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Multi Sector Directional Probability Integration of Wind Loads: Comparison against the Sector Method

N.K. Truong[1], A.W. Rofail[1]

[1]Windtech Consultants Pty Ltd,
607 Forest Road, Bexley NSW 2207 Australia
email: reception@windtech.com.au

Abstract

The method used to combine the directional response of a structure with the wind directionality at the site is important in determining the wind loads on that structure.

A survey of wind tunnel results from 55 buildings has been conducted and two methods of combining the directional response of the structure with the local wind directionality have been compared. 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 directional probability method (Holmes, 1990).

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.

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 often referred to as the Sector Method.

The multi-sector directional probability 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 as 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 (eg 1/1000). Holmes and Bekele (2015) recently demonstrated that the multi-sector method gives very accurate predictions when compared against the direct calculation of extreme base moments.

In this paper the results from a survey of 55 buildings from around the world with a range of heights, aspect ratios and wind climates has been conducted. The base moment and building acceleration results for the two directional methods have been compared. The influence of building properties and excitation mechanism on the comparison have also been examined.

Methodology

Summary 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 climates. The density of surrounding buildings varied from greenfield sites to dense urban.

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 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. The patch areas and moment arms were determined from the three dimensional CAD model.

The directional responses of the scale models in the wind tunnel were combined with the local wind climate using the direction multiplier method based on the Australian/New Zealand Standard for Wind Actions (Standards Australia, 2013) and the multi-sector directional probability method (Holmes, 1990).

Direction Multiplier Sector Method

The definition of wind direction multipliers calculated in this paper is the same as that used in the Australian/New Zealand Standard. The wind direction multipliers in the Australian/New Zealand Standard 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. For example, if the probability of exceedance is 0.001 for a non-directional analysis, then for directional analysis of 45-degree sectors the probability of exceedance is 0.0005.

There are alternative methods to calculate direction multipliers from the recorded meteorological data. The relative merits of the alternative techniques will not be discussed in depth in this paper. For further information on directional wind speeds and the calculation of directional multipliers see ESDU (1990), Holmes (2001) and Kasperski (2000).

Multi-Sector Method

The base moments were calculated using the Multi-Sector or directional probability integration 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 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.

Holmes and Bekele (2015) compared base moments calculated using the multi-sector method with base moments calculated using a direct calculation method (Rigato et. al., 2001). In the direct calculation method the annual extreme wind speeds are used directly and are not fitted to a probability distribution. These results represent an accurate estimate of the directional response of the structure. For a single tower rotated to represent four wind climates very good agreement was found between the methods.

Results

Overturning and Torsional Base Moments

Figure 1 presents a comparison between the overturning and torsional base moments calculated using the two methods. 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%.

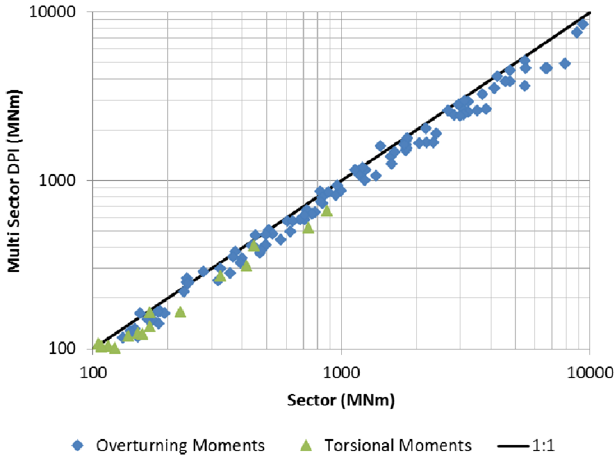

Figure 1. Overturning and Torsional Base moment comparison by direction

The data presented in Figure 1 has been separated based on the dominant wind excitation mechanism (Figure 2). The median overestimate of the sector method is the same for both mechanisms.

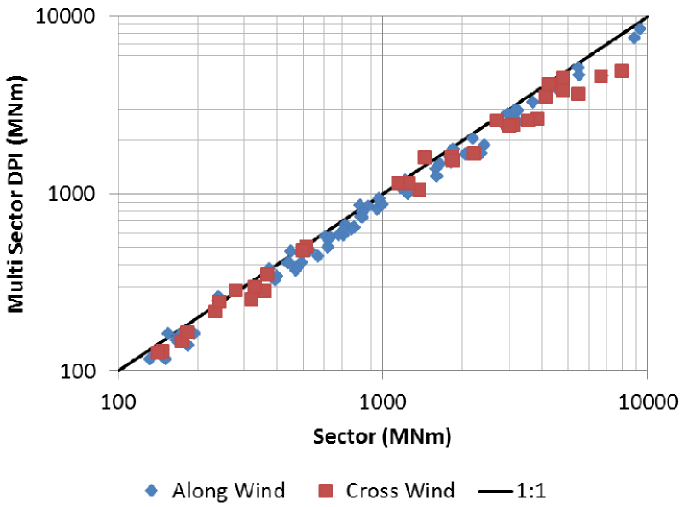

Figure 2. Overturning and Torsional Base moment comparison by dominant mechanism

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 3). 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%.

