The 2014 World Congress on
Advances in Civil, Environmental, and Materials Research (ACEM14)
Busan, Korea, August 24-28, 2014

Wind loading of industrial, mining and petrochemical structures– some case studies

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ABSTRACT

Industrial structures, such as those used for mining activities and petrochemical production, are typically high-value, and are often located in coastal areas of the globe exposed to high winds, such as those produced by tropical cyclones. This paper discusses several cases, in the experience of the author, in which wind loadings of some petrochemical and mining structures were examined in detail, and reviews alternative approaches, such as wind-tunnel tests and the use of codes and standards and specialist design guides

1. INTRODUCTION

Industrial structures, such as those used for mining activities and petrochemical production, are typically high-value, and are often located in coastal areas of the globe exposed to high winds, such as those produced by tropical cyclones, including hurricanes and typhoons. However, shape factors and force coefficients specified in wind codes and standards are usually heavily targeted towards enclosed buildings. Industrial structures typically consist of numerous individual elements including cylindrical vessels, pipes, valves, ladders, conveyors etc., with supporting framework. Thus, mutual shielding and aerodynamic interference effects are important. In many cases, structural designers attempt to use codes and standards which have inadequate provisions for industrial structures, and significantly over-estimate wind loads as a result of the neglect of shielding effects. In other cases where dynamic effects are important, such as flare stacks and chimneys, total wind loading, including the inertial loading produced by resonant response, may be underestimated.

This presentation discusses several cases, in the experience of the author, in which wind loadings of some petrochemical and mining structures were examined in detail, and will review alternative approaches, such as wind-tunnel tests, the use of specialist design guides such as that produced by the American Society of Civil Engineers (ASCE Petrochemical Energy Committee, 2011) and more advanced approaches for tall towers and chimneys, such as the 'equivalent static wind load approach' (Holmes, 1996).

2. DESIGN STANDARDS AND GUIDES

2.1 Wind loading codes and standards

[1)] Director

Wind loading codes and standards, such as Australian/New Zealand Standard AS/NZS 1170.2 (Standards Australia, 2011) and ASCE 7 (American Society of Civil Engineers, 2010), have primarily been written for buildings and generally provide aerodynamic shape factors, such as pressure and force coefficients, for prismatic shapes representing generic tall and medium rise buildings. For low-rise buildings pressure coefficients for various roof shapes and pitches are provided. Shape factors for shapes typical of industrial structures may be provided, but these have generally been less well researched, and are often consigned to Appendices or Annexes in these documents.

Table 1 shows a selection of shapes for which factors (i.e. pressure and force coefficients) are provided in five major codes and standards. The documents covered are as follows:

- International Standard ISO 4354:2009 Wind actions on structures. (International Standards Organization, 2009)
- Eurocode 1: Actions on Structures, Part 1-4. Wind actions. EN 1991-1-4:2005. (British Standards Institution, 2005)
- ASCE 7-10, Minimum design loads for buildings and other structures. Chapters 26-31: Wind loads. (American Society of Civil Engineers, 2010).
- AIJ Recommendations for loads on buildings. (Architectural Institute of Japan, 2004).
- Australian/ New Zealand Standard, AS/NZS 1170.2:2011. Structural design actions. Part 2: Wind actions. (Standards Australia, 2011)

As can be seen from Table 1, most of these documents provide information for basic elements that make up industrial, mining and petrochemical facilities. This information can generally be used to give conservative estimations of wind forces on sections of a plant that are composed of these elements. What is missing, however, is the mutual shielding and aerodynamic interference that results from closely-spaced elements. As a result, most code-based estimates of wind loads for industrial plant are highly conservative. There is clearly a need for specialist design documents that cover these issues in a less conservative way.

Table 1 Shape factors useful for industrial structures contained in five codes and standards

TYPE	ISO 4354	EN 1991	ASCE 7	AIJ	AS/NZS1170.2
Domes	no	yes	yes	yes	yes
Bins, silos, tanks	yes	yes	yes	no	yes
Circular sections	yes	yes	yes	yes	yes
Polygonal sections	no	yes	yes	no	yes
Structural angle sections	yes	yes	no	no	yes
Lattice sections	yes	yes	yes	no	yes
Sphere	no	yes	no	no	yes

2.2 Specialist design guides

There are relatively few alternative documents that provide wind loading information, available to structural designers of industrial, mining and petrochemical facilities.

