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Multi-Sector Directional Probability Integration of Wind Loads: Comparison against the Load-Effects and Sector Methods

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Abstract

The method used to combine the structural directional response of a development with the local wind directionality at that site is important in determining the overall wind loading.

The multi-sector method (Holmes, 1990), a form of directional probability integration, has been compared against the load effects method (also referred to as the Direct Method). Comparisons were repeated for two different wind climate sources: meteorological observations and simulated tropical cyclone data. The comparison was found to be very good. The load effects method has then been used to identify dominant wind directions from specific wind events, which may be used to generate custom load cases.

A survey of wind tunnel results from 55 buildings has been conducted and the directional multiplier sector method used in the Australian/New Zealand Standard for Wind Actions (Standards Australia, 2013) has been compared with the multi-sector method. It was found that generally the directional multiplier sector method overestimates the responses compared with the multi-sector method. For base moments the overestimate was on average 10%. For building accelerations, overestimates as large as 50% have been documented and the magnitude of the overestimate was influenced by the excitation mechanism.

Introduction

An analysis of meteorological data for a region typically shows that high speed wind events do not occur with equal probability from all wind sectors. Additionally, as the response of a structure to wind loading will generally be dependent on the orientation of the structure relative to the prevailing wind directions. Therefore the method used to combine the directional variation of the wind with the directional response of the structure will influence the accuracy of the predicted structural response.

Structural responses can be calculated directly, by combing every extreme wind event with measurements of building responses recorded in the wind tunnel. The Load Effects method, often referred to as the Direct Method, is considered a benchmark for evaluating the accuracy of other methods (Rigato et. al., 2001)

The method used in the Australian/New Zealand Standard for Wind Actions (Standards Australia, 2013) is to use wind direction multipliers. These multipliers are combined with the non-directional regional wind speed to calculate the directional wind speeds. The wind loads are then calculated for the wind occurring from each sector and each sector is analysed independently. This method is referred to as the Sector Method.

The multi-sector method (Holmes, 1990) is an approach which uses directional probability distributions from extreme wind speeds to estimate wind responses. This method combines the directional wind speed probability distribution with the directional response of the structure determined from the wind tunnel testing. The response level is then calculated by applying the constraint that the total of the directional probabilities equals the design annual probability.

In this paper the multi-sector method is compared against the load effects method using wind tunnel results from a highly dynamic 268m tall building. The building has been analysed for two wind climates, using data from two different sources: non-cyclonic (Melbourne, 46 years of metrological measurements) and cyclonic (Manila, 100,000 years of simulated tropical cyclone data).

The load effects method results have been analysed directionally, which allows for the identification of the dominant wind direction including the effect of wind climate and building form. An analysis of these data allow for the generation of detailed customised load cases and these load cases can then be used as a benchmark in assessing other generic means of creating load combinations such as those presented in wind loading standards.

The multi-sector method has been compared with the sector method using the results from 55 buildings from around the world with a range of heights, aspect ratios and wind climates.

Methodology

Wind Tunnel Methodology

The overturning and torsional base moments and highest occupiable level accelerations were determined using scale models tested in Windtech's boundary layer wind tunnel. Scale models of the buildings were produced using three-dimensional printing. Two methods were used to determine the building response: the High Frequency Force Balance (HFFB) method and the High Frequency Pressure Integration (HFPI) method. The directional responses of the scale models in the wind tunnel were combined with the local wind climate.

The HFFB method measures the wind loads using an array of strain gauges located within a very stiff building model. The HFPI method determines the wind loads by integrating simultaneously recorded surface pressure measurements with a patch area and moment arm. Both methods include the effect of the resonant component of the dynamic response of the structure.

Load Effects Method

The implementation process for the load effects method depends on whether the data has been sourced from meteorological measurements or from tropical cyclone simulations. For both approaches wind tunnel data for 36 wind directions has been combined with specific wind events to calculate a series of load effects and no probability distribution has been fitted.

When the data has been sourced from meteorological measurements, the measured monthly maximum wind speed from 36 wind directions has been considered. The maximum load effects for each month has then been calculated and analysed using the Gringorten method (Holmes, 2015).

When the data has been sourced from tropical cyclone simulations, the response has been calculated for each tropical cyclone event. The maximum load effects are then analysed following the probabilistic approach used by Vickery (2009).

