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Estimation of Torsional Loads on Tall Buildings

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Abstract

Four methods for the estimation of the maximum peak torsional moment from measured or calculated peak horizontal shear forces are presented. The relationship is based on the analysis of over 50 wind tunnel studies of tall buildings using the high frequency force balance. The heights of the subject buildings range from 70m to 290m.

The results support the estimation of the maximum peak torsion using a value of the eccentricity factor (*e*) of 0.2 multiplied by the maximum along wind loading and maximum width. However, the maximum peak torsional moment may be more accurately estimated using the maximum of the along wind or cross wind loading, which accounts for torsional loads generated by cross wind forces. This approach is generally suited to rectangular shaped buildings, with minimal local interference and aspect ratios (defined as minimum width divided by maximum width) between 0.2 and 1.

The two methods mentioned above are suitable for incorporation within a wind loading code as they are simple to apply and they only require the designer to convert the peak torsional moment from the peak horizontal shear force. For the purpose of codification, we recommend that this approach be limited to buildings that have a plan aspect ratio of greater than 0.4.

Introduction

Medium to tall buildings experience wind induced moments about their vertical axis or torsional moments. The torsional moments should be considered in combination with the buildings overturning moment. The magnitude of the torsion moment is affected by a number of factors including plan shape, eccentricity of the lift core relative to the centre of mass and the natural frequency of the torsional mode. The taller the building the more these torsional moments can contribute significantly to the loads on structural members.

A recent addition to the Australian / New Zealand Standard on Structural Design Actions Part 2: Wind Actions (Standards Australia (2011)) was the incorporation of the requirement to apply torsional loading to buildings of greater than 70m in height. Standards Australia (2011) recommends the torsion shall be based on applying the along wind loading to the building with an eccentricity of 20% of the maximum building width.

This study was undertaken to establish a simple relationship between the overturning moments and the torsional moments. As well as to explore the basis of the requirements of Standards Australia (2011) and determine if the provision can be extended or refined.

The wind tunnel results of over 50 tall buildings were used for this study. The aim is to examine the basis for and an appropriate value for an eccentricity factor (*e*).

Methodology

The results from over 50 of the most recently performed wind tunnel studies were analysed. As no selection or filtering of these studies were conducted these can be considered as a “snapshot” of recent building designs. As the buildings considered were proposed for development and the studies were conducted as part of their design process, the majority of the wind tunnel studies considered were conducted with local surrounding buildings in place.

In this paper the wind tunnel study results have been separated into three groups based on the plan shape and influence of surrounding buildings. The groups are defined as:

Group A: Rectangular plan shape with no or very low surrounding buildings

Group C: Rectangular plan shape with low or moderate surrounding buildings

Group C: All other buildings

There are 16 buildings in Group A, 14 buildings in Group B and 23 buildings in Group C. Buildings in Groups A and B can be considered to be covered by AS/NZS 1170.2.

The testing for these buildings was conducted in an atmospheric boundary layer wind tunnel with the wind speed and turbulence profiles matched to the environment surrounding the study buildings. The peak and mean overturning and torsional moments on these buildings were measured using the high frequency force balance technique. These values were measured for 36 wind directions. As the peak moments include the contribution from the background and resonant response of the buildings the calculation of these moments is depended on information on the building’s dynamic properties provided by the structural designer. For further details of the analysis techniques please see Holmes *et al* (2003).

The results from the wind tunnel studies were analysed in terms of the non-dimensional moment and force coefficients effectively ignoring directional variations in the reference wind speed. These coefficients are defined as:

$$C_{\hat{M}_z} = \frac{\hat{M}_z}{\frac{1}{2}\rho\bar{V}_{bh}^2 b_{\max}^2 h} \quad (1)$$

$$C_{\hat{F}_x} = \frac{\hat{F}_x}{\frac{1}{2}\rho\bar{V}_{bh}^2 b_{\max} h} \quad (2)$$

Where: $\hat{M}_z =$ Peak moments about z

$\hat{F}_x =$ Maximum Peak horizontal shear force (along-wind or cross-wind)

