not particularly detailed, due to the length that such detail would require. Interested readers who would like further information are encouraged to refer to the references, contact the author of this report, or contact the organisations and individuals mentioned in it.

2 WIND TUNNEL INVESTIGATION OF CROSS-WIND EXCITATION OF BUILDINGS

This research has been progressed further by a masters student, Mr Varun Jain, under the supervision of Prof. Richard Flay at the University of Auckland, and is a continuation of the masters research project by other students [2,3,4,5]. The current method used in New Zealand to determine the cross-wind excitation and response is described in AS/NZS1170.2:2010

[6]. One determines the reduced velocity, $V_r = V_h/(Bn_c)$ (where V_h is the wind speed at the top of the building, B is the building width normal to the wind, and n_c is the first mode cross-wind natural frequency) and then reads off the generalised force coefficient C_{fs} from an appropriate graph.

C_{fs} is a function of aspect ratio and only a few aspect ratios are available. Often the aspect ratios required are more 'slab-like' than those provided, such as the 51m:23.5m:7.4m (6.9:3.2:1) shape proposed for Auckland's CBD. This causes problems as the most common method for getting C_{fs} information uses the High Frequency Force Balance method which requires models to be as light and stiff as possible so that the model/balance natural frequency is well above the frequencies of interest. 'Slab-like' models are generally less stiff than conventional more compact shapes and thus can have first mode natural frequencies that lie within the region of interest of reduced velocities. Determining C_{fs} from multi-channel pressure measurements offers an advantage for investigating the generalised force spectrum for 'slab-like' aspect ratio buildings because the upper frequency range is not dependent on model stiffness, but on the frequency response of the tubing system. Thus potentially, high frequencies, corresponding to low reduced velocities are obtainable.

Thus the aim of this investigation was to measure C_{fs} for lower reduced velocities for aspect ratios available in the standard, as well as for more 'slab-like' shapes, and also to compare the spectra measured from the HFFB method with those obtained from multi-channel pressure measurements. Considerable effort has been expended trying to build stiff models and to eliminate noise from the signals, so that reliable results can be obtained from the wind tunnel, even at low wind speeds. Further details are available in [1,2,3,4,5]

3 INTERNAL PRESSURE IN LOW AND MEDIUM RISE BUILDINGS SUBJECTED TO HIGH WINDS

As reported in the 2010 APEC-WW NZ Economy report [1], Research on internal pressures in low and medium rise buildings is being carried out by Mr Tushar Kanti Guha for his PhD, under the supervision of Dr R.N. Sharma and A/Prof. Peter J. Richards. The research currently underway combines wind tunnel testing with some full scale tests. Some data were gathered at full scale on the large instrumented Tamaki wind tunnel building, with and without the roller door open. Wind tunnel tests are looking at the influence of background leakage, secondary openings, flexible envelope, and internal partitioning on characteristics of internal pressure; to be compared with code provisions. A recent focus has been on the internal dynamics of a leaky and quasi-statically flexible building with a dominant opening. Figure 1 shows a model with a flexible Styrofoam roof being subjected to tests in The University of Auckland's wind tunnel. The theoretical findings from this study have been validated by carrying out full-scale tests in the warehouse housing the Twisted Flow Wind Tunnel, and a 1/100th scale model (Figure 2) of the warehouse has also been subjected to wind tunnel tests. This research has resulted in a number of publications [7-13] since the last report.

Among the findings of this research has been shown the extent of the damping effects of "skin" flexibility and background leakage in moderating the internal pressure response under high wind conditions using design examples involving a typical industrial warehouse. While the effect of envelope flexibility is shown to lower the Helmholtz frequency of the building volume-opening combination, the lowering of the resonant peak in the internal and net roof pressure coefficient spectra is attributed to the increased damping in the system due to inherent background leakage and flexibility in the envelope. A significant anti-correlation is however, found to exist between the internal and the roof external pressure fluctuations in all cases studied, thus exhibiting the possibility of increased nett loads on the roof surface.

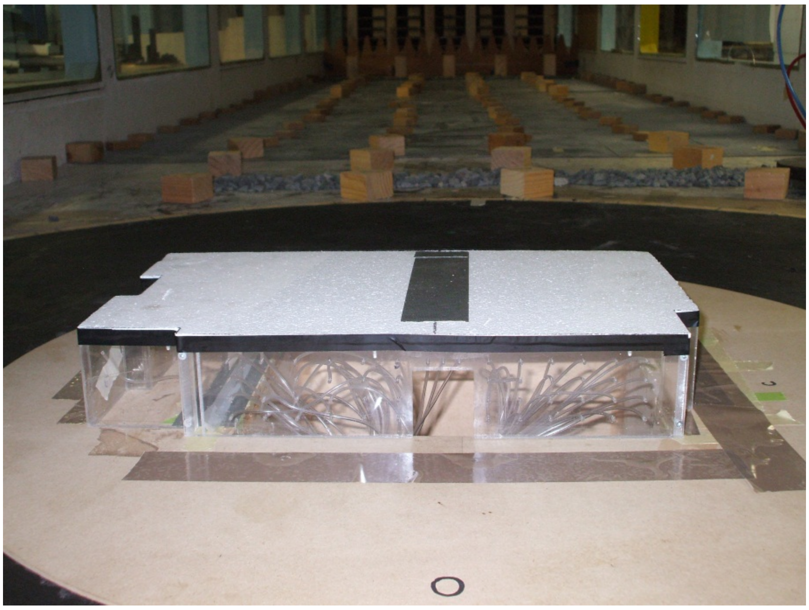

Figure 1: Model with a flexible Styrofoam roof inside the de Bray wind tunnel

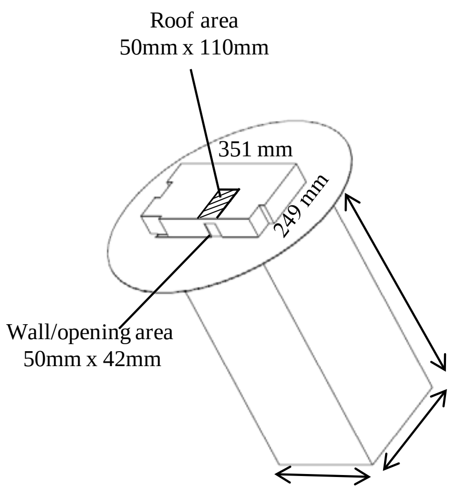

Figure 2: A 1:100 scale wind tunnel model of the TFWT building with volume scaling

4 WINDBORNE DEBRIS

There is continuing interest in windborne debris among wind engineering researchers, due to the fact that debris cause damage during storms, resulting in considerable cost to the community. Research on windborne debris has been underway at The University of Auckland of Auckland for several years, under the supervision of A/Prof. Peter Richards, and in collaboration with colleagues at the University of Birmingham, UK. The research in NZ has involved both theoretical studies that aim to predict the path of the debris, given certain information such as aerodynamic coefficients, shape, density, and wind speed etc., and experimental studies in the large 7m x 3.5 m wind tunnel at The University of Auckland. In these experimental studies the trajectory of debris is recorded using high speed video.

The paper 'The flight of roofing tiles during strong winds' reports a study which combines a CFD computed wind field with a trajectory model for roofing tiles. Figures 3 and 4 below illustrate some of the results.