A well-established series of design guides are the wind engineering data items of ESDU International of London U.K. These provide a comprehensive series of data covering all aspects of wind loading – i.e. on wind speeds, turbulence and adjustment for terrain and topography, shape factors for many shapes, and methods of dealing with dynamic response to wind – both along wind and cross wind. Detailed information is provided on pressures and forces on structures with circular cylindrical cross-section (ESDU 80025, 81017), and polygonal and elliptical cross sections (ESDU 79026). Forces on pairs of circular cylinders with various orientations to the wind are covered by ESDU 84015; however this would not be sufficient for a large number of circular sections, such as pipes in a pipe rack, that are common in petrochemical and other chemical facilities.

Force coefficients for sharp-edged structural sections, such as I and L sections, are provided in ESDU 82007. ESDU 81027 provides detailed advice on wind forces on single and multiple planar lattice frames; methods for dealing with additional drag-producing elements such as gusset plates are given, and a pipe bridge structure is used as an example. Tower-like space frames, including those with both flat-sided (angle) and circular members, and the effects of various internal and external ancillaries, are covered by ESDU 81028; although the original inspiration was communication towers, this Item would be useful for flare towers used in the oil and gas industry, and open lattice conveyors used in the mining sector.

At this point it should be noted that the data used in all codes, standards and guides for lattice towers with tubular members of circular cross-section, can all be traced back to a series of tests carried out in the U.K. in the nineteen-seventies (Gould and Raymer, 1972). These tests were unique in that they were carried out in a compressed-air wind tunnel, and thus Reynolds Numbers equivalent to those on full-scale lattice towers could be achieved without the use of roughening of the cylindrical elements. However, there are some questions regarding end effects, and blockage corrections for these test results, and new tests for this type of structure, common in the petrochemical industry should be carried out.

A useful document, that has been produced primarily for petrochemical structures, is the guide: 'Wind loads for petrochemical and other industrial facilities' produced by the American Society of Civil Engineers (ASCE Petrochemical Energy Committee, 2011). This is one of five documents produced by the ASCE Petrochemical Energy Committee.

Although directed at American (U.S.) practice with many references to other documents such as ASCE 7, the guide is generally useful to structural designers of petrochemical facilities, and similar industrial structures. It summarizes available information on shape factors for elements such as pipe racks (i.e. arrays of pipes of different diameters), open frame structures, partially clad structures, pressure vessels and cooling towers. In particular, recent generic research from Louisiana State University (e.g. Amoroso and Levitan, 2009; Amoroso *et al*., 2009 is summarized.

Appendix 5B of the ASCE guide is particularly useful, as it has provided a single formula for the maximum force coefficient (for most structures this can be taken as a drag coefficient) for ‘high solidity open frame structures’, comprising structural members and equipment and ancillaries such as piping, ladders, handrails, electrical cable trays etc. enclosed within the overall envelope of the framing. This formula is:

$$C_{D,max} = \frac{1.4\,\phi\sqrt{B^2+L^2}}{2B\left(1+\frac{B^2}{L^2}-\frac{B^2}{L^2}\sqrt{B^2+L^2}\right)} \quad (1)$$

B and L are the plan dimensions corresponding to the across-wind width and along-wind length respectively. ϕ is the total solidity, including equipment, presumably determined from an elevation projected in the nominal wind direction.

This formula provides an overall wind force, without providing a distribution of that force within the various elements of the system. The user needs to make a rational distribution of the overall load. It is presumably intended as a quasi-steady force coefficient intended to be used with the 3-second gust duration of ASCE 7, and hence may need modification for other gust durations such as the 0.2 second gust used in AS/NZS 1170.2, or the 10-minute mean wind speed used in Europe (e.g. Eurocode 1) and in several East Asian economies.

The formula is based on mean force coefficients from wind-tunnel tests, and therefore may not take into account correlation effects which would produce reduced loads over complexes with very large horizontal or vertical dimensions. However, Equation (1) could be used as a useful ‘reality check’ on the overall wind loads for complex plants, computed by accumulating contributions from individual elements with no allowance for shielding or aerodynamic interference, and thus giving highly conservative wind loads.

