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A Discussion on the Development of Wind Engineering for the Design of Mining-Related Structures

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Abstract

Mining related structures are often of a form which is outside of the guidance of published standards and guidelines due to the difficulty in assessing the aerodynamic shape factor. The historical drive to better understand the nature of wind loading on structures coincided with the failure of significant industrial revolution era structures, and now the general state of the art is well advanced. In an era of complex non-linear analysis, we still lack a detailed understanding of the wind loads for mining related structures. There is now the ability to digitally prototype a structure in CAD, analyse and optimise in CFD, then validate via wind tunnel testing a 3D printed hard-copy of the digital design. This paper examines the relevant history of the development of wind engineering for industrial structures and looks to the near future where risk and cost can be reduced in design using combinations of existing 3D technologies.

Short Contextual History of Wind Engineering

Development of our current understanding of the nature atmospheric wind and its effect on modern structures is an interesting piece of engineering history. This paper cannot do justice to the topic, and the interested reader is encouraged to consult Baker [5] for a comprehensive historical summary.

Figure 1. Tay Rail Bridge Disaster (https://www.railwaysarchive.co.uk)

Throughout human history in the construction of shelters, the design was influenced by experience from trial and error using available materials and the environmental conditions of the area. This changed with the industrial revolution period where humans decided to take charge of the environment. Failures of significant structures, such as the Tay Rail Bridge in Scotland in 1879, were attributed in part to an inadequacy of the estimated design wind forces. It was recognised by Anglin in 1905 that “the whole question of wind-pressure is in a very unsatisfactory state, and we can pretend to give information on the subject in a very approximate form” [4].

Notably, the Tay Bridge (similar to many significant engineering works of the time) was in the form of lattice construction, not unlike the modern industrial trussed gantry structures used on mine sites today.

Many ground breaking works were undertaken during the late 1800’s and early 1900’s, building on the achievements of the physicists such as Newton, Euler and Bernoulli, in trying to define both the nature of atmospheric wind and its effect on structures.

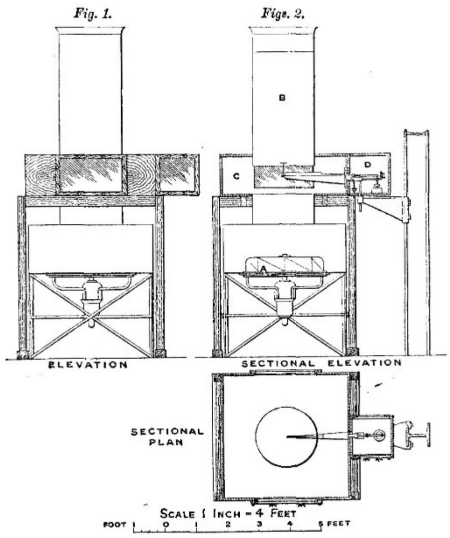

Figure 2. TE Stanton's Experimental Apparatus [12].

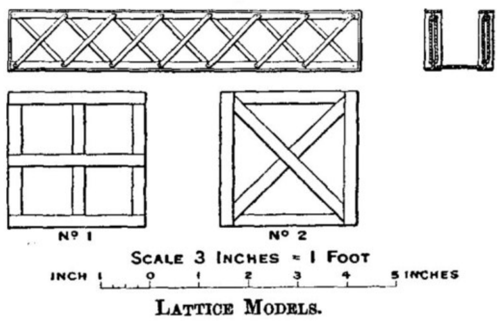

Figure 3. TE Stanton’s Lattice Module [12].

Hints to the future development of a drag coefficient or shape factor had emerged around 1905 [4]. Various experiments described in historical literature such as placing an anemometer on the locomotive of a fast train to correlate speed to wind pressure [6] resulted in breakthroughs such as the experiments undertaken by Thomas Stanton around 1904 [12] with defining the relation of the force generated by a constant velocity wind on a surface. His apparatus, shown in Figure 2, is now recognised as a wind tunnel. Importantly for the field of industrial structures, Stanton undertook works to define the resistance generated by lattice structures and the shielding effects of multiple lattice modules.