Direction Multiplier Sector Method

The definition of wind direction multipliers is the same as that used in the Australian/New Zealand Standard where they are derived from the probability distributions of recorded meteorological data. They are based on the hypothesis that the majority of the combined probability of exceedance of a load effect comes from two 45-degree sectors (Melbourne, 1984). It is then assumed that the probability of exceedance for each 45-degree sector is half that of the non-directional analysis. The assumption is also made that the directional data is uncorrelated. The hypothesis was developed from considering a rectangular shaped building. There are alternative methods to calculate direction multipliers and or further information their calculation see Holmes (2001) and Kasperski (2000). The comparison here is against the probability corrected sector method.

Multi-Sector Method

The multi-sector method (Holmes, 1990) which accounts for the probability of winds occurring from various directions.

Briefly, the multi-sector method uses the following procedure:

1. The directional extreme wind speed probability distribution is known from the wind climate analysis
2. The directional response of the structure as a function of wind speed is known from the wind tunnel testing.
3. The inverse of the functions from points 1 and 2 are combined such that the directional probability can be calculated for a given response level.
4. The response level is calculated from the functions from point 3 by applying the constraint that the total of the directional probabilities needs to equal the design probability.

The multi-sector method uses an extreme value distribution to describe the relationship between wind speed and probability. The Gumbel extreme value distribution has been used.

Survey of Buildings

55 recent wind tunnel studies were surveyed with the following representative parameters:

- Height Range : 30 to 300m
- Width Range : 10 to 95m
- Maximum Aspect Ratio (H:W): 13 to 1
- First mode natural frequency: 0.11 to 1.7 Hz

Buildings were located in various wind climates including equatorial, mixed and cyclonic. The density of surrounding buildings varied from greenfield sites to dense urban.

Comparison between the Multi-Sector and Load Effects Methods

Wind Tunnel Results

The building used for the basis of the comparison was an isolated 268m tall building with an aspect ratio of 1:1.3:11.5 (Figure 1) which was tested in a suburban terrain category.

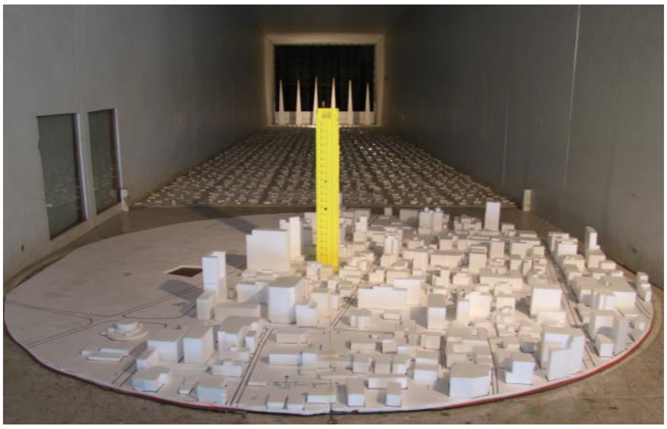

Figure 1. Building in Wind Tunnel

Figures 2a to 2b presents the bases moment coefficients for development and it can be seen that the response is dominated by cross winds response about both the X and the Y axis. This particular building was selected due to this characteristics.