Figure 3 shows the computed trajectories of clay tiles originating from the centre of the windward eaves of the 4.5 m high building assuming a range of gust wind speeds. As might be anticipated the stronger gusts lift the tiles more and carry then a much greater distance. With the weakest gust the tile barely clears the ridge and quickly drops into the wake of the building and falls to the ground. In Figure 4 the ratio of the tile's horizontal speed to the gust wind speed shows that not only does a weaker gust induce lower speeds but even the proportion is lower. With a 35 m/s gust the tile barely exceeds 40% of the gust speed whereas at 65 m/s the tile reaches 95% of the gust speed.

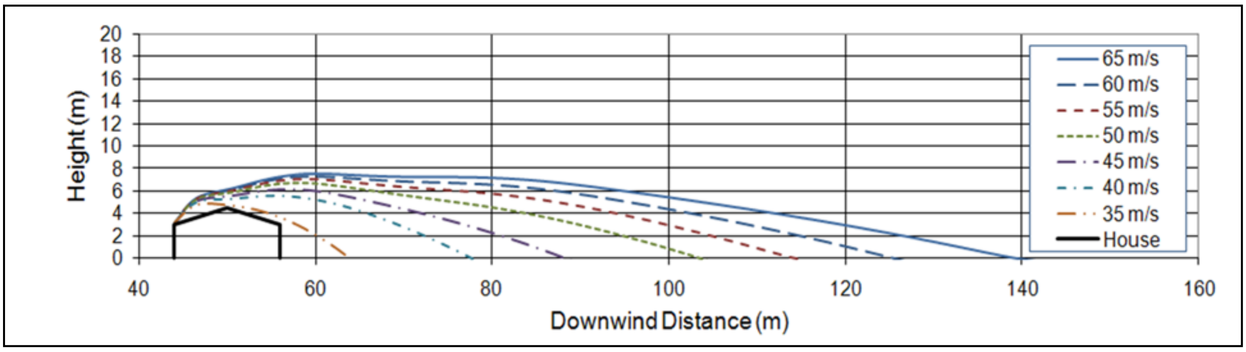

Figure 3. Computed trajectories of clay tiles originating from the windward eaves of the 4.5 m building with various gust wind speeds. Wind direction is perpendicular to the ridge.

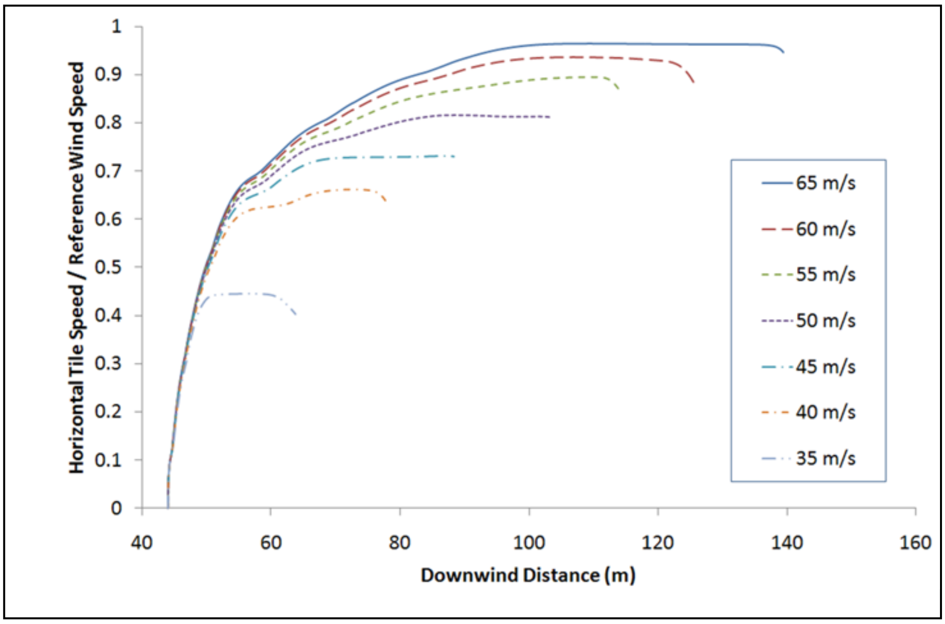

Figure 4. Ratio of clay tile horizontal speed to the reference gust speed as a function of downwind distance for the same cases as in Figure 3.

Further information on this research may be found in [14-17].

5 OTHER RESEARCH AT THE UNIVERSITY OF AUCKLAND

Research in other areas is also carried out by faculty at the University of Auckland. Some of these areas have been mentioned in previous NZ Economy reports such as in [1]. Although not strictly perhaps regarded as wind engineering, research is continuing on telescopic blade wind turbines. Such turbines are designed to have blades which extend when the wind speed is low, thus increasing the swept area, and giving significant increases in the capacity factor. Recent publications in this area are available at [18-22].

For some time, Richards and Norris have been interested in appropriate boundary conditions for CFD applications, and they updated an earlier paper in 2011 [23]. This topic has also been of interest to others, particularly in regard to wind flow over hills, and has been the subject of a PhD study with the thesis submitted in 2011 [24].

In collaboration with colleagues in the UK, Richards has worked on wind loading on the Silsoe cube, and related wind loading studies, and this research has resulted in a series of recent publications [25-27].

The Yacht Research Unit at The University of Auckland has built up a good reputation for its research on yachts and sails in order to improve the performance of elite yachts for prestigious races such as the America's Cup and the Volvo Round the World Race. While this is not really wind engineering, it is worth noting that many of the ideas and techniques that are used for the yacht research are related to and have developed from techniques that are used in wind engineering. In fact largely the same researchers are involved in both wind engineering and yacht engineering research, and use the same wind tunnels and instrumentation. One important difference is that it is very much more difficult to carry out full-scale experiments on sailing yachts, due to the harsh environment of the sea, the motion of the yacht, and the effects of salt water in electronics. For further information about yacht research publications, interested readers are advised to contact the author.

6 MONITORING OF WIND-INDUCED MOTION OF TALL BUILDINGS IN NEW ZEALAND

This research project has been aimed at monitoring the wind-induced building motion of five tall buildings between 2009 and 2012: four in Wellington and one in Auckland. The buildings were selected to be fairly representative of tall buildings in New Zealand; buildings which are known to experience high accelerations were not selected for the study. The measured accelerations were compared with acceptability criteria from ISO Standard 10137:2007. The accelerations were within the acceptability criteria for four of the buildings, and exceeded the criteria by about 20% for the fifth building. The relationship between wind speed and acceleration has been examined for three of the buildings. The measured wind-induced accelerations are approximately proportional to the cube of the wind speed, demonstrating that accurate estimation of the wind speed is critical for accurate design predictions of wind-induced building motion. Various aspects of the design of tall buildings with the potential to cause high accelerations have been discussed.

The research is being done is a collaboration between Opus International Consultants, GNS and the University of Auckland. The research is funded by the Building Research Association of New Zealand (BRANZ), and has been driven mainly by Carpenter and Cenek at Opus, with assistance from Flay at The University of Auckland. The following sections are excerpts from [28]. Further details on New Zealand building monitoring research projects are also available in [29-31].

6.1 *Selection of the buildings*

Two of the buildings which have been analysed are part of the New Zealand GeoNet project. The instrumentation was not specifically installed for the wind motion research. It was fortunate that data from these buildings became available for inclusion in this study.

