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Estimation of Force Coefficients for Unclad Mining Structures of Similar Solidity by Various Methods

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ABSTRACT

Mining related structures often differ to the general structural building forms encountered by designers and investigated by researchers. Guidance for structural design is limited and direct application of available data contained within existing codes and standards is not well defined. Using a modular structural analogue, analysis has been undertaken on three structural forms of similar projected area to provide an estimate of the global wind force shape coefficient. Comparison has been made between direct use of the methodology provided in the ASCE publication “Wind Loads for Petrochemical and Other Industrial Facilities” and a method employing Appendix E of Australian Standard AS/NZS1170.2:2021 “Structural Design Actions: Part 2 Wind Actions”. Using the values obtained above as a reference, numerical simulation has been undertaken using Computational Fluid Dynamics (CFD) modelling to examine alignment between prediction of the three methods with a view to extending the range of structures able to be assessed.

1. Introduction

Unclad mining and industrial structures present a difficulty to designers in estimating conservative yet economical wind forces for safe structural design. The structures can vary from low solidity frames similar to lattice towers to extremely high solidity structures with densely packed mechanical equipment, piping, bins and chute-work contained within the braced structural framework. Uncertainty lies in the amount of energy lost in wind flow impinging on elements within the structure generating the force to be resisted versus flows which are redirected and allowed to escape through the open structure. Some work has been undertaken in researching this problem and a small body of literature does exist providing guidance for structural designers.

This paper presents the concept of simplified parametric structural building analogue which may be configured into different structural forms and used to comparatively assess the outputs of two guidelines used within industry for design of mining and industry structures. In conjunction, Computational Fluid Dynamics (CFD) modelling has been undertaken to provide a further estimate. Limited work has previously been undertaken in direct research using CFD to date. Most literature surveyed on CFD on open frames relates to low solidity lattice tower type structures.

There is a practical need for this research, by adopting a different approach the potential insights can lead to the benefits of improved safety to personnel working at such facilities and the surrounding public, and in providing economical designs.

2. Published Guidelines

Two relevant guidelines from the body of research have been elected for this comparative study. The American Society of Civil Engineers (2011) work is based on research by Amoroso & Levitan (2009), Nadeem & Levitan (1997) and Georgiou, Vickery, & Church (1981). This work is based on wind tunnel testing of various framing configurations resulting in charts for estimating total structure force coefficients. The charts are based on as estimate of the solidity of the framework along with the frame spacing and overall width to the wind. The method does allow for inclusion of specific large pieces of equipment within the structure to account for the associated wind load generated.

In contrast, a method using Standards Australia & Standards New Zealand (2011) Appendix E was used. The shielding factors of Table E2 are based on wind tunnel tests by Georgiou & Vickery (1980) and provide shielding estimates for parallel identical frames. While the ASCE publication is based on whole structures, the AS/NZS work focuses on generic frame shielding. For the AS/NZS method, the concept of a “wind shadow” as described by Cook (1999) has been adopted whereby each upwind frame provides an amount of shielding to the downwind frames.

3. Structural Analogue

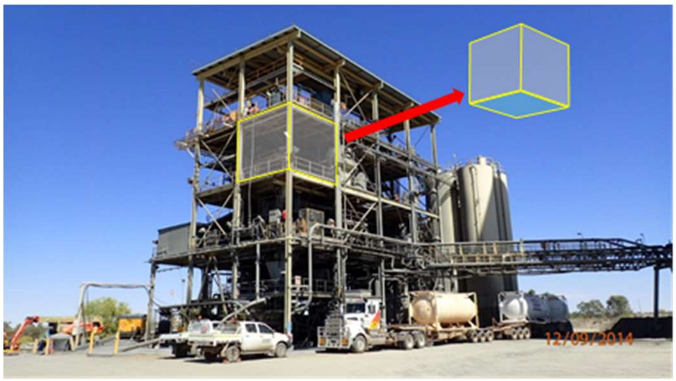

Figure 1 Typical mining building from Reis (2014)

Most mining and industrial structures consist of braced frame structures on repeating grids in the horizontal and vertical directions, ranging from discrete towers to wide, broad structures. Given a typical building as shown in Figure 1, it is possible to conceptualise a parametric unit building module, as shown in Figure 2, which may be assembled into various building configurations.