$\hat{F}_{AW}$ = Peak horizontal along wind shear force

$\hat{F}_{CW}$ = Peak horizontal cross wind shear force

θ = Wind direction causing wind action

$\overline{V}_{bh}$ = Mean wind speed at building height

h = Building Height

$b_{\max}$ = Maximum Width

As introduced previously the torsional moments can be estimated from the couple defined as

$$\hat{M}_z = e.b_{\max}.\hat{F}_x \tag{3}$$

where e is the eccentricity factor. This can be expressed in coefficient form as:

$$C_{\hat{M}_z} = e.C_{\hat{F}_x} \tag{4}$$

where $C_{\hat{F}_x}$ is obtained by dividing the peak bending moment by the height of the corresponding line of action of force. The height of the line of action of the force is determined by distributing the mean component of the peak base moment as per AS/NZS1170.2 for a quasi-steady load and the dynamic component according to the inertial moment distribution for that axis.

It can be seen that the eccentricity factor is simply the ratio of the torsional moment coefficient to the force coefficient. In this paper the eccentricity factor is presented for the three building groups based on variations in the method of selection of the peak horizontal shear force coefficient in equation (4). In all cases, the eccentricity factor, e has been calculated from the overall maximum peak torsional moment coefficient. In addition, the effect of local directional wind speed variations was analysed.

The results have been plotted as a function of the aspect ratio of the building, where the aspect ratio is defined as the minimum breadth divided by the maximum breadth.

Results and Discussion

Method 1

The eccentricity factor (e) can be calculated from equation (5) based on the peak along wind shear force coefficient that occurs from the same direction as the maximum peak torsional moment coefficient. These results are presented in Figure 1 for the three building-surrounds groups.

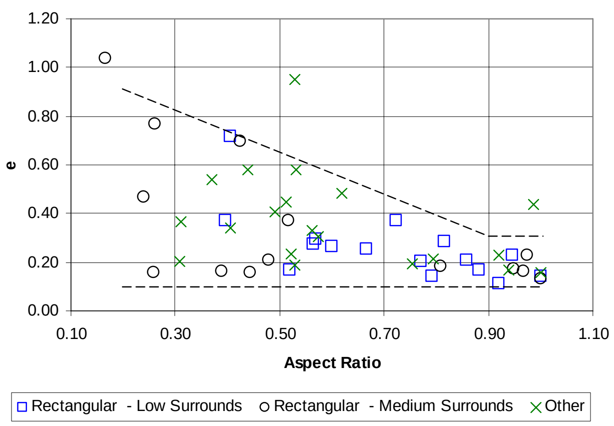

Figure 1. Eccentricity factor based on peak torsional moment and the corresponding along wind force for the three building groups.

$$\max(C_{\hat{M}_{z,\theta}}) = e.C_{\hat{F}_{AW,\theta}} \tag{5}$$

It can be seen in Figure 1 that there is a large variation in the calculated value of e and that e ranges in values between 0.1 and 1. The factor e increases for buildings with a small plan aspect ratio and these large e values are probably due to the torsional moments being generated by cross wind forces rather than the along wind forces which were used to calculate e..

Method 2

Alternatively, e can be calculated from equation (6) based on the maximum peak along wind shear force coefficient (Figure 2). This force coefficient may occur from a different wind direction to that of the maximum peak torsional moment coefficient.

$$\max(C_{\hat{M}_z}) = e.\max(C_{\hat{F}_{AW}}) \tag{6}$$

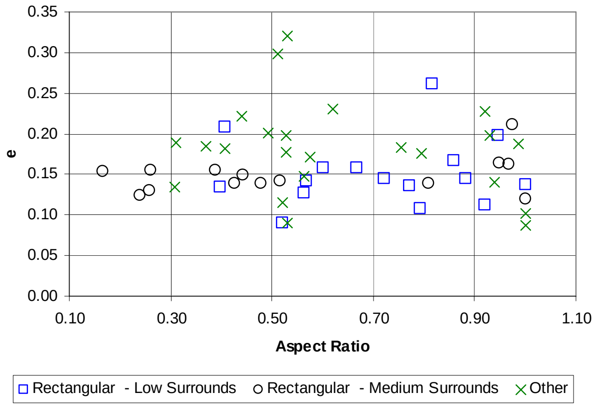

Figure 2. Eccentricity factor based on peak torsional moment and the maximum peak along wind force for the three building groups.