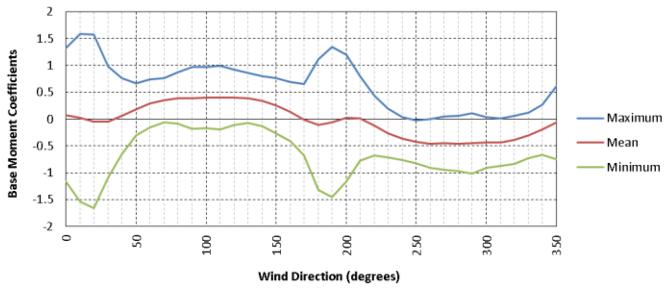

Figure 2a: Bases Moment Coefficients about the X-axis

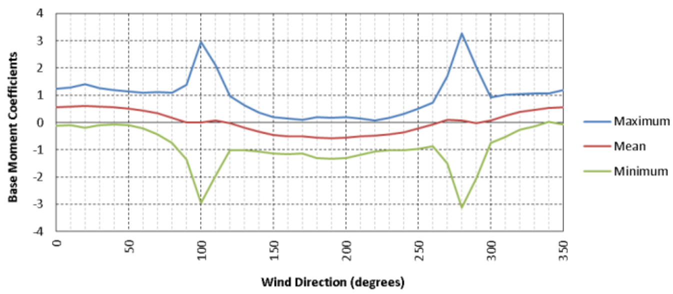

Figure 2b: Bases Moment Coefficients about the Y-axis

Non-Cyclonic (Melbourne) Wind Climate Results

The wind tunnel results we analysed using a non-cyclonic wind climate model (Melbourne). This wind climate is directionally highly non-uniform and characterised by strong northerly and westerly winds. The results were analysed twice, initially using the building and wind climate orientated as tested (Figure 3), and the second time using a wind climate that has been rotated by 50 degrees (Figure 4).

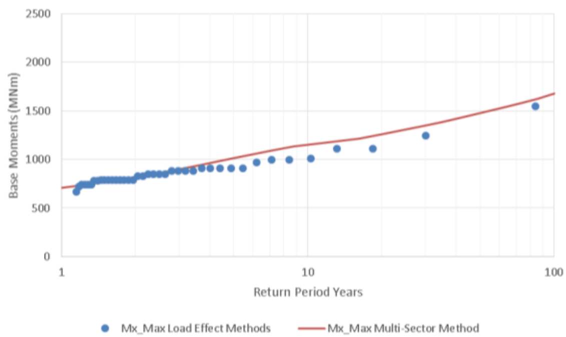

Figure 3a: Max Base Moment about the X-Axis - Non-Cyclonic

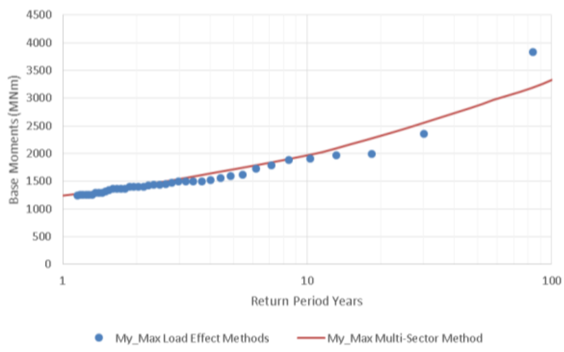

Figure 3b: Max Base Moment about the Y-Axis - Non-Cyclonic

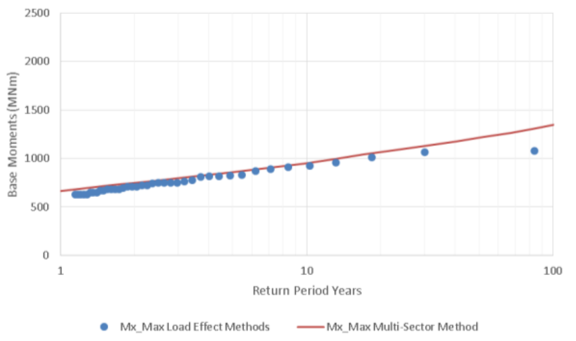

Figure 4a: Base Moment about the X-Axis - Non-Cyclonic 50° Rotation

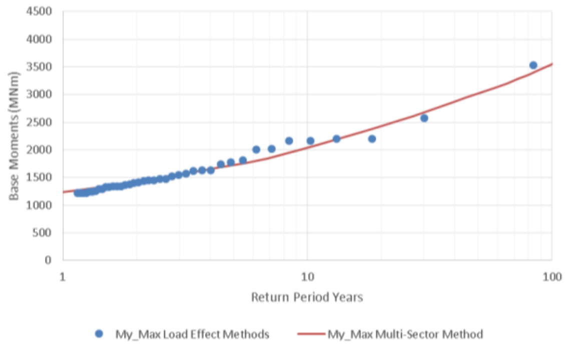

Figure 4b: Bases Moment about the Y-Axis - Non-Cyclonic 50° Rotation

Cyclonic (Manila) Wind Climate Results

The wind tunnel results were analysed using simulated cyclonic data (Manila) an example is shown in Figure 5. The simulated data produces a relatively uniform directional distribution of wind speeds, with a slight basis to the east.

