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Wind Engineering for a Complex Structure

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Abstract

Windtech Consultants was engaged to model the extreme loads and pressures acting on a 107m (305ft) tall statue in the form of Lord Shiva, to be constructed in Nathdwara, India. To add to the complexity, the form of the statue includes a trident held from the base and having the form of a 58m high mast. This paper details the methodology adopted for this study as well as some of the findings.

Introduction

The site for the statue is Nathdwara in the state of Rajasthan, India. The site is approximately 500km south-west of New Delhi and 600km north of Mumbai. It is proposed that the statue will be constructed within a newly landscaped parkland and that the statue will be positioned on the top of a ridgeline. The statue will be constructed from a concrete skin over steel framework. A sprayed metal finish will be then applied to the concrete. The trident will be constructed from a concrete staff and the head of the trident is a metal skin over a steel frame (Figure 1).

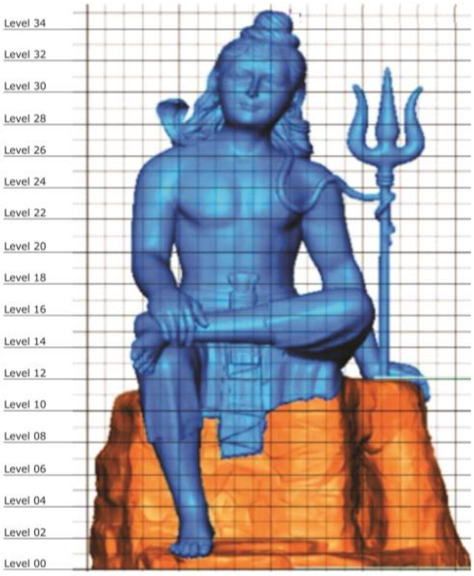

Figure 1: Shiva Statue Elevation

To determine the extreme wind loads on the statute a detailed wind tunnel study was undertake and the following areas were considered: analysis of the local wind climate, determination of the wind loads on the main statue, determination of the wind loads on the trident and determination of the surface pressure distribution on the statue and the trident. In this paper the first three items will be discussed.

Wind Tunnel Model

A small model of the statue was initially sculpted by a renowned artist and then three-dimensionally scanned. This three-dimensional CAD file was used to construct the model using three-dimensional printing. The complete statue was constructed at a scale of 1:200 and additionally a detailed model of the head of the trident and top of the statue was constructed at 1:100 scale (Figure 2). These models were used in the subsequent wind tunnel testing.

Figure 2: 1:200 Scale model setup in the wind tunnel

Local Wind Climate

A detailed wind climate analysis was conducted for the Nathdwara region using data from the nearby Jaipur and Kota Airports. Other nearby airports, such as Jodhpur were not used due to topographical and geographical differences between the development site and the airports. The wind speed measurements were terrain corrected and analyzed using the Gringorton's extreme value technique (Holmes, 2001). Due to the projected long lifetime of the structure, a wind speed based on a mean recurrence interval of 250 years was requested.

Figure 3 presents a comparison of the results of the wind climate analysis with the Indian wind loading code (Bureau of Indian Standards, 2007) and the Asia-Pacific wind speed handbook (Holmes & Weller, 2002). For subsequent analysis the 250 year basic gust wind speed of 49.2 m/s as determined by Windtech was used. Directional wind speed probability distribution was also determined for this site. The directional probabilities were modified to account for uncertainties in the wind climate data.

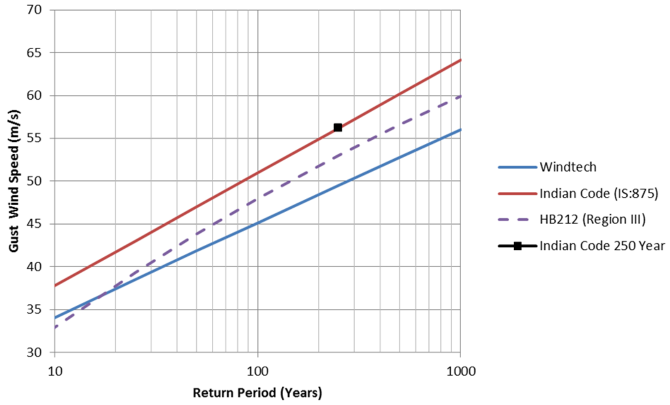

Figure 3: Comparison of basic 3 second gust wind speeds for the Nathdwara Region (referenced to 10m height in open terrain)

Wind Loads on the Main Statue

Method

The wind loads on the structure were determined using the high frequency pressure integration method. The high frequency pressure integration method determines the wind loads by integrating simultaneously recorded surface pressure measurements with a patch area and moment arm. This method was preferred over the high frequency force balance method due to the practical issue that there was the potential for the vibrational natural frequency of the wind tunnel model to conflict with the first mode natural frequency of the completed statue, during the calculation of the resonant response. The patch areas and moment arms were determined from the three dimensional CAD model.