Three of the buildings were specifically chosen by Opus and University of Auckland for wind motion research. The factors which were considered in selecting these buildings were as follows:

- Two buildings in Wellington were chosen, primarily due to the high proportion of windy conditions in Wellington.
- One building in Auckland was also selected, to provide a wider geographical spread of buildings.
- Some New Zealand buildings have been reported to us as having high or uncomfortable motion in strong winds. We made a decision not to focus on these buildings, preferring to study representative tall buildings which could have wind-induced motion at around the acceptability criteria limits. Consequently, none of the buildings that we studied had been previously reported to us as having detectable wind-induced motion.
- The equipment was located on the building roofs, where it would not typically be noticeable to building users. Buildings with sloping roofs, or with roofs where access was unsafe were therefore unsuitable.
- Relatively modern buildings were chosen, less than 20 years old.
- Some building owners decided that there was a risk of adverse publicity if it became known that their buildings were being investigated for wind-induced motion, and therefore declined our request for access. Consequently, we made it standard practice in our approach to building owners, that it was stated that the buildings would not be named in publications arising from the research.

6.2 *Description of the buildings*

The five buildings which have been analysed are referred to as Buildings A, B, C, D and E, which are listed in the order that monitoring commenced. As part of our agreement with the building owners, these buildings have not been named.

Building A is in Wellington. It is 10 storeys high, with a rectangular planform, and a steel frame structure. Monitoring as part of the New Zealand GeoNet project has been ongoing since early 2009.

Building B is in Wellington. It is 25 storeys high, with an approximately square planform, and has a structure consisting of concrete perimeter columns with a central core. It was monitored by Opus during the period from 21 August 2009 to 15 October 2009.

Building C is in Wellington. It is 17 storeys high, with an approximately square planform, and has a concrete structure including a wall on one side, and an offset core adjacent to the concrete wall. It was monitored by Opus during the period from 21 October 2009 to 22 February 2010.

Building D is in Auckland. It is 25 storeys high, with a rectangular planform, and has a concrete structure. It was monitored by Opus during the period from 20 October 2010 to 27 May 2011.

Building E is in Wellington. It is 28 storeys high, and has a concrete structure. Monitoring as part of the New Zealand GeoNet project has been ongoing since early 2012.

Multiple modes of vibration have been identified for each building through analysis of the motion time histories. The measured X, Y and Torsion frequencies for each building are listed in Table 1.

A notable feature of these measured frequencies is the low torsion frequency of Building C. The frequencies in the Y direction and in torsion are the same, indicating that the building oscillates with coupled mode response, producing a motion similar to that of a windscreen wiper blade.

Table 1: *Measured X, Y and Torsion frequencies for the five buildings*

Building	X direction	Y direction	Torsion
A	1.56 Hz (~EW)	1.42 Hz (~NS)	2.10 Hz
B	0.55 Hz (~NS)	0.54 Hz (~EW)	0.84 Hz
C	0.63 Hz (~NS)	0.65 Hz (~EW)	0.65 Hz
D	1.09 Hz (~NS)	0.79 Hz (~EW)	1.41 Hz
E	0.44 Hz (~NS)	0.46 Hz (~EW)	0.68 Hz

Table 2: *Summary of accelerations measured during the single biggest building-motion event for each building.*

	Building				
Measured	A	B	C	D	E
X direction at centre of building (milli-g)	2.1	1.1	1.8	0.6	3.2
Y direction at centre of building (milli-g)	3.2	2.9	3.0	1.3	4.3
Combined XY at centre of building (milli-g)	3.3	2.9	3.6	1.3	4.4
Acceleration at the corners due to torsion (milli-g)	2.3	0.7	3.6	0.5	2.9
Corner (max acceleration at either corner) (milli-g)	3.6	3.2	5.8	1.7	6.2
Amplitude at centre of building (mm)		5.4	3.8	1.2	10.5
Date	23 May 2009	26 Aug 2009	08 Jan 2010	18 Apr 2011	8 Sept 2012
Airport mean wind speed (m/s)	23	16	14	14	18
Airport wind direction	210	300	340	240	340

6.3 *Data Analysis*

Table 2 lists a summary of accelerations measured during the single biggest building-motion event for each building. The most extensive data was obtained for Buildings C and D.

Note:

1. Accelerations in torsion are measured at the corners of the building, relative to the centre of the building.
2. Auckland reference wind speed was measured at Whenuapai Airport

Figure 5 shows a 100 s period of accelerations measured for one of the biggest acceleration events for Building C. It may be seen that the amplitude of the oscillation of the building rises to a peak and then decays over a period of about 30 seconds. This type of behaviour is fairly typical. Building C is unusual in that the measured accelerations in torsion were higher than either the X or Y accelerations.

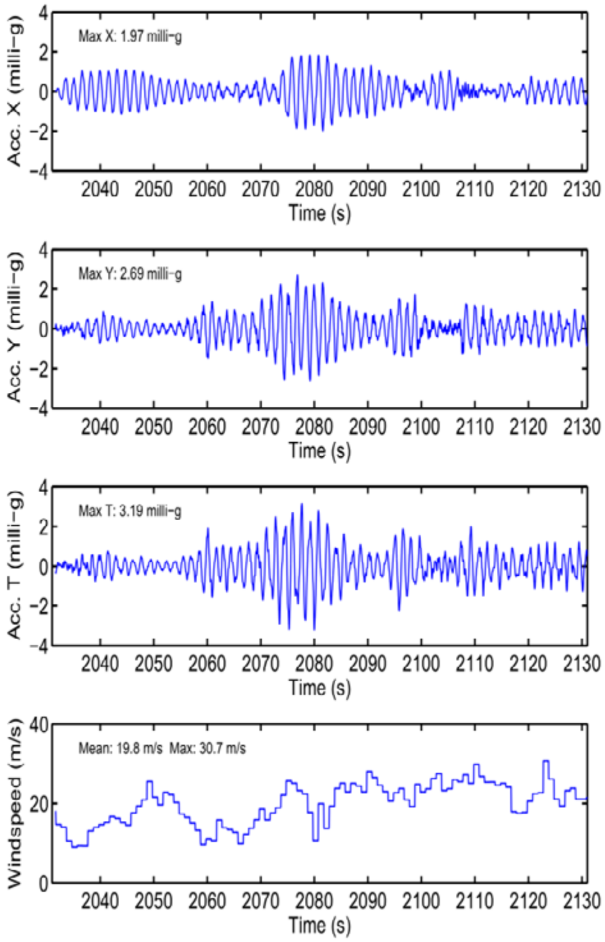

Figure 5: Building C. Accelerations recorded 13 Feb 2010 10:45am. (X at building centre, Y at building centre, Torsion, Wind speed on roof.)

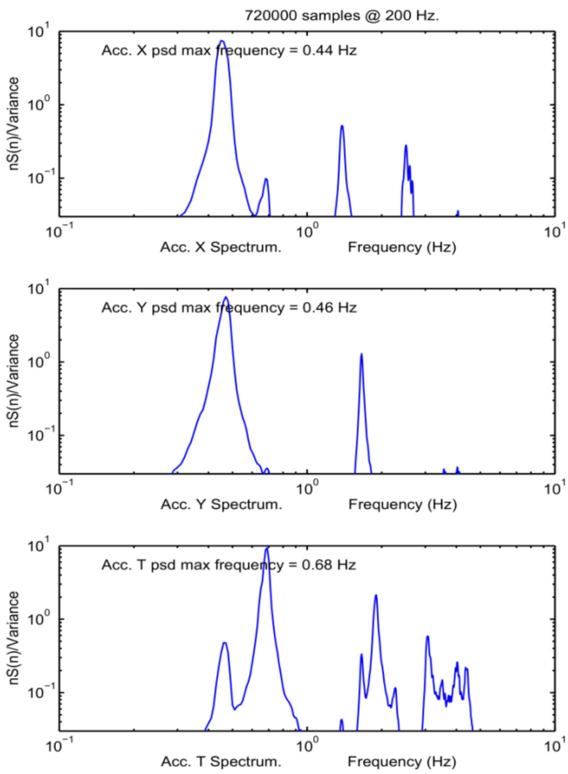

Figure 6: Building E. X, Y and Torsion frequency spectra.