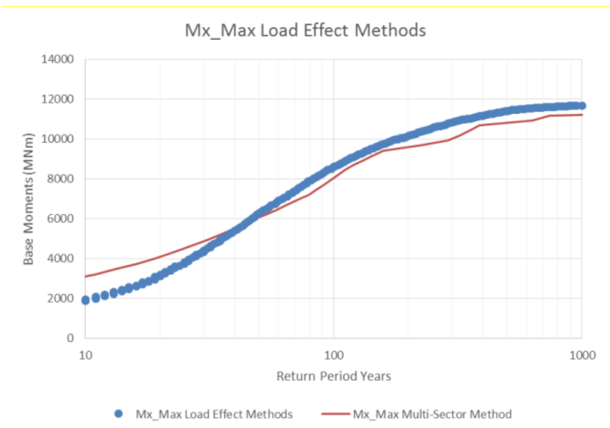

Figure 5: Max Base Moment about the X-Axis - Cyclonic

Analysis of Dominant Wind Angles -determining load cases

The specific wind events which generated the top 20 load effects for maximum and minimum moments about the X, Y and Z axis can been identified for any of the above cases. An example for one of the cases is plotted in Figure 6. Note that the radial axis is the hourly mean wind speed converted back to 10m height in open terrain.

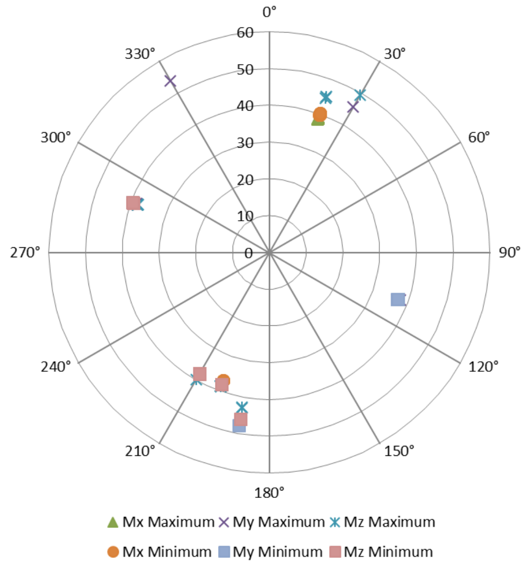

Figure 6: Dominant Wind Angle - Cyclonic (Manila)

Discussion

The comparisons between the multi-sector method and load effects method shows that generally the responses calculated using the two methods are in very good agreement over a wide range of return periods. This results is particularly difficult to achieve for a highly dynamic building such as this. This result is consistent with the results of Holmes and Bekele (2015).

There are individual wind events which create load effects slightly greater than those predicted using the multi-sector method. For the non-cyclonic case (Figures 3 and 4) the match is very good at the shorter return periods. The increased scatter at the higher return periods in the Load Effects method is caused by a lack of resolution at the higher return periods, due to the reducing number of extreme events and highlights the advantage of the Multi-Sector method in addressing this issue.

In Figure 5, which presents a comparison for the cyclonic climate model, there are some differences between the two methods which are caused by factors associated with the practical generation of a multi-sector wind climate model, for example the requirement to fit a Gumbel extreme value distribution to the cyclonic wind speed data, where a type III extreme value distribution may be more appropriate.

In some cases the calculation of the directional probability for a given response level in the multi-sector method will result in relatively uniform response levels over several probabilities (ie a non-unique solution to the inverse problem). In these cases, the most likely directional probability is used (lowest corresponding reference wind speed).

When responses are calculated using the multi-sector method directional information is lost compared with the sector method. This information is important when forming load cases for structural design. As, when a peak load is applied about one axis it should be applied with loads about the other axes that are expected to occur simultaneously. There are several possible methods that can be employed by wind tunnel laboratories to generate these combinations. One approach is to examine the dominant wind angle from the load effects analysis. For example the top 20 wind events for the 6 response (Figure 6) can be examined and the responses calculated in the dominant and non-dominant axes. The responses are then rationalised by enveloping the responses and normalised to create load combinations factors to be compared against alternatives.

Comparison between the Multi-Sector and Sector Methods

Overturning and Torsional Base Moments

Figure 7 presents a comparison between the overturning and torsional base moments calculated using the two methods separated based on the dominant wind excitation mechanism. It can be seen that the sector method generally overestimates the base moments compared with the multi-sector method. The median overestimate is 12% and ranges from an underestimate of 11% to and overestimate of 60%. The median overestimate of the sector method is the same for both mechanisms.