As with all previous human history, war has brought about swift technological change, and the period covering the two World Wars saw a significant growth in the definition of aerodynamics for aircraft and weapons. This simultaneously produced advances in civil engineering with new materials and improved design. Urban densification was made possible through the development of hi-rise construction, and communication was made possible with the growth of radio masts and lattice towers. The emergent aeronautical industry developed the wind tunnel prior to World War I, although it was not until 1944 when the issue of scaling and correction for boundary layer effects were resolved. It is of note that an early adopter of the technology was Eiffel, who made his first wind tunnel measurements in 1909 [5].

Progress on the statistical nature of wind and a standardised approach to wind loading on structures came into focus with the development of codes of practice, with British Standards Institution first publishing in 1944. This was recognised as necessary to provide practical guidance for engineers based on the research breakthroughs established up until this time.

The use of Computational Fluid Dynamics (CFD) to examine the effects and estimate wind loads on buildings has been traced back to the 1980's with working groups developing guidelines as early as 1992 [13].

Continued use of wind tunnels to study structures, boundary layer effects on atmospheric wind, further collection and statistical analysis of historic wind events and the more recent explosion in the use of computer technology has seen the art of wind engineering develop from the unsatisfactory state of 1905, to a generally well prescribed art. Well-established frameworks of design criteria for most of the regular structures encountered by the general practitioner exist, however there are still a number of areas where additional research is required.

Mining Related Structures

According to Amoroso [3] *"Structures that are typical of the petrochemical and process industries have structural forms that confound the application of standard wind load estimation techniques."*

Mining related structures are characterised by multiple bays of open or partially clad structural framing, forming an envelope for process equipment and interconnecting conveyors, chute-work and pipework. The design requires estimation of wind loads for the entire assembly and is complicated by the interactions of the wind with the features noted above.

The wind loads for the structural framing are a function of the solidity ratio of the frame. Upwind frames tend to shield downwind frames to a large degree, based on the frame spacing. The downstream members do not receive the same wind load as the upwind frame as the momentum in the flow has been dissipated into turbulence by the preceding frame. In addition to the structural framing, the equipment elements housed within the structure contribute to the overall wind load on a structure, but also contribute to the shielding of downwind elements.

Of all industries, Structures used in the Petrochemical Industry are the closest match to those of the Mining and Mineral processing industry, with some subtle differences.

The petrochemical industry processes liquids and the structures are mainly circular vessels and piping support structures. The mining and metals industry processes solids and the structures support bulk materials handling (conveyors), storage (bins, chutes, silos) and processing (crushers, screening plant) equipment. In comparison, the mining industry has arguably a smaller number of larger interconnected ground mounted structures, of relatively high stiffness due to the gravity loads of the bulk solids and the need to counteract the dynamic loads of processing them. Typical examples are shown in Figure 4 and Figure 5.

Figure 4. A typical open-framed mine process structure.

Figure 5. A typical mine elevated conveyor structure.

As can be seen by Figure 6 from AS1170.2:2011 [11], the scope of the Australian standard does not include specific provisions for these types of structures, with the closest analogous model being lattice structures. Considering a power transmission tower (Figure 7) there is little similarity to the structures in Figure 4 and Figure 5. Consider the case of the conveyor in Figure 5. Being bridge-like, the structure lies in the plane of the surface wind, and not perpendicular to it. The Aerodynamic shape factor may be estimated fairly readily for wind perpendicular to the span, but with some skew, the effective solidity changes significantly, and the actual design values become difficult to assess. Similarly, other international standards are limited in detail for mining related structures, including EN-1991-1-4 [7] and ASCE/SEI 7-10 [1].