3. WIND-TUNNEL STUDIES

In the following, four examples of petrochemical and mining structures, for which detailed assessments of wind loading were made by the use of wind-tunnel tests, are discussed. For all of these structures, estimates of wind loading were initially made using codes and standards; however these loads resulted in structural design problems and led to requests for the wind-tunnel tests. Two were new structures still in the design stage at the time of the assessments. Two of the structures were existing structures (both about twenty years old at the time of the assessments), but structural checking had raised some doubts about their adequacy into the future. For commercial reasons, the identity and exact location of these structures, or numerical details of the shape factors, or their response to wind cannot be presented. However, useful general information is provided in the following.

3.1 Structure A: LNG loading platform

Figure 1 shows a wind-tunnel model (1/70 scale) of a platform used to load liquified natural gas (LNG) on to ships. The platform is located at the end of a jetty more than 1 kilometre long, so that it is exposed to the open ocean from all directions. Furthermore the location is regularly visited by tropical cyclones (typhoons), so that wind loading is a critical factor in the structural design of the platform, particularly for the piles supporting the platform from the ocean floor.

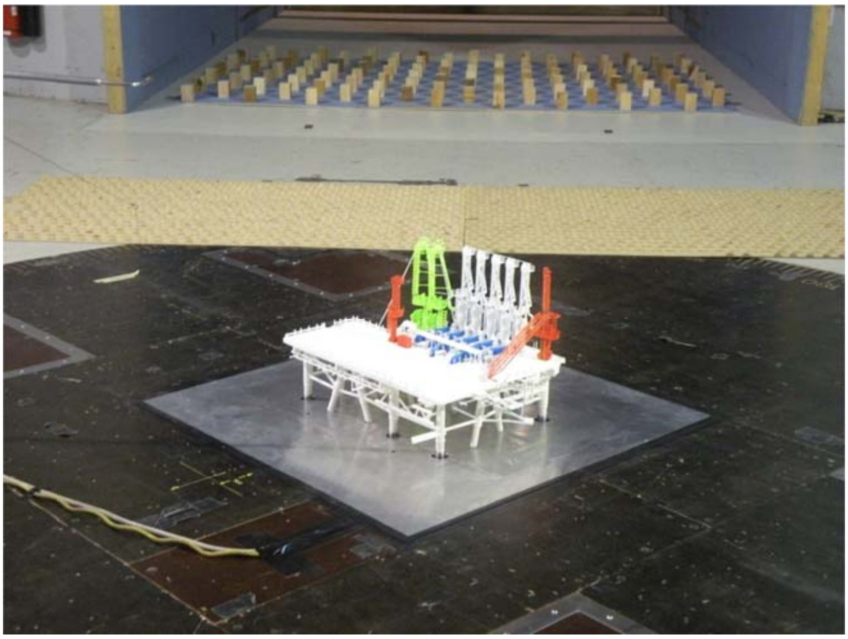

Fig. 1 1/70 scale wind-tunnel model of a LNG loading platform (Structure A)

The plan dimensions of the concrete decks of the full-scale platform are 45m by 34m. The upper deck of the platform supports several ship-loading arms, as well as other equipment, such as a crane, fire monitor tower, and pipework above and below the decks. An accurate model of the platform above water level, and the ancillaries above and below the decks was made using the stereo-lithography (3-d printing) technique making use of digital drawings supplied by the client. To account for the sub-critical Reynolds Numbers on the model, in contrast to the super-critical flow in full-scale conditions, the major elements of circular cross section were reduced in diameter by one third from that corresponding to the nominal geometric scaling ratio of 1/70.

The model was mounted on a high-frequency force balance and exposed to a simulated atmospheric boundary layer in a large wind tunnel. The simulations included accurate modeling of the mean velocity profile, longitudinal turbulence intensity, and longitudinal turbulence spectrum, following the provisions of the AWES Quality Assurance Manual AWES-QAM-1 (Australasian Wind Engineering Society, 2001). The top of the upper deck of the platform was mounted at a height above the surface to represent the design condition in which the strong winds from a tropical cyclone are accompanied by a storm surge.

Time histories of the three components of wind forces on the model were recorded and processed to give mean, maximum and minimum values of the full-scale equivalent. The largest resultant maximum horizontal wind force was found to occur for a wind direction approximately along the line of the diagonal, seen when viewing the platform from above. However, the value of this force in full scale, as determined from the wind-tunnel testing, was found to be very much less than that estimated by the client, using a wind loading standard, before the wind-tunnel study was carried out. This result enabled resolution of some design issues associated with resisting the calculated uplift on at the base of several of the supporting piles of the platform.