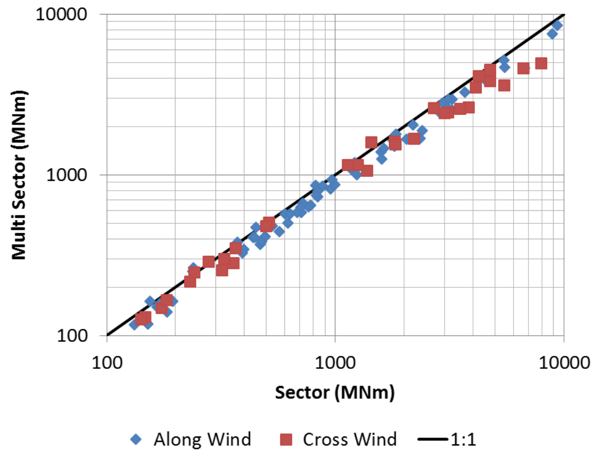

Figure 7. Overturning and Torsional Base moment comparison by dominant mechanism

Occupant Comfort

The peak one year return period accelerations on the highest occupiable level for the 55 buildings has been calculated and separated based on the dominant wind excitation mechanism (Figure 8). For accelerations greater than 1 milli-g, the median overestimates is 14% and ranges from an underestimate of 40% to and overestimate of 30%. The overestimates are greater for along wind dominated response than for cross wind with a median overestimate of 20% compared to 11%.

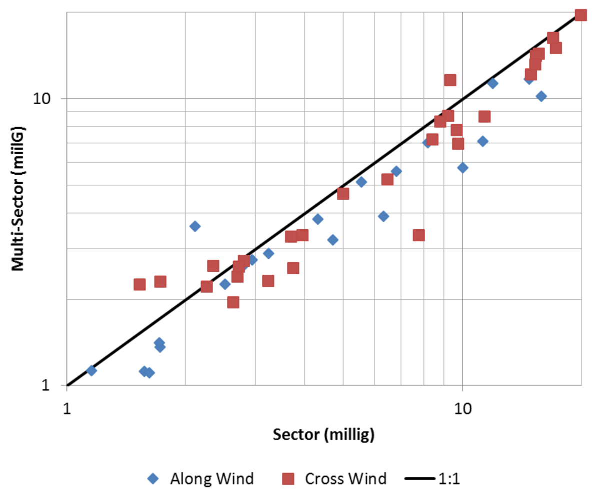

Figure 8. Highest occupiable level acceleration by dominant mechanism

Discussion

The source of the differences between the two methods are the core assumptions of the direction multiplier sector method, that the majority of the combined probability of exceedance of a load effect comes from two 45-degree sectors and that the probability of exceedance for each 45-degree sector is half that of the non-directional analysis. For the occupant comfort comparison a similar effect is seen. Additionally, the overestimate is greater in the along wind dominated cases compared with the cross wind cases. The likely cause of this is that when a strong cross wind response occurs, it typically also occurs with a moderate along wind response, whereas when there is an along wind dominated case the converse is not usually true. This means that generally there are more wind directions contributing to the acceleration response in the cross wind case resulting in a smaller overestimate.

Conclusion

The multi-sector method compares well with the load effects method. However, the method may be improved by allowing the use of alternative extreme value distributions such as the type III extreme value distribution where the distribution asymptotes towards an upper limit. The load effects method allows for the calculation of peak responses but also may be used to analyse dominant wind directions for a particular site. This information may be used to validation existing and proposed methods of calculation load combination factors for use in structural design.

A survey has been conducted of 55 recent building projects that have been wind tunnel tested and a comparison has been made between the response calculated using the direction multiplier sector method and the multi-sector method of combining the wind tunnel data with the local wind climate. Compared with the multi-sector method, the assumptions of the sector method result in a conservative estimate of base moments and accelerations for the large majority of cases and is suitable for codification purposes. However, when a detailed analysis is undertaken, such as when wind tunnel testing has been performed, a directional probability method such as the multi-sector method should be applied, particularly since there are a minority of cases where the sector method can be unconservative.

Acknowledgments

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