Figure 6 shows the X, Y and Torsion spectra for Building E. These measured frequencies are about 25% higher than was estimated in the original design calculations. The X and Y mode frequencies are similar, while the torsion mode frequency is about 50 % bigger. There is some crossover of the signals apparent i.e. X and Y frequencies in the torsion spectra. About 8 mode frequencies can be clearly identified in the figure.

Figure 7 shows the building displacement at the centre of Building E over a period of 10 seconds. The 5 s prior to the maximum acceleration is shown in black, and the 5 s after it is shown in red. This displacement has been calculated by integration of the acceleration data. Therefore the displacement shown is only that due to the motion of the building, and does not include any mean displacement due to wind loading. It may be seen in Figure 7 that the orientation of the building oscillation slowly rotates in a clockwise direction. This is due to the similarity of the X and Y modal frequencies.

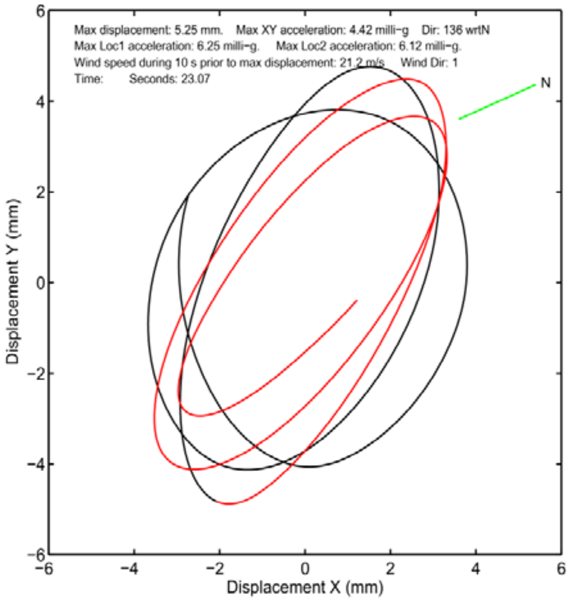

Figure 7: Building E. Plot of largest measured displacement at the centre of the top floor of the building, showing 10 seconds of recording. (Black changing to red at maximum displacement).

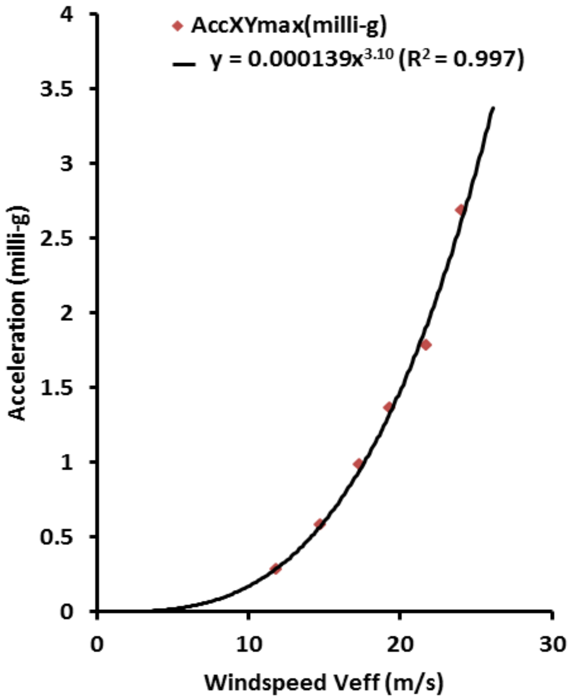

Figure 8: Building C. Relationship between wind speed and acceleration. Data averaged into acceleration bands.

6.4 *Relationship between wind speed and acceleration*

The relationship between wind speed measured on the roof of the building, and the acceleration at the centre of the roof of the building, has been analysed for Buildings B, C and D. This has been done for all hours when the 1-hour mean wind speed at the building for northerly winds exceeded 7 m/s for Buildings B and C, and exceeded 4m/s for Building D. There were 55 hours of data in this category which were recorded for Building B, 535 hours for Building C, and 588 hours for Building D. Data for lower wind speeds has been omitted mainly because, at the lower wind speeds, accelerations measured due to the operation of machinery on the building roofs was greater than the accelerations due to wind. Data identified as associated with earthquakes was also omitted. This analysis has been done for various wind speed measures. The best correlation, on average, was achieved by using the so-called "effective wind speed" measure of wind speed (the average of the 1-hour mean wind speed and the maximum gust speed in the hour).

The data was analysed by averaging the measured accelerations into bands, so that measurements in each band were given equal weighting. For Buildings B and C, these bands are 0.4 milli-g wide for accelerations up to 2.0 milli-g, with all the data above 2.0 milli-g averaged together. For Building D, the bands are 0.15 milli-g wide for accelerations up to 0.9 milli-g, with all the data above 0.9 milli-g averaged together. The resulting plot for Building C is shown in Figure 8. There was a very good power-law fit to the band-averaged data for all three buildings.

The exponent of the power-law fit calculated for the band-averaged data is as follows for the three buildings for which we have sufficient data to do this analysis:

Building B	2.89
Building C	3.10
Building D	3.18

For the three buildings combined, the average exponent of the power-law fit is 3.06. The measurements consequently confirm our expectation that the exponent would be close to 3 for these buildings, as proposed by Cenek et al [32].

Irwin [33] has shown data for very tall buildings (much taller than the buildings in the current study) with exponent of around 3 for buildings without vortex excitation, and also shows the effect of wind speed increasing dramatically when vortex excitation occurs, so that a 10% increase in wind speed can cause a doubling (i.e. an exponent of about 7) of the resulting building acceleration within the wind speed range where vortex excitation occurs.

The wind loading standard [6] includes a complex method for predicting wind-induced motion of tall buildings. It subdivides the analysis into along-wind and across-wind components. The estimation of the across-wind acceleration is usually much larger than the estimation of the along-wind acceleration. For the type of buildings that have been monitored, and in the wind speed range that occurred during the monitoring, the standard predicts an increase in acceleration with increasing wind speed with an exponent of around 2.3 to 2.4. The standard therefore under predicts the effect of increasing wind speed for these buildings. However the method also typically overestimates the predicted 1-year accelerations, and consequently the overestimation reduces for longer return periods. The observation can also be made, in relation to the emphasis in the wind loading standard on across-wind forces, that no particular indication of resulting across-wind oscillations is apparent in the full-scale data.

6.5 *Predictive Equation for Accelerations*

A predictive equation was developed in 1989 [32] which uses 1-hour mean wind speed in the analysis, which was consistent with the dynamic analysis procedures in the wind loading standard at that time. Based on the present work, a revised predictive equation is presented, Eq (1), which can be used with a one-year return period gust speed from [6], and some basic building dimensions, in order to estimate the acceleration in a very simple manner. The equation is:

$$a = \frac{0.113 V_{des,1-year}^3}{f m_0} \tag{1}$$

where $V_{des,1\text{-}year}$ may be calculated using AS/NZS 1170.2.