3.2 Structure B: Stockpile cover

Wind loads were required for a large existing mineral stockpile cover for a gold mine. This structure is approximately conical in shape – consisting of twenty-four separate faces spaced at 15 degree intervals. The lower edge is approximately 14 metres above ground level when the stockpile is empty. The top of the cover is 32 metres above ground level, and the overall diameter at the widest point is 57 metres. The site is an inland location at which thunderstorms are the dominant extreme wind.

Wind-tunnel tests were carried out at a geometric scaling ratio of 1/100 using a pressure-tapped model (Figure 2), in turbulent boundary-layer winds. The pressure measurements consisted solely of mean pressure coefficients – i.e. fluctuating and peak pressures were not processed. However, external and internal (i.e. on the underside of the cover) pressures were measured and the results presented as net pressure differences. The effects of the radial conveyor (seen in Figure 2), and an upwind embankment for one wind direction, were included.

Design loads were calculated using the ‘quasi-steady’ principle (e.g. Holmes, 2007) in which mean pressure coefficients are applied with a gust wind speed, in this case a 0.2-second gust, as used in Australian Standard, AS/NZS 1170.2:2011. Pressure coefficients equivalent to those used in the standard were requested by the client. This approach was adopted even though techniques are available for producing effective static wind load distributions for large roofs, making use of information on fluctuating pressures and their correlations over large areas. However, the validity of these approaches for a site dominated by thunderstorm winds, with uncertain turbulence and correlation properties, may be questionable. The domination of thunderstorm winds is shown in Figure 3 in which the extreme value analyses of gust wind speeds from the nearby airport, separated by storm type, are shown.

Fig. 2 1/100 scale pressure-tapped wind-tunnel model of a mineral ore stockpile cover (Structure B)

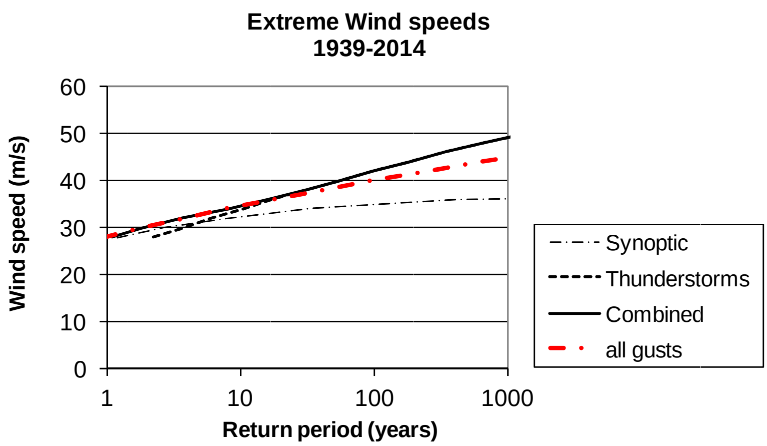

Fig. 3 Extreme value analyses of wind gusts near the site for Structure B

Figure 4 shows a daily anemometer chart recording (produced by a Dines anemometer), for the same location, on a day when an extreme wind gust produced by a severe downdraft from a thunderstorm occurred. This project raises the unsolved question of how to reasonably simulate this type of event in a conventional wind tunnel, for sites, like in this case, where this type of severe wind event is dominant.