Due to the complex form of the statue, the reliability of the integration patch areas and moment arms was confirmed by testing the statue using the high frequency force balance method and comparing the mean response. The mean overturning base moment from the two methods were compared and good agreement was found (Figure 4 and Figure 5).

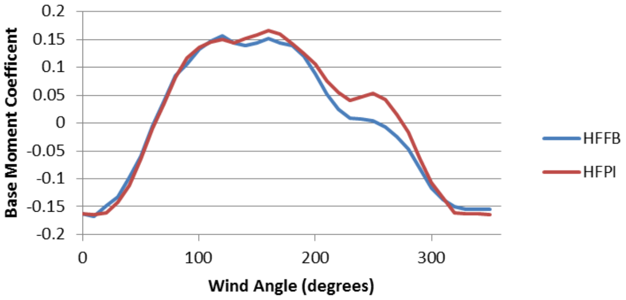

Figure 4: Comparison of Base Moments high frequency pressure integration (HFPI) vs high frequency force balance (HFFB), moments about the Y-Axis

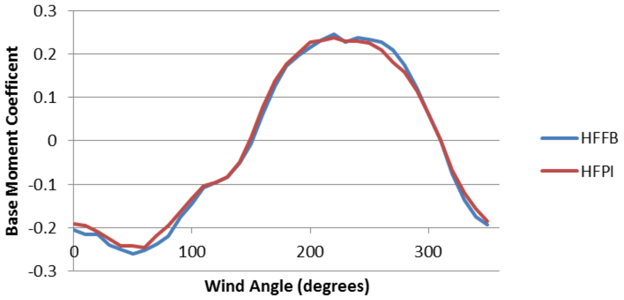

Figure 5: Comparison of Base Moments high frequency pressure integration (HFPI) vs high frequency force balance (HFFB, moments about the X-Axis

Results

The wind tunnel results from the high frequency pressure integration test were combined with the wind climate model to determine the base moments. The base moments were calculated using the directional probability integration method (multi-sector method) (Holmes, 1990) which accounts for the probability of winds occurring from various directions. Figure 6 presents the axis diagram and the directional contribution to the moments about the X and Y-axis. Figure 7 and Figure 8 show that the response of the statue to wind loading is not overly directional. The probability integration method estimates the loads to be 9% lower for moments about the X-axis and 19% lower for loads about the Y-axis, compared with the traditional sector by sector calculation method. These modest reductions are typical for structures which have a broad directional response.