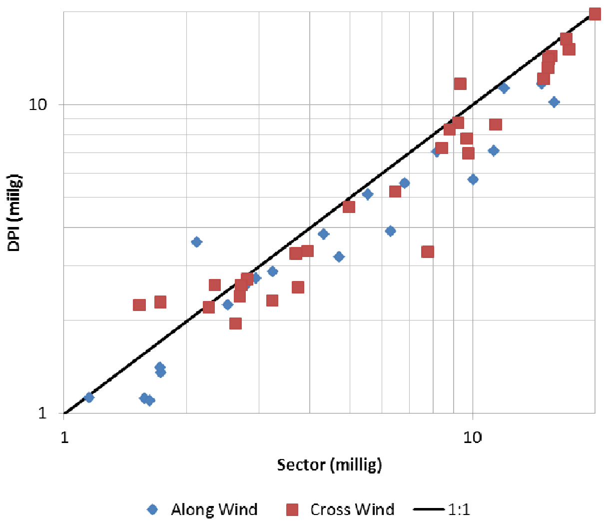

Figure 3. Highest occupiable level acceleration by dominant mechanism

Influence of Building Form on Comparison

The influence of building height, building slenderness and the first mode natural frequency, on the comparison between the sector method and multi-sector method, for building base moments and accelerations has been considered. As shown in Figures 4 to 6 there is no discernible influence of these three factors on the sector method to multi-sector method comparison.

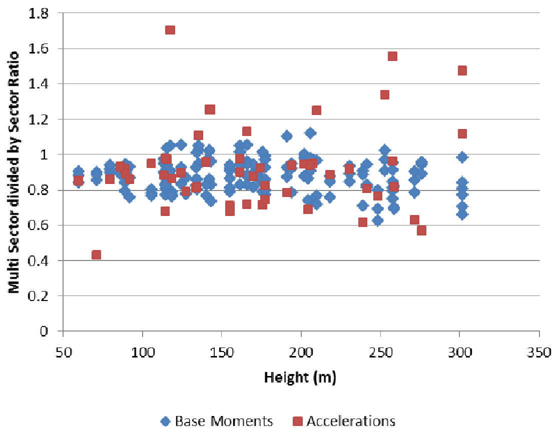

Figure 4. Influence of Height on Base Moments and Accelerations

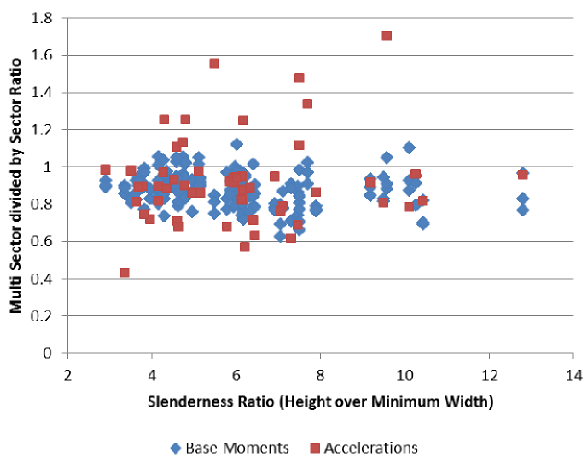

Figure 5. Influence of Slenderness on Base Moments and Accelerations

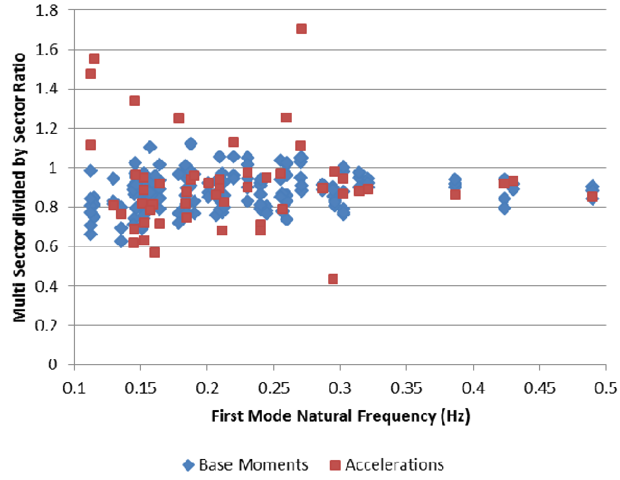

Figure 6. Influence of first mode natural frequency on Base Moments and Accelerations

Case Study Comparison

To gain an insight in to the source of the differences between the two methods, the directional base moment plots for three examples have been considered.