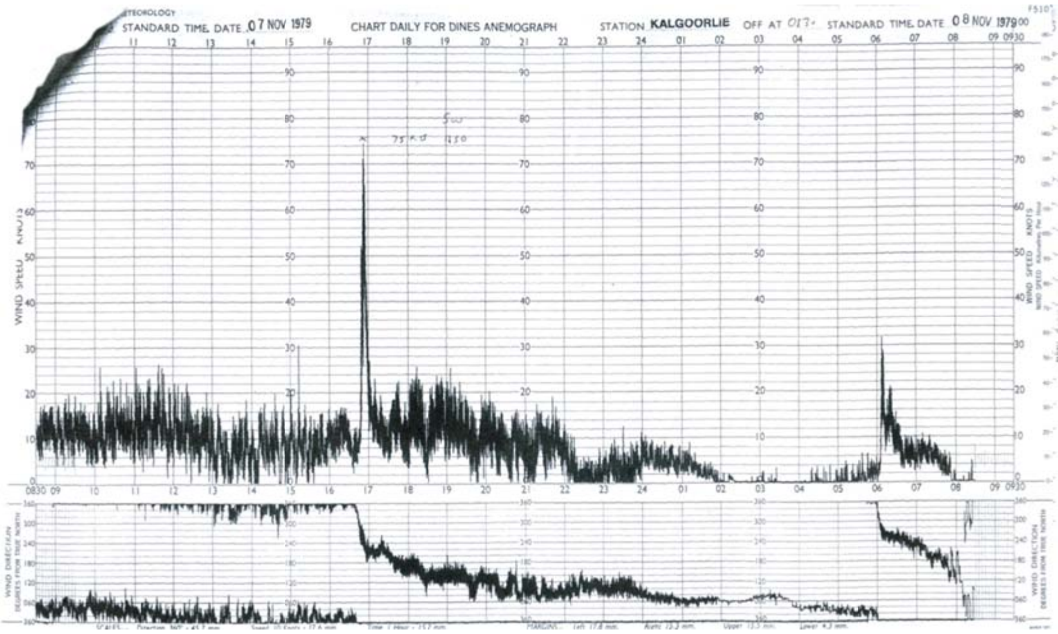

Fig. 4 Severe thunderstorm downdraft wind recorded near the site of Structure B by a Dines anemometer
(upper chart shows wind speed, lower chart shows wind direction)

3.3 Structure C: Shiploader

The third structure was a new shiploader planned for large mining company at a port in the north east of Australia – also a region subjected to tropical cyclones. The structure is to be mounted on an existing wharf, and there were concerns that extreme wind loads on the shiploader, and transmitted to the wharf, could cause structural problems for the latter. A major element of the shiploader is a conveyor boom 36 metres long, with a near rectangular cross section with dimensions of 4.5 m by 4.0 m. Environmental legislation requires this boom, which conveys bulk mineral ore when in operation, to be fully clad over its whole length. When the shiploader is not in operation, which will be the case when there is a tropical cyclone warning, the boom will be raised to a near vertical position.

A 1/100 scale model was constructed and mounted on a force balance in a wind tunnel (Figure 5), in which boundary-layer simulations for over-water and over-land winds were simulated depending on the wind direction under consideration. Orginally the model was designed to be rigid, and quasi-static wind forces and pressures would be measured. However it was clear that wind-induced vibrations of the 36m boom, both in the along-wind and cross-wind directions, would be significant at design wind speeds, and that element of the structure was operated as a dynamic model (see Holmes, 2007, Section 7.6.6).

Fig. 5 1/100 scale wind-tunnel model of a shiploader (Structure C)

To interpret the wind tunnel force measurements the wind tunnel velocity scaling was chosen so the reduced velocity, ($\bar{U}b/n_1$), was the same in model and full scale. n_1 is the first mode natural frequency of the boom, and b is the section width normal to the wind. This is not a true aeroelastic model since the mass distribution is not modeled correctly, and deflections and accelerations are not reproduced correctly. However, a correctly scaled dynamic model will correctly match the model frequency with the frequencies in the wind flow (including vortex shedding frequencies), and hence will correctly reproduce forces, including inertial forces (i.e. mass times acceleration), provided that aeroelastic effects are not significant.

The cross-wind vibration of the boom, in the near vertical position, was significant and found to increase the base shear and moment on the shiploader by about 30%. This was unacceptable both for the shiploader and the wharf, and remedial measures were required. To inhibit vortex shedding near the top, it was recommended that the cladding panels near the corners of the boom, over the top third of its height, be made removable, and that they be removed during a tropical cyclone warning. It was estimated that this measure should reduce the cross-wind loads by about 50%, and hence make the along-wind loading critical. Unfortunately however, time and budget did not permit this to be verified by further wind tunnel testing.

3.4 Structure D: Flare tower

The final structure discussed is a flare tower on an offshore platform. This is an existing steel lattice tower over 100 metres tall, with its base on the platform at about 40 metres above mean sea level. The location has one of the highest occurrences of tropical cyclones anywhere in the world. Although the tower was already about twenty years old at the time of the structural re-assessment, the operators wanted a more accurate definition of the wind loads on the structure, including dynamic effects than could be obtained by application of codes and standards.

The height of the tower, the relatively low natural frequencies of vibration, and the high wind speeds at the site, make the structure very prone to along-wind turbulent buffeting with significant dynamic response. Cross-wind response can generally be neglected for lattice towers. All the members of the tower were circular in cross-section, as is common practice in the petrochemical industry, leading to some uncertainty in the appropriate drag coefficients for the tower sections.