Figure 2 shows that for the buildings in Group A and B that the majority of the buildings have an e value of less than or equal to 0.2 with an average value of 0.15. There is also no clear dependency of aspect ratio as was the case in Figure 1 for the aspect ratios between 0.2 and 1.

There is a notable outlier from Group A, with an aspect ratio of 0.82 and e value of 0.26. This building was approximately 150m tall and was tested with only low rise surrounding buildings. The plan shape of this building is shown in Figure 3. Although the building is predominately rectangular in plan form, there are extensions on the east and west sides of the building. These extensions are most likely responsible for increasing the torsional moments on the buildings compared with the other similar buildings presented in Figure 2.

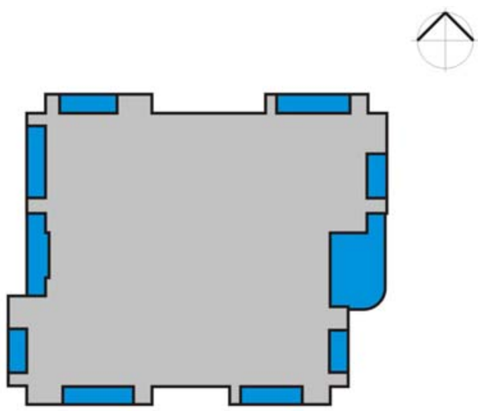

Figure 3. Plan shape of outlier from Figure 2.

Method 3

The angle between the wind direction inducing the largest torsional moment and direction normal to the widest face has been plotted as a function of aspect ratio (Figure 4). For buildings in Group A and B (square and circle markers) there is a bimodal distribution of the angles where the peak torsion occurs with 93% of the buildings have peak torsion occurring for angles between 5°and 25° or 75° and 90°. For Group A buildings (square markers, very low interference), with an aspect ratio of less than 0.8, the maximum peak torsion always occurs for angles between 80° and 90° to the longest face. That is, the wind is occurring for directions normal to the shorter face and this suggests that in these cases the crosswind response is generating the maximum peak torsion.

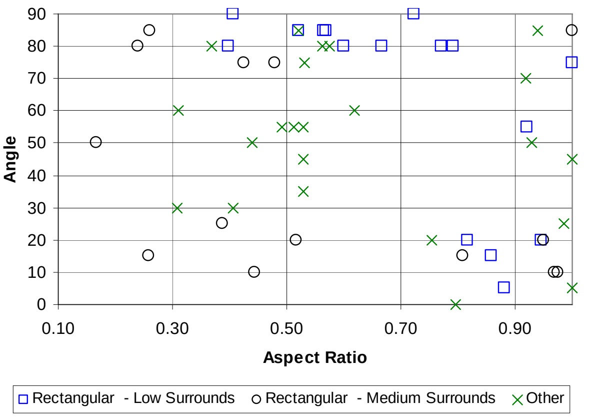

Figure 4. Angle between the wind direction inducing the largest torsional moment and direction normal to the widest face.

Based on the observation from Figure 4, *e* has been calculated from equation (7) based on the maximum overall peak force coefficient. This force coefficient may occur from a different wind direction to that of the maximum peak torsional moment coefficient and may be a result of an along or cross wind force. The results are presented in (Figure 5).