The examples cover three common cases:

- The directional response is a single narrow peak.
- The directional response is a single wide peak.
- The directional response is a double peak.

These cases are shown in detail in Figures 7 to 9.

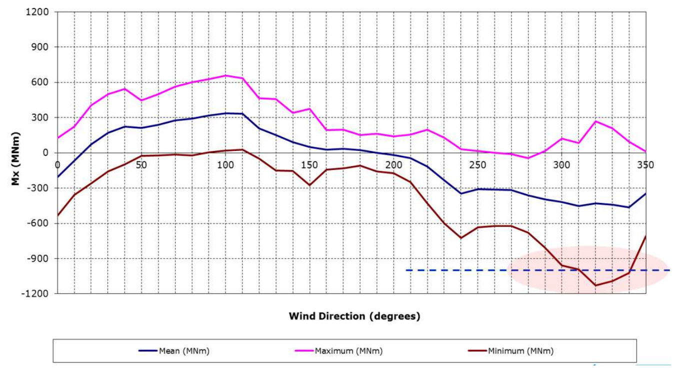

Figure 7. Directional Base Moment Comparison – Narrow Peak

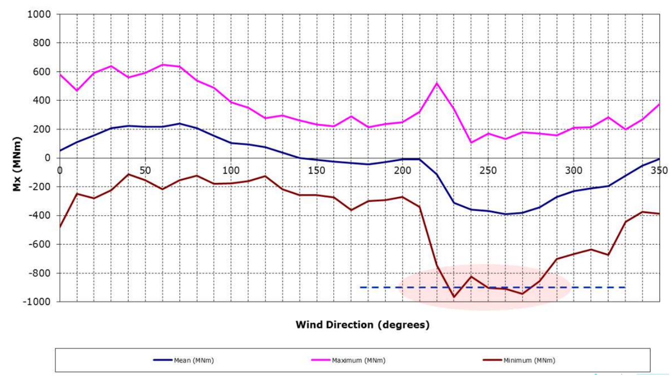

Figure 8. Directional Base Moment Comparison – Wide Peak

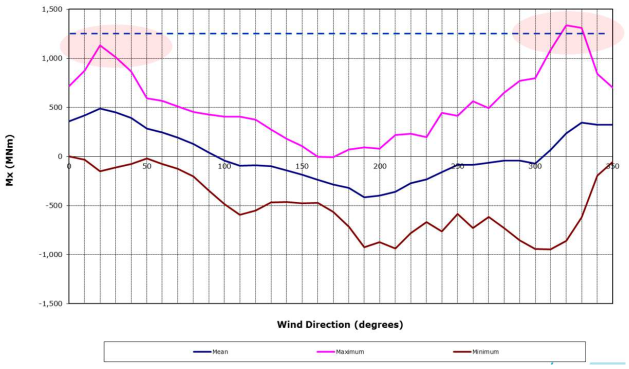

Figure 9. Directional Base Moment Comparison – Double Peak

For the wider peak and double peak case the peak response is occurs over approximately 60^{o} and the overestimates are 8 and 6% respectively. Whereas for the single peak case the peak response occurs over a narrow directional range of approximately 30^{o} and the overestimate is 19%.

A similar comparison can been made for the peak accelerations, where for a single peak the overestimate is 19% (Figure 10).

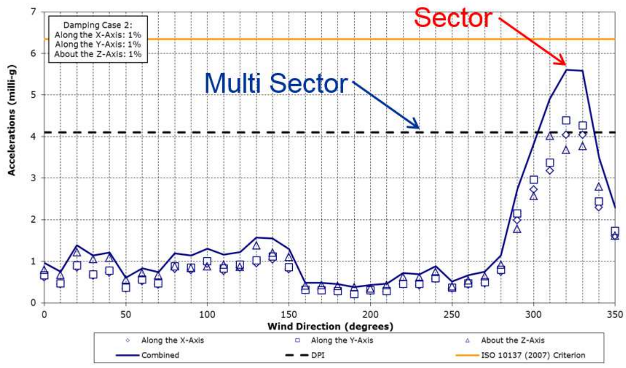

Figure 10. Highest occupiable level acceleration comparison

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.
- The probability of exceedance for each 45-degree sector is half that of the non-directional analysis.

This effect can be seen in the case study examples, where the two cases with the broader directional response have only a small overestimate compared with the narrower example where the overestimate is larger.

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

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.

For base moments the median overestimate of the sector method compared with the multi-sector method is 12% and for peak building accelerations measured at the highest occupiable level greater than 1 milli-g, the median overestimates is 14%.

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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