This led to wind-tunnel tests of two different types:

- Section model tests of the upper sections of the tower at a scale of 1:4.25 (Figure 6). For these tests, surface roughening of the model cylinders was used to produce super-critical flow around the members. The 'roughness Reynolds Number' scaling technique proposed by Szechenyi (1975) was used; this technique was validated by drag measurements on individual members (Holmes *et al*., 2012). These tests enabled the overall drag coefficients for the upper sections of the tower to be determined accurately. The model included the two gas risers running through the middle of the tower, and the rails on one face used on the prototype structure, for transporting the flare tip to the top of the tower.
- An aeroelastic model test at a scale of 1/70 (Figure 7). For this an aluminium 'spine' was machined to reproduce the bending stiffness of the structure based on the chosen length and velocity scaling ratios. As for Structure A discussed earlier, the diameters of the circular members on the model were 'distorted' – i.e. reduced by about one third, to allow for the sub-critical flow around them. At this model scale and small diameters, it is not possible to use surface roughness to reproduce super-critical flow on the model.

The results of the wind-tunnel tests were used as input and calibration for a 'desktop' calculation of wind loads and response of the prototype structure, using an equivalent static wind load (ESWL) approach (Holmes, 1996). This separately calculates the equivalent static wind loads for the mean, background (fluctuating sub-resonant) and resonant components of the loading, and these components are shown diagrammatically, for a hypothetical tower structure in Figure 8. These components generally have different distributions, although for Structure D, the mean and background distributions were similar in shape, but both very different to the resonant loading.

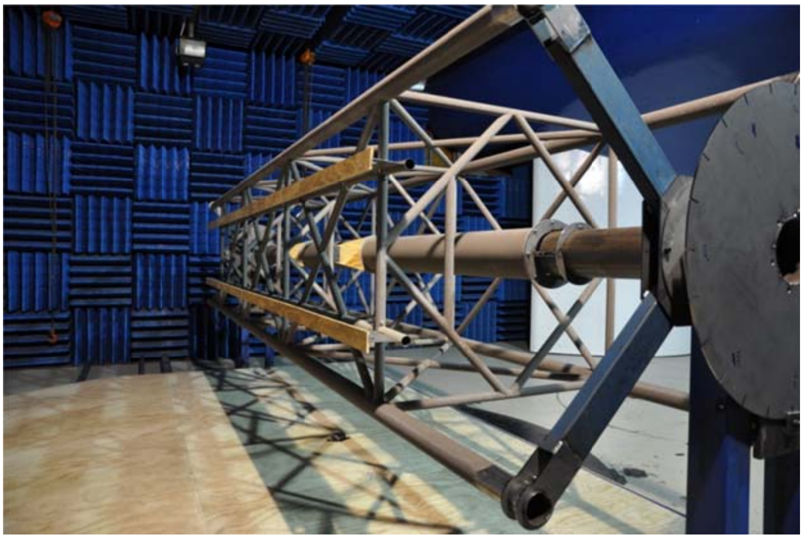

Fig. 6 Large scale section model test for a flare tower (Structure D)

Fig. 7 1/70 scale aeroelastic model test for a flare tower (Structure D)