$$\max(C_{\hat{M}_z}) = e.\max(C_{\hat{F}_{AW}}, C_{\hat{F}_{CW}}) \qquad (7)$$

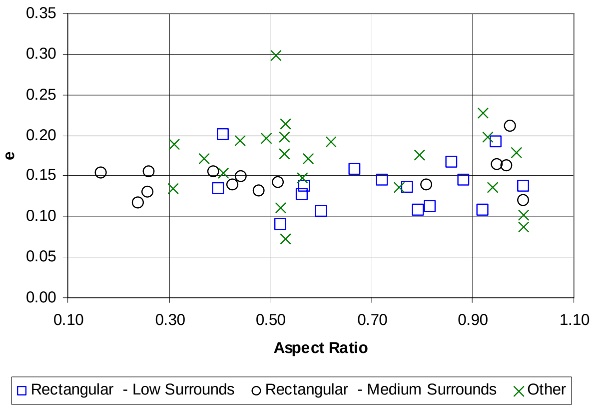

Figure 5. Eccentricity factor based on peak torsional moment and the maximum peak along force for the three building groups.

Figure 5 shows that compared with Figure 2, there is a closer agreement with an *e* value of 0.2 as an upper bound for all the building groups. For example, the outlier from Group A in Figure 2 and highlighted in Figure 3 has an *e* value of less than 0.2 based on equation (7). The highest value of e calculated was 0.30. The larger than expected torsional moment for this building is most likely due to its plan shape which is a parallelogram with deep recesses in the middle of each of the two long faces and its low natural frequency for vibration about the vertical axis which are comparable to the natural frequencies for vibration about the horizontal axes.

Method 4

In equations (5) to (7) *e* has been calculated based on the maximum width of the building. An alternative method is to calculate *e* based on the maximum plan form diagonal length of the building. Results for *e* based on this method are shown in Figure 6. Note that the moment and force coefficients are still defined using the maximum plan form width as described in equations (1) and (2).

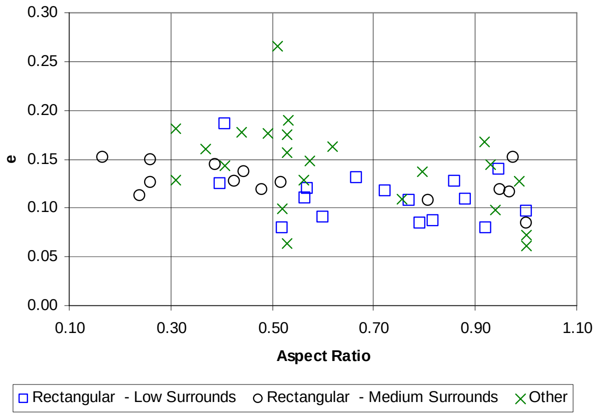

Figure 6. Eccentricity factor based on peak torsional moment and the maximum peak force for the three building groups using the maximum plan form diagonal length of the building.

Figure 6 shows that for the buildings in Group A and B that the majority of the buildings have an *e* value of less than or equal to 0.15 and there is also no clear dependency on aspect ratio. As *e* based on the maximum plan form diagonal length can be related to *e* based on the maximum width by:

$$e_{diag} = \frac{1}{\sqrt{1+\left(\frac{b}{d}\right)^2}} e \qquad (8)$$

The effect of using the maximum plan form diagonal length and using a lower value of *e* is to reduce the calculated torsional moments on the buildings with small aspect ratios while maintaining the calculated torsion for buildings which are approximately square in plan form.

Effect of shape parameter

The *e* value calculated in Figure 5 were re-plotted against the shape parameter *f* which is defined as:

$$f = \left(\frac{b_{\min}}{b_{\max}}\right)^2 \qquad (9)$$

where b_{min} is the minimum projected width and b_{max} the maximum projected width. Torsional moment coefficients have previously been analysed using this parameter as the abscissa (Cheung and Melbourne, 1992). Figure 7 shows similar results to Figure 5 with no improvement in the correlation between *e* and the shape parameter.