It is instructive to apply this revised predictive equation to consider a hypothetical slender tall lightweight apartment building (say about 100 m tall) with characteristics as follows:

f = 0.4 Hz
$V_{des,\,1\text{-}year}$ = 40 m/s
ρ_b = 200 kg/m^3
A = 400 m^2
$\therefore\ m_0$ = 80000 kg/m

The predicted acceleration using equation (1) is 23 milli-g. This is therefore nearly 4 times the limit acceleration for this building of 6.1 milli-g from ISO 10137. The wind-induced motion of this building would clearly be very unsettling for the occupants of the upper floors.

As previously noted, the buildings that have been monitored for the current study are all of fairly representative shape and size, and do not produce the very high accelerations of the lightweight slender hypothetical building suggested above. The validity of the prediction for such buildings therefore remains in doubt, with potential for significantly higher accelerations to occur.

Note also that the frequencies that have been used in this calculation are the measured 1st mode frequencies for each building. We have commented that the measured frequencies are typically higher than those estimated in structural design calculations. One should therefore be aware that use of the design calculation frequencies are likely to calculate somewhat higher accelerations.

6.6 *Conclusions*

This paper describes the results of monitoring the wind-induced building motion of five tall buildings between 2009 and 2012: four in Wellington and one in Auckland. The buildings were selected to be fairly representative of tall buildings in New Zealand; buildings which are known to experience high accelerations were not selected for the study.

The measured accelerations were compared with acceptability criteria from ISO Standard 10137:2007. The accelerations were within the acceptability criteria for four of the buildings, and exceeded the criteria by about 20% for the fifth building.

The relationship between wind speed and acceleration has been examined for three of the buildings. The measured wind-induced accelerations are approximately proportional to the cube of the wind speed for all three buildings for which the relationship was examined. This demonstrates that accurate estimation of the wind speed is critical for accurate design predictions of wind-induced building motion.

Various aspects of the design of tall buildings with the potential to cause high accelerations have been discussed.

7 WIND SPEED UP MEASUREMENTS OVER BELMONT HILL IN COMPLEX TERRAIN

This section presents results from a research project which compares measured wind speedups over the rugged Belmont hills in the Wellington area of New Zealand with wind speedups estimated using the AS/NZS1170.2 loadings code by two organisations. It was found that the AS/NZS1170.2 predictions differed significantly between the organisations. Extensive work was also carried out to investigate the performance of CFD software in predicting wind speed up over the Belmont Hill for the 345°wind direction, but that information is not included herewith due to the space it would occupy.

7.1 *Introduction*

The aim of the research described in this section is to reduce the vulnerability of New Zealand's built infrastructure to wind damage through provision of improved design wind speed procedures. Wind flow in New Zealand is strongly influenced by the hilly terrain over which it passes, with both valleys and hill crests experiencing stronger, and in some instances much stronger, wind speeds than over flat terrain. Increased wind speeds are a potential hazard for towers and pylons used to support both infrastructure and communications equipment which are often located near or on hilltops. In New Zealand, at locations far from any wind measurements, design winds are frequently estimated for such proposed structures by applying the AS/NZS 1170.2 loadings standard [6] – a reference document for the NZ building code which prescribes the minimum loadings for buildings in NZ.

Within the Standard wind forces are prescribed as the product of the wind's dynamic pressure $(\frac{1}{2}\rho V^2)$ and a shape-related pressure coefficient, C_{pe}. Topographic enhancement is allowed for with a topographic multiplier, M_t ($1<M_t<1.71$ resulting in up to 3x wind force), which depends on the hill shape and steepness, and the distance of the site from the hill crest.

It also requires a Lee Multiplier, M_{lee} be applied within Lee Zones. While the physical basis for including these effects is clear, the method by which these factors are calculated is unfortunately weak and when determining Lee Zones possibly ambiguous. This fact combined with some recent severe wind events: 2004 Molesworth Windstorm [34]; 2007 Taranaki Tornadoes [35]; 2008 Greymouth windstorm [36]; the March 2010 Wellington southerly storm (in which gusts of 60 m/s and 77 m/s were recorded at Baring Head and Makara Wind Farm respectively – both with significant topographic effects involved); the 2011 Auckland EF2 tornado, also the inclusion of winds as hazard in RiskScape have caused renewed interest in wind engineering and a questioning of the guidance offered by the loadings code. Consequently the present research project was set up to provide the basis for reviewing the calculation methods in the Standard for M_t. Further details are available in the final report on the research project [37] and in a short conference publication [38].

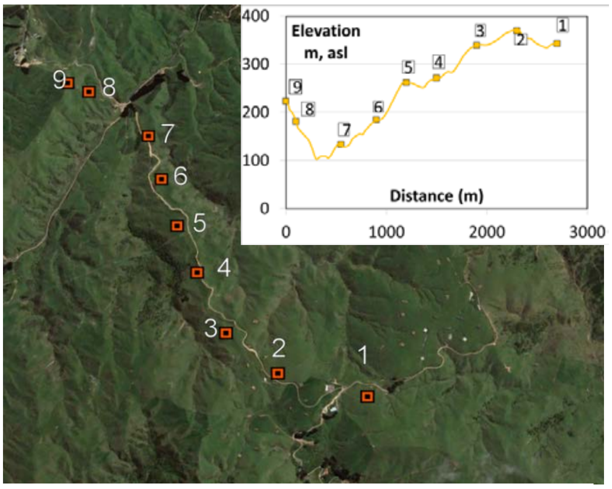

Figure 9: A Quickbird image (courtesy of KiwiImage) looking down on Belmont Regional Park near Wellington, with locations and profile of heights for the portable

Figure 10: View showing the area studied, looking directly upwind for the 345° wind direction, showing built up area in the background. Ridge used for masts is slightly to right of centre.

7.2 *Measurements of Wind Speedup*

The research project was focused on measurements and modelling of topographic speed-up effects within the Belmont Regional Park near Wellington. The area, shown in figure 9, is typical of much New Zealand hill country where important infrastructure is located. The terrain is not simple - a lower ridge upstream (in a North-wester) and approximately parallel to the highest elevations adds complexity to the situation in that turbulent eddies shed from this terrain feature near mast 9, should impact the gust characteristics downstream. Furthermore the valley behind this ridge could be expected to be somewhat sheltered. Vegetation was mainly short to moderate grass with the few trees and scrub in the vicinity confined to gullies giving a design wind terrain category of 2, according to [6], although the terrain perturbations are much larger than the terrain roughness.

Nine portable masts (5 m high) with Vector A101m 3-cup wind speed sensors (accurate to 1% in the 10-55 m/s range) and Vector W200P wind vanes (direction accurate to ± 3°) were deployed. Siting of the masts was aided to some extent by prior CFD modelling with Gerris under idealised NNW flow [39,40], but the main consideration was reasonable access to the masts from roads/tracks in the park.

7.2.1 *Full-scale Speedup Observations*

Several sets of full-scale measurements of wind speed were made over the first 6 months of 2011. While a design wind event was not anticipated in such a short period, several strong northerly/north-north-westerly events did occur although they were less frequent than normal due to the La Niña that dominated during this time. The paper focuses on the 18-hour observation period from 12 noon on February 6 to 6am on February 7, 2011 when the wind direction was approximately 345°. Figure 10 shows the site looking upwind for this direction. Three-second wind observations were collected at all 9 masts during this period. Means, maxima, standard deviations, turbulence intensity plus directions of average and maximum winds for this period are displayed in figure 3.