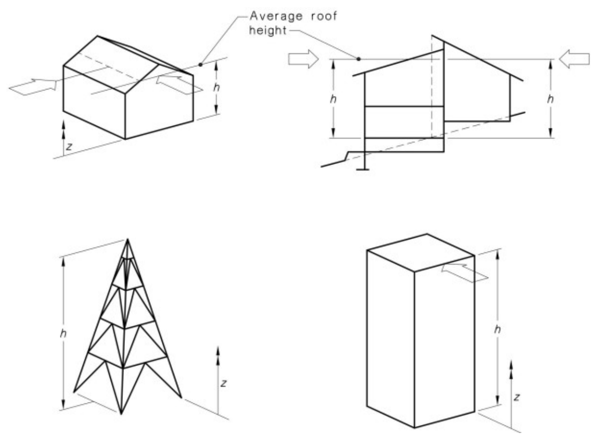

Figure 6. AS/NZS 1170.2:2011 Clause 2.2 [11]

For the structure shown in Figure 4, the upper level may be approximated readily using lattice or open frames analysis, but the lower levels are quite dense with equipment and are effectively blocked. Although the upwind frames may lower the momentum of the entering wind, the residual momentum is eventually dissipated within the structure and the flow redirected to shed to the sides.

Australian Design Practice Experience

As a graduate engineer faced with the responsibility of designing a large industrial process structure in a cyclonic region, the Author turned to his peers for advice on appropriate methodology to use for such a structure. The advice received ranged from:

Optimistic: use effective C_{fig} of 1.3 which is in line with the maximum windward and leeward pressures (C_{pe} = +0.8 Windward / -0.5 Leeward) for a full clad building per AS1170.2, multiplied by the gross area enclosed by the structure, a partially clad structure should be less;

Pessimistic: use effective C_{fig} of 2.2 which is the maximum value for a bluff body per AS1170.2 which cannot be exceeded, multiplied by the nett projected area.

For a densely packed structure, the nett projected area may approach the gross enclosed area of the optimistic approach.

Figure 7. A typical lattice frame electricity transmission tower. (www.freeimages.co.uk)

The real value likely lies somewhere between optimistic and pessimistic. Although the pragmatic designer may choose the pessimistic approach to be safe, there are problems discussed later in this paper with such approaches. Regardless of technical arguments, having a range of uncertainty with a factor of 1.7 on the design C_{fig} value is not desirable for public confidence in design.

In the Australian industrial design landscape, there is minimal effort expended in understanding the effects of wind loading on industrial structures. From time to time, experts are engaged to undertake commissions to validate designs as being safe, but the understanding of how these structures actually work is limited.

AS1170.2:2011 does include provisions for estimating the effective aerodynamic shape factor for structures comprising series of similar open frames. The method employed modifies the overall gross aerodynamic shape factor for the structure by summing the series for each bay of framing, using the relative shielding factor multiplied by the first frame shape factor. It is not clearly defined how to take into account the differences in solidity that may be occur across multiple bays.

For a structure similar to that shown in Figure 4, it is overly conservative to calculate the wind load for one frame and multiply this force by the number of frames.

The most representative guide for the design of mining related structures is the ASCE publication “Wind Loads for Petrochemical and Other Industrial Facilities” [2]. This publication has been developed based on alignment with ASCE/SEI 7-10 and integrates research from wind tunnel testing. Based on the paper by Amoroso [3], there is scope to extend the research incorporated in [1] to cover higher solidity structures and long span structures such as the conveyor of Figure 5.

Emergent Techniques

For more than a century, the wind tunnel has been the core tool of wind engineering research. Numerical modelling techniques with the availability of desktop multiple core computer hardware has taken CFD software out of the realms of supercomputer research labs and into mainstream, and has in itself been utilised for wind engineering research for more than thirty years.

Neither of these two technologies can be called emergent, rather it is the combination of multiple technologies that brings forth the possibility of new tools and discoveries.