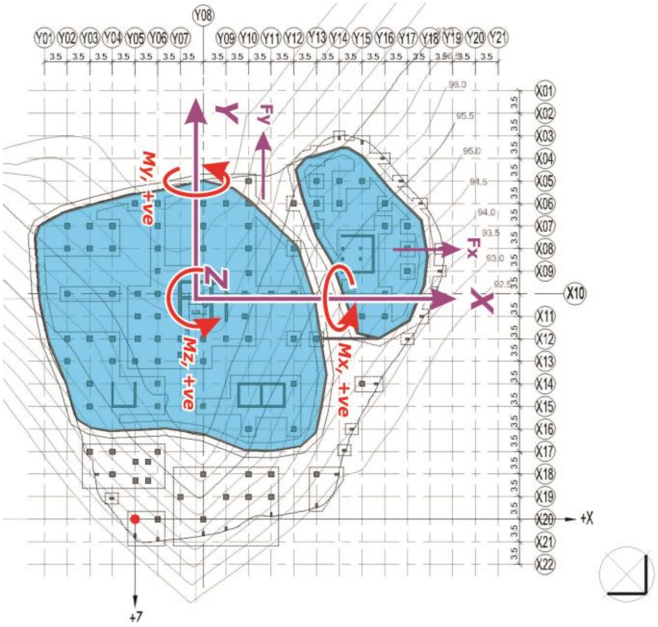

Figure 6: Main Statue Results - Axis Diagram

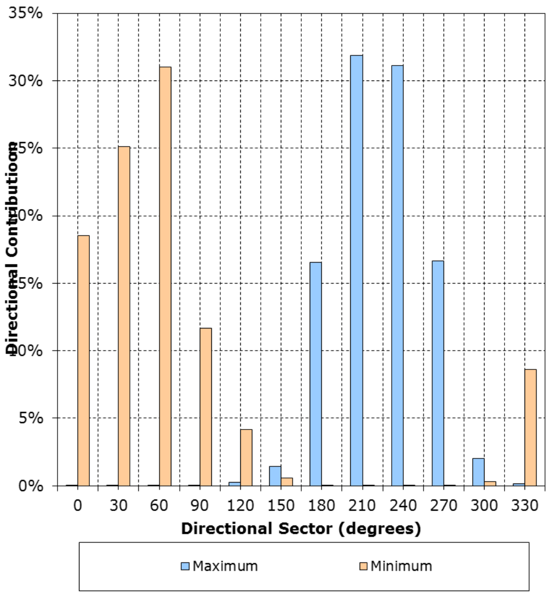

Figure 7: Main Statue Results - Moments about X-Axis

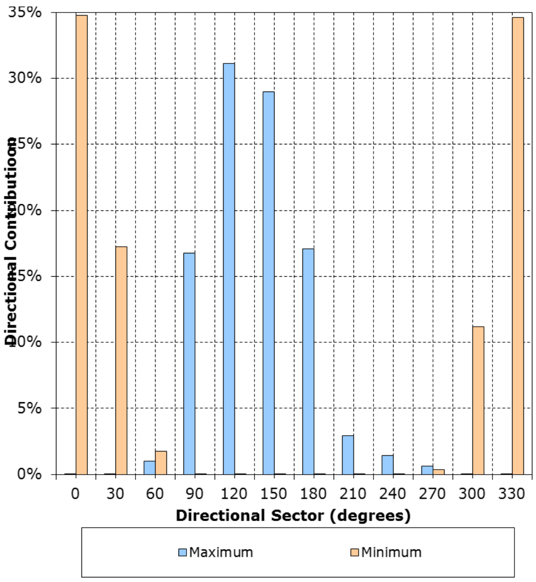

Figure 8: Main Statue Results - Moments about Y-Axis

Wind Loads on the Trident

Method

The statue design team were considering two structural linkage design options for the trident. In the first option, the trident is linked to the statue only at the base of the trident on Level 12 and in the second option the trident is also structurally linked to the statue by the tail of the snake. In the case of the first option the snake is only ornamental. Wind loads were estimated for the first case with the results of this study to inform the decision on whether a structural linking using the snake should be incorporated into the final design.

The wind loads on the trident were determined using the effective static loads method (Holmes, 1996; Holmes, 2002). In this method the mean, background and resonant response are calculated separately and then combined to provide an effective load distribution. To enable the application of this method the drag coefficient of the head of the trident was determined using a 1:100 scale wind tunnel model. The impact of the statue in increasing the wind speed around the trident head for selected wind angles was measured using a wind tunnel test including the top of the statue (Figure 9 and Figure 10). These increases were included in the final load calculations.