The key dimensions of the module can be adjusted parametrically to vary all aspects of the effective density or solidity of the structure. Modules can then be assembled into various larger building configurations for CFD simulations. For this work, 3 similar configurations have been chosen (refer Figure 3), and a single sizing regime indicative of a 40 – 50% nominal solidity. The nominal solidity is the ratio of the total projected area of framing and equipment (i.e. the “flattened” area) to the gross envelope area. The key module dimensions and the details of the building configurations are listed in Table 1 and Table 2. The dimensions chosen were selected by the first Author based on industry experience of being typical for such structures. The “chute” represents an internal bay blockage being a piece of mechanical equipment or the like.

4. Methodology

The following general assumptions have been made for this analysis.

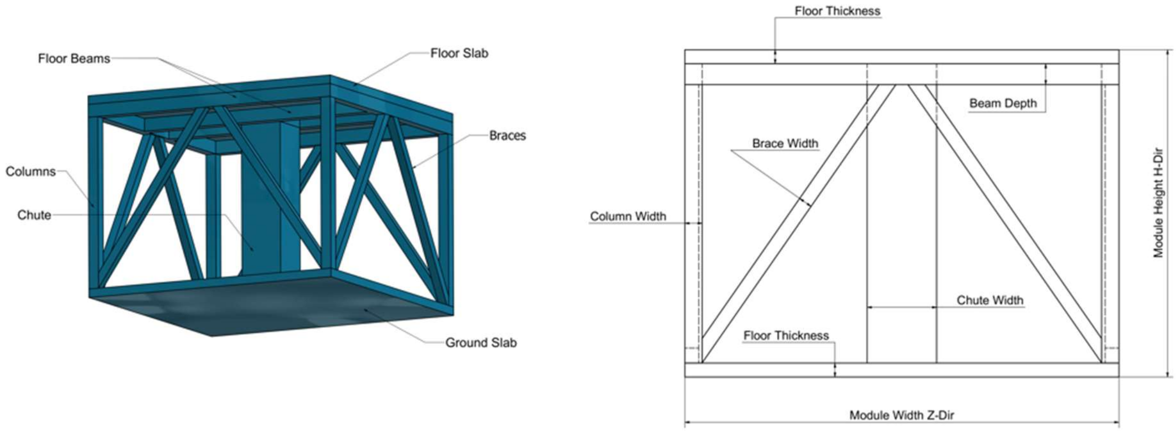

Figure 2 Structural Analogue Module and Key Dimensions

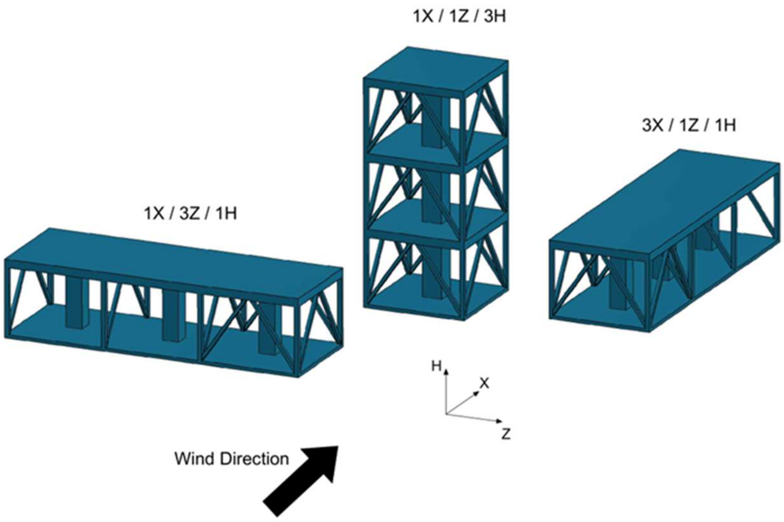

Figure 3 Structure configurations analysed

Table 1 Unit module dimensions

Element	**Dimension (m)**
Module Grid Spacing X-Dir (Along Wind)	6.0
Module Grid Spacing Z-Dir (Across Wind)	6.0
Module Floor to Floor Height H-Dir (Vertical)	4.5
Floor Thickness	0.2
Chute	1.0m Wide x 1.0m Deep
Floor and Perimeter Beams	0.3m Deep x 0.25m Wide
Columns	0.25m Wide x 0.25m Deep
Braces	0.2m Wide x 0.2m Deep

To enable the comparative analysis there was a need to select a relevant wind speed. For the Australian context, selection of a non-cyclonic, ultimate (strength) limit state wind was chosen. This is representative of the largest forces in principle required to be withstood by a structure with an appropriate Reynolds Number. The value used is that for a peak gust with an equivalent moving average time of approximately 2 seconds in accordance with Standards Australia & Standards New Zealand (2021).