In addition to above, we have seen computer aided drafting (CAD) transform in the last 30 – 40 years from a tool which digitally mimicked pen and paper two- dimensional drafting with advances in computing power to now provide a fully immersive 3 dimensional representation of the design environment.

Another technology coming of age is 3D printing. Objects requiring expensive tooling to manufacture twenty years ago can now be printed by hobbyists at home, Product manufacturers are embracing the technology to replace historical fabrication techniques.

There is now the ability to digitally prototype a structure in CAD, analyse and optimise in CFD, then validate via wind tunnel testing a 3D printed scale hard-copy of the digital design.

With mining related structures, this promises to give design engineers the opportunity to understand the direct effect of wind in a cost effective manner which goes beyond the general guidance provided by codes alone. Examples of the use of 3D printing in preparing industrial models for wind tunnel tests are included in the paper by Holmes [8], while comparative analysis of non-industrial structures between wind tunnel and CFD has been undertaken by other researchers such as the paper by Jeong and Choi [9].

Direction of Future Work

Despite the research industry’s experience with wind tunnel and CFD experimentation, the digital workflow outlined above is not yet common practice. Most CAD models are not readily suitable for 3D printing or CFD analysis and require significant post-processing to modify for use. Further work is required to develop the base representative models for the research. This will take an amount of trial and error experimentation to observe the critical aspects of the different base models.

There is a fundamental issue with CFD in that even though relatively complex models can be analysed on the desktop, it is not possible to fully model and analyse an industrial structure in detail without a step-wise process of superposition. The question remains as to what minimum level of detail is required to capture the design case.

If it can be shown that the current designs are conservative, does this signify a problem, and is this new work necessary? The answer to this lies in the examination of risk and cost.

Risk

Simiu [10] provides an introduction to the topic of uncertainty and risk with regards to the design of structures for wind resistance, including "*Improved estimates of risk are desirable because they help to achieve design that are risk-consistent throughout a community and can thus help to enhance community resilience*".

For Structural Engineering, uncertainty presents risk. To say that a design appears to be "conservative", i.e. the design limit state strength capacity exceeds the wind force derived from a standard for a given return interval wind does not mean that we actually understand how that structure will perform if that loading scenario occurs. The actual performance will be a complex non-linear interaction of the actual frame loading and connection interaction.

The design sector relies heavily on the use of non-linear structural models to prepare designs to withstand the ultimate strength limit state. Design for mine related facilities in cyclonic regions typically consider a 1/500 year wind as one of the primary load cases. The design wind velocity is a theoretical value based on extrapolation of the available historical records, and there is the real possibility that this value could be exceeded. With limited modelling of the structural behaviour at loading above the 1/500 year wind for mining structures, the confidence of the safety of the structure may become questionable. As there is uncertainty to the manner in which the wind pressures actually manifest in and around the structure, simulated frame behaviour post the design wind event is unlikely to representative, especially when considering structural stability and collapse mechanisms.

Cost

It is inevitable that any engineering work has cost associated with it. The cost of the design component is constantly questioned and its value queried. The drive for cost savings during construction are also without question.

In terms of design, as mentioned above it is rare for wind tunnel testing to be undertaken for mining related structures, mainly due to the direct cost associated with a modelling and testing programme and the schedule duration. There has been little work undertaken in cost-benefit studies of the engineering design cost of properly understanding the effects of wind and the potential to reduce the final construction cost. The trade-off needs to be balanced with an understanding of the risk of adopting a non-codified design.

A digital workflow design which enables a relatively quick examination of the structural performance under wind loading using CFD will make the potential for design optimisation more attractive and may lead to savings in construction cost which can be fully validated if required.

Conclusions

Structural Wind Engineering has undergone extensive development since it was formally recognised as an important part of the human environment in the late 1800's as the industrial revolution changed the world. There are still areas of uncertainty in some areas of design which need to be addressed to improve our confidence in design. The combination of several maturing technologies into a single digital workflow may help the design industry close the gap on the uncertainties, but further research is required.

Acknowledgments

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