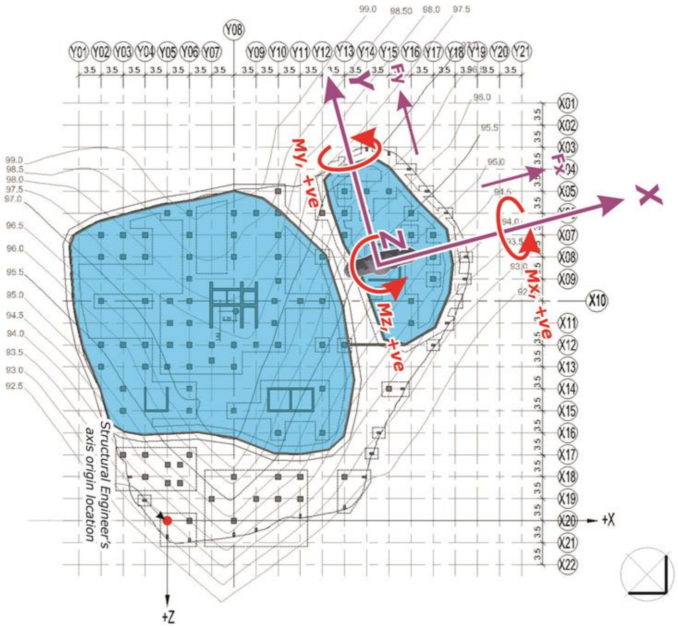

Figure 9: Trident Axis Diagram

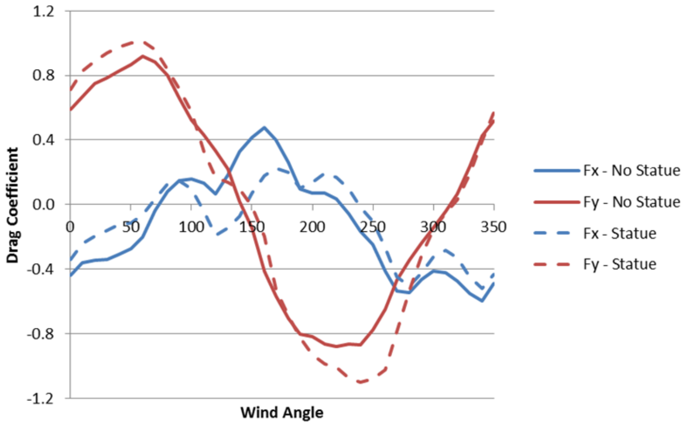

Figure 10: Trident - Comparison of Drag Coefficients for cases

Results

The mean, background and resonant response of the trident were calculated using the effective static loads method and the estimated pressure distributions are shown in Figure 11. The mean and background pressure distributions are follow the expected trends. However, the effective resonant pressure distribution has a large peak at Level 24. This is associated with the transition from a concrete staff to a steel framed trident head as well as the mass of the cross bar of the trident.

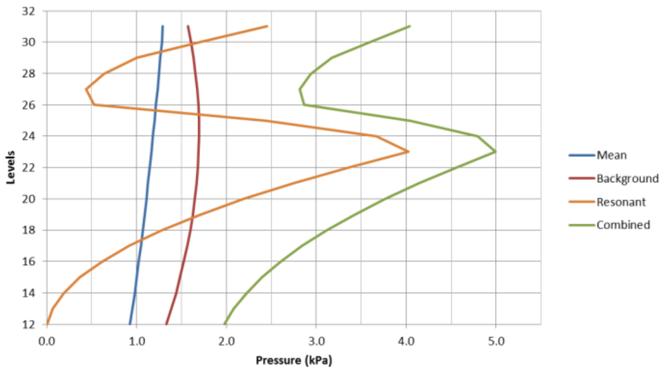

Figure 11 : Trident Results - Pressure Distribution

A feature of the effective static loads method is the inclusion of the effect of aerodynamic damping. For this structure the aerodynamic damping was estimated to be 1.4% of critical which is approximately two-thirds of the total damping of the structure. The final force distribution is calculated by using the combined pressure distribution with the drag coefficients from the 1:100 scale model tests. The drag coefficient for the shaft was based on the surface roughness and was taken from the Australian and New Zealand Standard on wind actions (Standards Australia, 2013).

Figure 12 shows the final shear force distribution as a percentage of the total shear force.

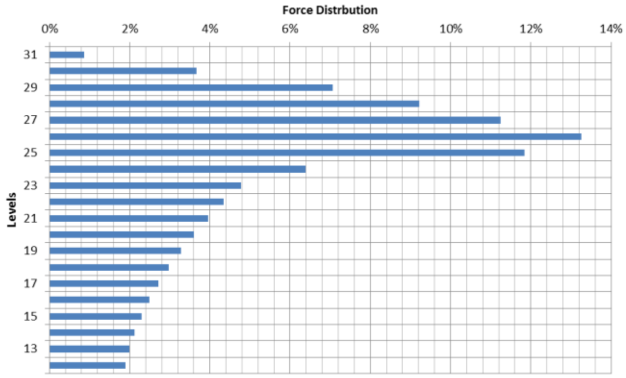

Figure 12 : Trident Results - Force Distribution

Conclusions

A methodology has been presented for the study of wind induced structural responses for a complex building form. There was good comparison between the mean high frequency pressure integration and force balance methods and the high frequency pressure integration method has been found to be an effective method for determining the wind loads on this complex structure.

Acknowledgments

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