Figure 11 shows that: the wind direction is nearly constant across the grid from about 345° except at the sheltered masts 6, 7 and 8; the average speed and the maximum gust vary very similarly across the masts; the standard deviation (STD) of the wind speed is fairly constant at about 2.5 m/s across all the masts; the maximum gust at each mast is given within a few % by the mean speed plus 3.7*STD.

In order to determine hill-shape multipliers based on these observations, an estimate of the wind at a 5 m elevation at a neighbouring site at a location not affected by the Belmont Hills was required. Wellington Airport has one of the most reliable wind records in the region and earlier research [41,42], indicates that the winds there are in general larger by a factor of 1.1 compared to neighbouring locations unaffected by topography. Hourly means and maximum wind gusts are available at 7 m at Wellington Airport so in order to establish the speedups as determined by the observations, these values were adjusted to a height of 5 m and by the 1.1 channelling factor mentioned above for each of the 18 one-hour periods for which the Belmont observations were available. The full-scale measured gust speedups are given in figure 12.

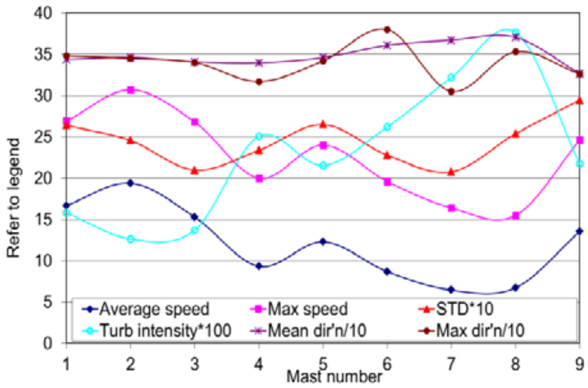

Figure 11: Belmont wind statistics for 18 hour period during 6 - 7 Feb 2011.

7.2.2 *AS/NZS 1170.2 Loadings Standard Speedup Estimates*

The Wind Loading Standard [6] has provision for determining the effect of hills on the wind speed. It is a simplified approach, based on various published data from a number of wind tunnel tests, as well as full scale measurements. When one attempts to apply this procedure to the Belmont Hill that was used for the full-scale experiments, it is immediately apparent that the procedure is very difficult to apply. The procedure is based on 2D hills, whereas the Belmont Hill is very much 3D. Furthermore, the full-scale measurements are along a ridge as shown in figures 9 and 10.

The approach in the Standard requires the user to look upwind over an arc of +/- 22.5° with respect to the direction under consideration, and to determine the worst case for the topographic multiplier. This means that one needs multiple contours through each point of interest in order to determine the Hill-shape multiplier, M_h. Such a process would be regarded as very time consuming in a building design situation, as it would mean that many hill profile contours would need to be obtained and analysed.

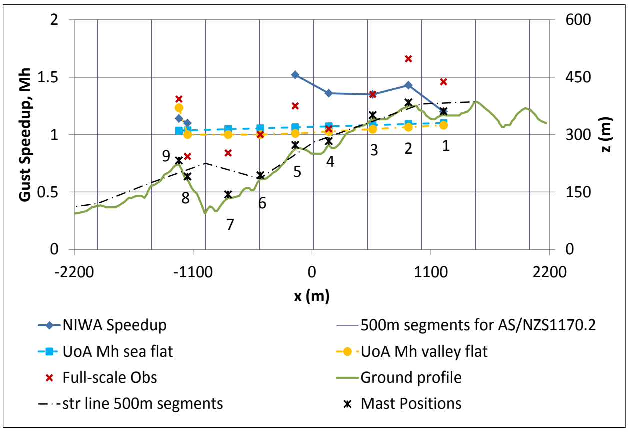

Figure 12: Ground contour along the measurement line, 500 m segments upwind from the crest. Gust speedup from full-scale measurements, and from NIWA and UoA using AS/NZS1170.2. Two sets of UoA results are shown. One set assumes that the "hill" starts are sea level. The other set assumes that the "valley" is flat, and that the hill for masts 1 to 5 starts at an elevation of 225 m.

Calculations for the gust hill-shape multipliers were carried out for each of the mast locations using the AS/NZS Loading Standards 1170.2 [6] for the 345° wind direction by NIWA. This involved using software that had been developed by NIWA to implement the speedup method of [6], but on close inspection, it appeared that the approach did not follow the method set out in [6] exactly, and for example, in the case of a large complicated hill such as being studied in the present research project, the method did not determine a flat "upwind" location as the beginning of the hill, but considered bumps or hills on the larger scale hilly terrain. The estimates from NIWA are given in figure 12. Because they were very sheltered, AS/NZS 1170 estimates were not performed for mast locations 6 and 7 by NIWA.

Independent estimates of the speedup were also made by the University of Auckland (UoA) using the procedures outlined in AS/NZS1170.2 [6] and its commentary, except that only the 345° direction was analysed, not the worst contour in upwind 22.5° arcs, as specified in [6]. Difficulties in dealing with the valley shown at top-left of figure 1, and near the top of figure 2 resulted in the UoA carrying out two sets of predictions of wind speedup. One set assumed that the "hill" started at the sea, and the other set assumed that the large valley between masts 6 and 9 could be assumed to be flat, thus resulting in the "start" of the hill at this location for masts further downwind. For the latter calculations, the speedup at masts 6, 7 and 8 are really undefined, since they are in the valley, and thus one would expect these masts to be relatively sheltered from wind at 345°. Mast 9 was assumed to be on the crest of an upstream hill starting at the sea. The speedup predictions for the gust speed are shown in figure 12. It is clearly evident in figure 12 that the estimates using AS/NZS1170.2 from NIWA and UoA are very different. This means that the Standard is very open to error in its use in such complex terrain, which

is very common in New Zealand. This is a very interesting result, which is some cause for concern, and may mean that this section in the Standard on the Hill-shape multiplier should be subjected to a rewrite in the future to reduce possible ambiguity and possible error in order to reduce the potential hazard of wind and the risk to important infrastructure [43,44].

7.3 *3.0 Discussion and Conclusions*

In order to attempt to answer the question – "How good is the AS/NZS 1170 loadings code at estimating wind speedup over hills in rugged terrain?"– observed speedups in the Belmont Hills region of Wellington have been compared with speedup estimates based on: the AS/NZS 1170.2 Standard.

It was found that in this complex and rugged Belmont Hill region terrain, where shedding of eddies by upstream hills is likely to have an important influence on wind speeds, and the presence of valleys and ridges along the wind direction further complicates the picture, assessments of winds based on the AS/NZS 1170.2 Loadings Code struggles to differentiate as well between sheltered and exposed sites– tending to produce variable estimates of design winds depending on the assumptions made by the person carrying out the estimate.

In terms of practical advice for someone wanting to estimate a design wind speed in a remote location with rugged topography, the following comments are made. The loadings code generates a result for a single point whereas the wind tunnel and CFD methods generate values over a large 10 km square at 100 m resolution – potentially for many points. For an isolated single location it may be cheaper to apply the loadings code, but because of the potential inaccuracies in the method, it may be necessary to be conservative (apply an over-estimate of the wind speedup). Depending on the size of the proposed structure this may lead to a considerably larger building cost – potentially far outweighing the extra cost in estimating the wind speed more accurately. If estimates at many (more than 10) locations are required in a given 10 km square then it will almost certainly be more cost effective to use a CFD or wind tunnel based method.