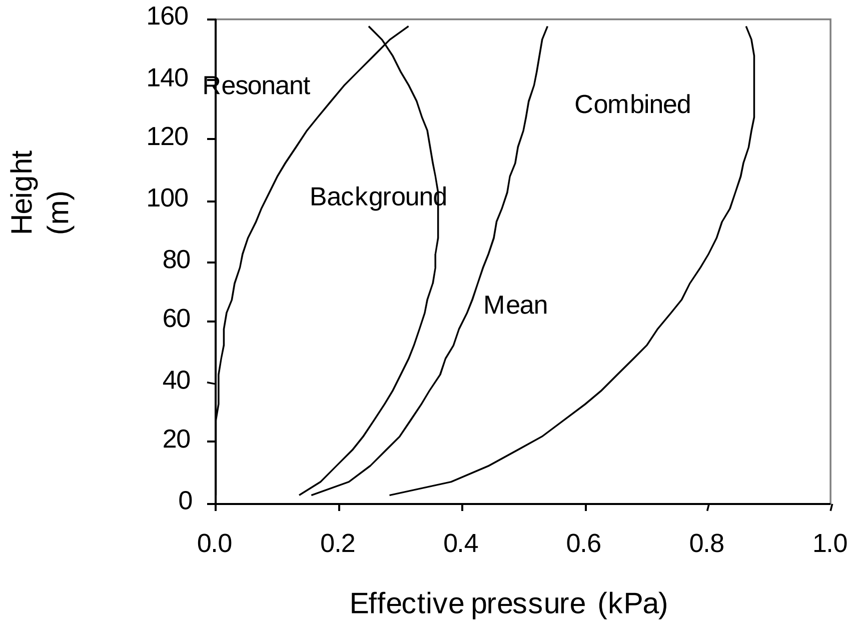

Fig. 8 Components of the effective static wind loading for a hypothetical tower (Holmes, 1996)

4. OTHER INDUSTRIAL STRUCTURES

4.1 Stacks, chimneys and pressure vessels

Stacks and chimneys of circular cross section are common elements of industrial facilities. The response of these structures to wind loads has long been of concern. In the nineteenth century, brick masonry chimneys regularly failed under wind loads and focused designers on the low tensile strength of brick mortar. In the nineteen-fifties and -sixties the dynamic response of steel chimneys to wind forces was of great interest and focus of research activity. One result of this was the development of a variety of devices to suppress vortex shedding, and hence cross-wind forces on structures with circular sections. The most well known and ubiquitous of these are the triple-start helical strakes developed at the National Physical Laboratory of the United Kingdom. However, strakes increase the drag coefficient greatly and although they effectively suppress the cross-wind response of chimneys, the along-wind response is amplified. This was probably the force component producing the failure of the sugar mill stack shown in Figure 9.

Several methods are available for prediction of the cross-wind response of chimneys and stacks of circular section. However, this is a difficult phenomenon to quantify with many variables affecting it, such as: aspect ratio, chimney taper and upwind turbulence intensity, and the various methods give varying predictions. For example, Verboom and van Koten (2009) applied the two approaches, given in Eurocode 1 (known as '*Approach 1*' and '*Approach 2*'), for prediction of the cross-wind response to vortex shedding of 13 steel chimneys in Europe, the operational history of which was known in some detail. Verboom and van Koten concluded that *Approach 1* 'seriously underestimated' the stresses caused by cross-wind vibrations, and hence would have overestimated the fatigue life for five of the 13 chimneys. *Approach 2* mostly over-estimated the stresses, and hence would have unjustly rejected six out of the 13 chimneys as being 'unsafe'.

Fig. 9 A failed steel stack equipped with helical strakes

Probably, a better design approach is to prevent the occurrence of vortex-induced vibrations by either aerodynamic means (such as the installation of helical strakes), structural means such as increasing mass per unit height and/or damping (and hence the Scruton Number), installing guy cables, or structurally linking several stacks in a group.

4.2 Open-lattice conveyors

Open-lattice frame structures, enclosing belt conveyors for moving bulk commodities such as iron ore and coal, from stockpiles to ships, are common. The axes of these structures are usually near horizontal, but basic drag coefficients from lattice towers can be used for the enclosing structure. What is missing at present appears to be force coefficients for the belt conveyor, and shielding or interference factors resulting from the enclosed lattice structure. It is likely that cross-wind forces as well as drag are significant for the belt conveyor.

Some generic wind-tunnel studies of wind forces on belt conveyors, with and without enclosed lattice structures, are therefore needed.

5. CONCLUSIONS

This paper has reviewed wind loading of industrial structure, with particular emphasis on those used in the mining and petrochemical industries. Generally these structures have received far less attention from wind engineers in comparison with other structures, such as buildings, bridges, communication structures and transmission line systems.

The main aspects from four example structures, for which wind-tunnel tests were undertaken, are described. Other sources available to designers are also described. The need for further research on structures such as belt conveyors and on the mutual shielding between various elements of a complex industrial plant have been emphasized. There is also a need for new wind-tunnel tests at high Reynolds Numbers (actual or simulated using roughness), for sections of lattice towers and frameworks made from circular members.

ACKNOWLEDGEMENTS

The author acknowledges the input of many colleagues with whom he has collaborated on the example structures described in this paper, in particular: Cam Leitch and John Ginger (James Cook University), David Burton (Monash University), Seifu Bekele (Global Wind Technology Services), and Harry Fricke (JDH Consulting).

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