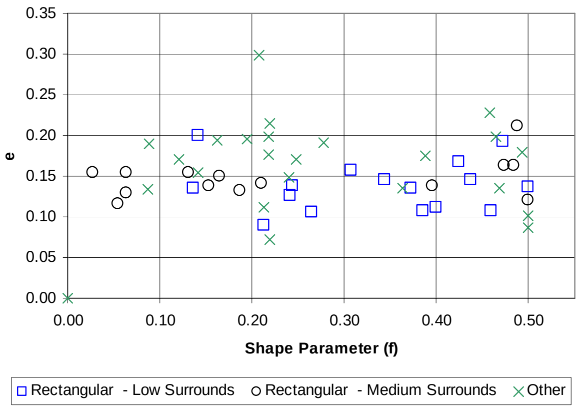

Figure 7. Eccentricity factor based on peak torsional moment and the maximum peak force for the three building groups plotted against the shape parameter f.

Effect of directional wind speeds

The *e* value was also calculated using the full scale moments and force results from the wind tunnel studies. As these moments and forces have not been non-dimensionalised by the wind speed, these results included any directional effects of the local wind climate. Figure 8 shows that there is increased variation in the value for *e*. However, a maximum value of *e* of 0.2 is still applicable for buildings in Group A or Group B. These results are based on Method 3 in the selection of the peak horizontal shear force coefficient.

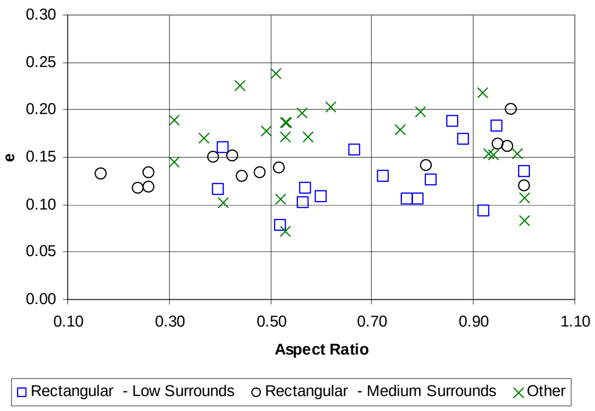

Figure 8. Eccentricity factor based on peak torsional moment and the maximum peak along wind force for the three building groups calculated using the dimensional moment and force results.

Conclusions

This study shows that for buildings which are rectangular in shape and surrounded by very low to medium height buildings the angle between the wind direction inducing the largest torsional moment and direction normal to the widest face was found to have a bimodal distribution, with the peak torsion generally occurring for angles between 5^o and 25^o or 75^o and 90^o. For buildings with very low surrounding buildings and an aspect ratio of less than 0.8, the maximum peak torsion always occurs for angles between 80^o and 90^o to the longest face. This suggests that in these cases the crosswind response is responsible for generating the maximum peak torsion.

The above indicates that the maximum peak torsion is best predicted using the maximum of the along wind or cross wind loading as this accounts for torsional loads generated by cross wind forces, combined with an eccentricity factor of 0.2 with respect to the maximum overall width. For rectangular shaped buildings with minimal local interference this method is suitable for aspect ratios between 0.2 and 1.

Notwithstanding the above, using a value of the eccentricity factor (*e*) of 0.2 combined with the maximum along wind loading and maximum width is a suitable method.

The two methods mentioned above are suitable for incorporation within a wind loading code as they are simple to apply and they only require the designer to convert the peak torsional moment from the peak horizontal shear force. Considering the sparse number of buildings in this study having a plan aspect ratio of less than 0.4 and the range of plan aspect ratios provided in the standard for the computation of the cross-wind response, for codification it is appropriate to limit the applicability of these methods to cases where the plan aspect ratio is greater than 0.4.

Acknowledgments

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References

Cheung JCK, Melbourne WH, (1992), Torsional Moments of Tall Buildings, J. Wind Engineering and Industrial Aerodynamics, Vol 41-44:1125-1126.

Holmes JD, Rofail AW, Aurelius LJ, (2003), "High frequency base balance methodologies for tall buildings with torsional and coupled resonant modes." 11th International Conference of Wind Engineering, Lubbock, Texas.

Standards Australia/Standards New Zealand (2011) Structural Design Actions Part 2: Wind Actions, AS/NZS 1170.2:2011, Standards Australia, Sydney, NSW