Given a 1:500 Design Event for a Structural Importance Level of 2 from Australian Building Codes Board (2019), for a AS/NZS1170.2 Region A wind (non-coastal, non-cyclonic) and Terrain Category 2 for a maximum structure height of 30m, an ultimate design wind speed of 50m/s is obtained. Uniform wind speed has been considered to maintain direct comparison of force coefficient regardless of height, although it is recognised that the boundary layer turbulence will vary the results.

Table 2 Structural model reference data

Model	**Key dimensions**			**Solidity Values**			**Natural Frequency**
	Along Wind X-Dir (m)	Across Wind Z-Dir (m)	Vertical H-Dir (m)	Gross Windward Area (m^2)	Nominal Projected Area (m^2)	Nominal Solidity Projected / Gross (%)	**(Hz)**
1X / 1Z / 1H	6.250	6.250	4.700	29.4	15.2	52	N/A
1X / 1Z / 3H	6.250	6.250	13.700	85.6	43.2	50	5.9
3X / 1Z / 1H	18.250	6.250	4.700	29.4	15.2	52	9.2
1X / 3Z / 1H	6.250	18.250	4.700	85.8	36.7	43	9.2

A finite element model was created for each of the three models to estimate the first mode natural frequencies. The modelling was undertaken following the guidelines from Strand7 (2022). The models were found to have frequencies as shown in Table 2. Given they are significantly higher than 1 Hz they are unlikely to be affected by aeroelastic effects.

4.1 ASCE

The method followed the procedure in Section 5.2 of the publication but considered the "chute" an internal frame. Values derived are for the orthogonal (i.e., wind parallel to X-Axis).

4.2 AS/NZS 1170.2

For each frame, a projected area was calculated. A shielding value was calculated based on the method given in Section E2.3 of the standard for the contribution of each upwind frame on the down-wind frames. The shielding values were multiplied together to determine a total wind shielding effect for each down-wind frame.

4.3 CFD

Due to the nature of the simulations, it was expected that it would be necessary to use an unsteady solution due to the periodic fluctuations generated by the sharp-edged square elements. This effect would prevent convergence of a steady solution as described by Mochidaa, Tominagab, & Yoshiec (2006).

In sizing the domain, consideration of the blockage created by the test model was required as it increases the velocity and correspondingly the dynamic pressure within the domain to maintain continuity of momentum. The resultant forces are correspondingly increased. To account for this, in sizing the domain the side and top offsets were adjusted to achieve a maximum 5% blockage for each model. To reduce the cell count and expedite the simulations, the domain extents were reduced. This was confirmed via an initial sensitivity analysis to ensure that the results were not adversely affected. An inlet length of twice the structure height and outlet length of 5 times the structure height was used. A possible impact of this approach is that a fully developed turbulent boundary layer is not established so there is a margin of error on these results which requires future validation.

A process of structured mesh refinements was followed as part of an initial mesh convergence study to arrive at a sizing regime where an increase in the cell count did not vary the results. The $k\omega - SST$ turbulence model was used for the steady precursor simulation study following the guidelines of Gerasimov (2016). The simulations were run with sufficient iterations until the mean force values remained constant as the models are highly unsteady and do not converge using typical convergence criteria. The study showed the guidelines of Menter (2015) using the criteria of 20 cells across of characteristic dimension provided a stable result. The boundary conditions of the domain consisted of a velocity inlet with a uniform 50 m/s flow, a pressure outlet, no-slip wall for the ground plane, and free slip walls and top.