It should be noted that these results are based on one eighteen hour period of strong winds from a specific direction at a single location. It is intended that further research will be carried out at this site to confirm more generally the relative merits of the various methods for other locations and wind directions. Full results are available in [37], and the results of the wind tunnel test on the Belmont Hill, for the 34° direction are available in [45].

7.4 *Acknowledgments*

The success of this study on wind speedup over the Belmont Hill has shown the benefit of a collaborative research effort between NIWA, GNS, OPUS, and the University of Auckland. The authors would like to thank the following people and organisations: Tony Bromley and Ross Martin at NIWA for setting up equipment, making measurements, liaising with land-owners, etc; Sylvia Nichol at NIWA for making the AS/NZS 1170 loadings code calculations; Callum Murton at OPUS for making the wind tunnel measurements; DOC & GWRC for allowing access to land and mast data; M Nayyerloo and SR Uma of GNS Science for reviewing the report; NZ Government’s Foundation for Research, Science and Technology for supporting this work under the Natural Hazards Research Platform Contract 2010-GNS-04-NHRP.

8 PROBABILISTIC LOSS MODELLING FOR WIND-STORMS (NEW ZEALAND) IN THE RISKSCAPE PROJECT

NIWA and GNS scientists have been working on developing methods for probabilistic loss modelling for different natural hazards such as Earthquake, Tsunami, Flooding, Landslides, and Wind Storms. One of the challenges has been to come up with a “standard” approach that the probabilistic losses can be correctly compared. In the last year or so, each “hazard” was challenged to come up with an approach, and in June 2012, each presented their methodologies at a workshop. Generally, the procedures with some minor adjustments were able to fitted into a common framework for development. The procedure for wind storms is as follows: (1) Identify each source, which is the n-year return period wind speed for each the 8 main wind directions (this partially accounts for storm type, e.g. NW lee-slope and S-SW convective storms in Christchurch); (2) Construct a single source loss curve (3) Add the frequencies of occurrence for each source to obtain the combined loss curve, where the loss curves can be for repair cost, casualties, etc.; (4) Discretise each loss curve at 3 different levels: unlikely, rare and very rare; and (5) Present as a table of losses together with loss curves. This has the advantage of correctly accounting for different hazards and makes it easy to distinguish between significant sources.

The work plan in the coming year (i.e. 2013) is to come up table of losses with loss curves (within RiskScape) for the three study areas (Christchurch, Westport, and Napier). Progress to date has seen items (1) and (2) completed for each of the study areas. GNS and NIWA are also working on a tool to interface RiskScape with real-time gust forecasts to be able to forecast storm losses in real time. The researchers have been "re-forecasting" the Wellington 12March 2010 southerly storm with NWP models with grid-scales down to 100 m as well as downscaling large-scale 12 km NWP models with high-resolution 40 m GERRIS speed-up maps. Further description of Riskscape is available in [43,44].

9 CONCLUSIONS

The New Zealand Economy Report shows that there are a number of interesting research projects being carried out in New Zealand, in spite of the low level of research grants that are available to fund such work. They encompass a range of wind engineering activities from laboratory work by students, to extensive full-scale activities such as the Natural Hazards Platform Research project being carried out by GNS, Opus International Consultants, the University of Auckland and NIWA, and the full-scale monitoring of building motion.

10 REFERENCES

1. FLAY, R.G.J., KING, A. 'New Zealand economy report for APEC-WW 2010', APEC-WW2010 6th Workshop on Regional harmonization of Wind Loading and wind Environmental Specifications in Asia-Pacific Economies, Youn-duk Kim, Yohanes Joni T.C.(ed.), Proceedings of the 6th Workshop on Regional harmonization of Wind Loading and wind Environmental Specifications in Asia-Pacific Economies, Institute of Environmental Research (DAEWON), Kwandong University, South Korea, 21-23 October, 2010, p.162-169.
2. Bhatt, J., *Across-wind Force Spectra for Low Values of Reduced Velocity*. Master of Engineering Thesis, Mechanical Engineering Department, University of Auckland, New Zealand, November 2005.
3. Judge, A. R. Cross-wind generalised force spectra for slender shapes, Master of Engineering Thesis, Mechanical Engineering Department, The University of Auckland, New Zealand, February 2010.
4. Alexander R. Judge, Richard G.J. Flay, Wind Tunnel Investigation of Crosswind Generalised Force Spectra for Slender Shapes, 14th Australasian Wind Engineering Society Workshop, Geoscience Australia, Canberra, 4-6 August 2010.
5. Flay, R.G.J. and Judge, A.R. Crosswind generalised force spectra for slender prisms at low reduced velocities, Proceedings of the 13th International conference on wind engineering, Copenhagen, The Netherlands, 10-15 July, 2011.
6. Standards Australia/Standards New Zealand, *AS/NZS 1170:2010 Structural Design Actions, Part 2: Wind Actions*., Standards New Zealand, Private Bag 2439, Wellington 6020, New Zealand.
7. GUHA, T.K., SHARMA, R.N., RICHARDS, P.J., 'Dynamic wind load on an internal partition wall inside a compartmentalized building with an external dominant opening', Journal of Architectural Engineering, doi:10.1061/(ASCE)AE.1943-5568.0000113, on-line Sept 2012.
8. GUHA, T.K., SHARMA, R.N., RICHARDS, P.J., 'Internal pressure in a building with multiple dominant openings in a single wall: Comparison with the single opening situation', Journal of Wind Engineering and Industrial Aerodynamics, 107-108, 244-255, 2012.
9. GUHA, T.K., SHARMA, R.N., RICHARDS, P.J., 'Influence factors for wind induced internal pressure in a low rise building with a dominant opening', Journal of Wind and Engineering, 8(2), 1-17, 2011.
10. GUHA, T.K., SHARMA, R.N., RICHARDS, P.J., 'Internal pressure dynamics of a leaky building with a dominant opening', Journal of Wind Engineering and Industrial Aerodynamics, 99, 1151-1161, 2011.

11. GUHA, T.K., SHARMA, R.N., RICHARDS, P.J., 'Internal pressure in real flexible porous buildings: A design perspective', 7th International Colloquium on Bluff Body Aerodynamics and Applications, Shanghai, China, 2-6 September 2012.
12. GUHA, T.K., SHARMA, R.N., RICHARDS, P.J., 'Full-scale studies of wind induced internal pressure in a warehouse', 13th International Conference on Wind Engineering, Amsterdam, Netherlands, 10-15 July 2011.
13. GUHA, T.K., SHARMA, R.N., RICHARDS, P.J., 'On the internal pressure dynamics of a leaky and flexible low rise building with a dominant opening', 13th International Conference on Wind Engineering, Amsterdam, Netherlands, 10-15 July 2011.
14. RICHARDS, P.J., 'Dispersion of windborne debris', Journal of Wind Engineering and Industrial Aerodynamics,104-106, 594-602, 2012 (Also presented at 13th International Conference on Wind Engineering, Amsterdam, Netherlands, 10-15 July 2011.)
15. MARTINEZ-VAZQUEZ, P., STERLING, M., BAKER, C.J., QUINN, A., RICHARDS, P.J., 'Autorotation of square plates, with application to windborne debris', Journal of Wind and Structures, 14(2), 167-186, 2011.
16. RICHARDS, P.J., NORRIS, S., 'The flight of roofing tiles during strong winds', 7th International Colloquium on Bluff Body Aerodynamics and Applications, Shanghai, China, 2-6 September 2012.
17. MARTINEZ-VAZQUEZ, P., BAKER, C.J., STERLING, M., QUINN, A.D., RICHARDS, P.J., 'Non-averaged wind forces acting on a rotating square plate', 13th International Conference on Wind Engineering, Amsterdam, Netherlands, 10-15 July 2011.
18. Imraan, M., Sharma, R. N., & Flay, R. G. (2011). Wind Tunnel Testing of a Telescopic Blades Wind Turbine. In Proceedings of the ASME Power Conference (POWER2011) (pp. 1-8). Denver, Colorado,USA.
19. Imraan, M., Sharma, R. N., & Flay, R. G. (2011). Wind tunnel testing of a wind turbine with telescopic blades. In C. Guerts (Ed.), *Proceedings of the 13th International Conference on Wind Engineering (ICWE13)* (pp. 1-8). Amsterdam, The Netherlands. Retrieved from http://folk.ntnu.no/karpa/ICWE%2013/ICWE13%20Proceedings/start/papers/581_8page_wind_tunnel_testing_of_a_wind_turbine_with_telescopic_blades.pdf
20. Imraan, M., Sharma, R. N., & Flay, R. G. (2011). Telescopic Blade Wind Turbine to Capture Energy at Low Wind Speeds. In *New Zealand Wind Energy Conference and Exhibition*. Palmerston North, New Zealand.
21. Imraan, M., Sharma, R. N., & Flay, R. G. (2010). Wind tunnel testing of a Wind Turbine with the Telescopic Blades: the influence of step change in chord. In *Proceedings of the 17th Australasian Fluid Mechanics Conference* (pp. 1-4). Auckland, New Zealand. Retrieved from http://www.mech.unimelb.edu.au/people/staffresearch/AFMS%20site/17/359_Paper.pdf
22. Imraan, M., Sharma, R. N., & Flay, R. G. J. F. (2010, December 5). Wind tunnel testing of a Wind Turbine with the Telescopic Blades: the influence of step change in chord. In *Proceedings of the 17AFMC* (pp. 4 pages). The University of Auckland, Auckland, NEW ZEALAND.
23. RICHARDS, P.J., NORRIS, S.E., 'Appropriate boundary conditions for computational wind engineering models revisited', *Journal of Wind Engineering and Industrial Aerodynamics*, 99, 257-266, 2011.
24. O'Sullivan, J. P., Archer, R. A., & Flay, R. G. J. (2011). Consistent boundary conditions for flows within the atmospheric boundary layer. *JOURNAL OF WIND ENGINEERING AND INDUSTRIAL AERODYNAMICS, 99*(1), 65-77. doi:10.1016/j.jweia.2010.10.009
25. RICHARDS, P.J., HOXEY, R.P., 'Pressures on a cubic building –Part 2: Quasi-steady and other processes', *Journal of Wind Engineering and Industrial Aerodynamics*, 102, 87-96, 2012.
26. RICHARDS, P.J., HOXEY, R.P., 'Pressures on a cubic building –Part 1: Full-scale results', *Journal of Wind Engineering and Industrial Aerodynamics*, 102, 72-86, 2012.
27. HOXEY, R.P., RICHARDS, P.J., QUINN, A.D. ''Static pressure' in turbulent flow and its contribution to wind loads', *13th International Conference on Wind Engineering, Amsterdam, Netherlands, 10-15 July 2011*.
28. Carpenter, P., Cenek, P.D., and Flay, R.G.J. *Monitoring of wind-induced motion of tall buildings in New Zealand*, New Zealand Society of Structural Engineers: 2012 Inaugural

Structural Engineering Biennial Conference "From Theory to Practice", SESOC, Rendezvous Hotel, Auckland, New Zealand, 2-3 November 2012.
29. Carpenter P, Cenek P.D., 2008. Research programme: improved prediction of wind induced building motion. Australasian Wind Engineering Society Workshop, AWES13, Hobart, Australia, 4-5 Dec, 2008.
30. Carpenter P, Cenek P.D., 2008. Monitoring of wind-induced building motion for three Wellington buildings. Australasian Wind Engineering Society Workshop, AWES14, Canberra, Australia, 4-6 Aug, 2010.
31. Carpenter P, Cenek P.D., Flay R.G.J., 2011. Monitoring of wind-induced building motion. International Conference on Wind Engineering, ICWE13, Amsterdam, 10-15 July, 2011.
32. Cenek P.D., George S., Wood J., 1989. Designing for building dynamic serviceability under wind loading. 2nd Asia Pacific Symposium on Wind Engineering, Beijing, China, 1989.
33. Irwin P.A., 2010. Wind issues in the design of tall buildings. Los Angeles Tall Building Structural Design Council, May 7, 2010.
34. Reid, S., Turner, R. 2004. Severe winds near Molesworth on 9 January 2004. NIWA report WLG2004-63. 16 pp
35. Reese, S., Revell, M., Turner, R., Thurston, S., Reid, S., Uma, S.R., Schroeder, S. 2007. Taranaki Tornadoes of 4-5 July 2007: Post event damage survey. NIWA report WLG2007-71, 43 pp.
36. Revell, M., Popinet, S., Reese, S. 2009. Downslope winds – an explanation for roof damage in Cobden, Greymouth in July 2008. Paper presented at the joint New Zealand Meteorological and Marine and Freshwater Societies conference at Auckland University, September, 2009.
37. King, A.B., Revell, M., Carpenter, P., Turner, R., Cenek, P. and Flay, R.G.J. 2012. Modified wind speed due to topographic effects, GNS Science Report 2012/07. 34 p.
38. Flay, R.G.J., Turner, R., Revell, M., Carpenter, P., Cenek, P., King, A. B. 2011. "The potential wind hazard of wind speedup over hills and complex terrain, and the risk to infrastructure", 7th APRU Research Symposium on Multi-hazards around the Pacific Rim, Auckland, November 2011.
39. Popinet, S., Smith, M., Stevens, C. 2004. Experimental and Numerical Study of the Turbulence Characteristics of Airflow around a Research Vessel. J. Atmos. And Oceanic Technology. 21, 1575-1589.
40. Popinet, S., 2003. Gerris: a tree-based adaptive solver for the incompressible Euler equations in complex geometries. J. Comput. Phys., 190:572-600, 2003.
41. Jackson, P. S., and Hunt, J. C. R. 1975 Turbulent wind flow over a low hill. Quart. J. R. Meteor. Soc., 101, 929-955.
42. Carpenter, P., Reid, S. 1990. "Aspects of the Assessment of Design Wind Speeds for Building Sites in New Zealand" Opus Report 90-29116.
43. King, A.B., Cousins, W.J., Heron, D.W., Maitcham, I., Pringle, R., Bell, R., Reese, S., Schmidt, J., Henderson, R. 2008. Regional RiskScape: a multi-hazard loss modelling tool. 11 p. IN: 4th International i-Rec Conference 2008: building resilience: achieving effective post-disaster reconstruction: conference papers and presentations. Christchurch, NZ: i-Rec.
44. King, A. B., Bell, R., 2009. RiskScape Project 2004-2008. GNS Consultancy Report 2009/247. 162pp.
45. Carpenter, P., Murton, C., Cenek, P. 2011. "Simulated wind flow measurements over hill terrain – Opus report", Opus Central Laboratories Report 11-529B50.