The Scale Adaptive Simulation (SAS) turbulence model of Menter & Egorov (2010) has been used for the simulations following review of similar works. The model has been developed to account for flows with strong instabilities associated with separation zones behind bluff bodies, however discussion of the mathematical details of this model are outside the scope of this paper. Poulain, Craig, & Meyer (2021) concluded it produced acceptable drag force results for bluff body flow while being computationally affordable. The simulations follow the guidelines of Menter (2015) for the numerical settings. A Courant number of 1 for the smallest calculated cell size and the free stream velocity was used as the basis of the time step size. The duration was set to 4 seconds of flow time, of which the latter 3 seconds was used for sampling the forces, ignoring the first 1 second for flow field stabilisation. As a result, the simulation used 10000 steps at 0.0004 seconds per step. Estimates of the maximum force were derived using a block-maxima average based on the most significant frequencies from power spectral density analysis of the time series.

5. Results and Discussion

Results from the analysis are presented in Table 3. The force coefficients derived (C_{fx} and C_{fz}) are the global force coefficient for the structure in each of the orthogonal X and Z directions calculated from:

$$C_f = F/(A_g \times q_{dyn}) \tag{1}$$

where C_f is the wind force coefficient, F is the calculated or simulated force, A_g is the gross windward area of the envelope of the structure and q_{dyn} is the dynamic wind pressure calculated from the velocity in Section 4.1.

Table 3 Force and force coefficient estimates

Model	Force Estimates (kN)			Force Coefficient Estimates		
	ASCE	AS/NZS	CFD	ASCE	AS/NZS	CFD
1X / 1Z / 3H	121	131	118	0.93	1.01	0.91
1X / 3Z / 1H	97	129	50	0.74	0.99	0.38
3X / 1Z / 1H	82	71	106	1.83	1.58	2.37

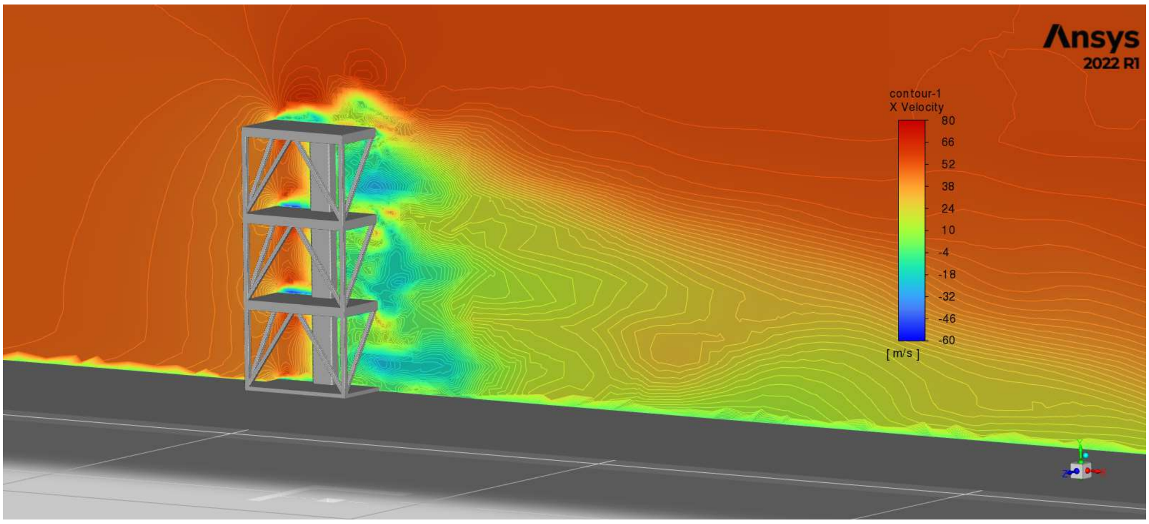

Figure 4 Horizontal wind velocity profile through 1X / 1Z / 1H Model

The results for all three methods show significant variation, the best alignment being for the 1X / 1Z / 3H case, where the values were within a 10% margin. While AS / NZS 1170.2 is more conservative than ASCE for the first two models, it is not for the third. The CFD showed extreme divergence for the second and third models as list in Table 3. The level of agreement on the first model suggest that the methods work for simple cases with lower complexity. Further analysis is required to understand the differences in the second and third models.

6. Conclusions

The analysis undertaken here has raised questions around the alignment of the existing publications. Whether the values shown are overly conservative leading to uneconomical design or under conservative leading to unsafe design is debatable. The CFD provided some alignment of the simplistic model yet had a vast difference in the other models where the complexity is increased. These differences require further investigation.

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