Prediction of Drag Force Coefficient for Single-Column-Supported Billboard Structures

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Abstract

A code-based approach can only be used to determine the wind loading on conventional single-plate billboards for normal wind direction. Based on the literature, no simplified method is available to estimate the drag force coefficient for single-plate and two-plate billboards for various aspects, clearance ratios, and wind angles. With many experimental kinds of research done on single-plate billboards, a database was created for the drag force coefficient, for various aspects, clearance ratios, and wind angles. For the case of two-plate billboards, a very limited number of experimental results have been reported. In order to generate adequate data, CFD simulations were done. However, only limited publications are available regarding the selection of mesh size and the most suitable turbulence model. Based on the trial and error approach, a 2-equation k-ω SST model was selected and a mesh sensitivity analysis was done to identify the proper mesh size. Linear-Static analyses were carried out using the pressure values obtained from the CFD analysis to compute the drag force and the torsional moment about the base, which governs the structural design of billboards. With the results obtained, two separate equations were developed to predict the drag force coefficients for the required aspect, clearance ratios, and wind angle for single-plate and two-plate billboards. For both types of billboards, the critical range of wind angle was identified as -45° to +45°. The maximum torsion about the base can be estimated by multiplying the maximum drag force with 16% of the billboard width for single-plate billboards and 22% for two-plate billboards.

1. Introduction

Owing to increasing land prices and improvement of the road network, large single-column-supported billboard structures are becoming popular for outdoor advertising in Sri Lanka. Most of them are rectangular-shaped and 20-50m in height with reasonable clearance. These structures are often composed of steel trusses and tubes. With the height they rise above the ground, these are vulnerable to large wind loads. Unlike in Sri Lanka, hurricanes are frequent in some other parts of the world. That may have been the reason for the poor development of Wind Engineering in Sri Lanka. The failure of these types of structures includes damage to the truss, failure of supporting structure, and the collapse of the whole structure resulting from foundation failure. On average, 5-10 billboards are collapsed each year in Sri Lanka. One of the major reasons may be due to outdated and oversimplified design practices. In reality, wind-induced pressure is not static; it is fluctuating with time. So normally the pressure distribution over the billboard is not uniform, hence the resulting drag force will generally be offset from the board’s geometric center. This horizontal offset (eccentricity) results in torsion (even for the normal wind direction), which might produce significant effects on the structure.

Scientists around the world have performed extensive studies to predict the wind loading on billboards through wind tunnel testing. Letchford (2001) conducted wind tunnel tests for a range of rectangular signboards or hoardings with varying aspect ratios, clearance ratios and porosity’s for a range of wind directions. Letchford (2001) has presented a simple equation to predict the drag force coefficient and it can be used only for the normal wind direction. Warnitchai et al. (2009) conducted wind tunnel tests for both single-plate and two-plate billboards and presented the variation of drag force coefficient and eccentricity with wind direction. Zuo et al. (2014) conducted a three-phase experimental campaign to study the wind loading of rectangular box type, single-plate, and two-plate sign structures. Smith et al. (2014) conducted full-scale field tests for a box type billboard sign and more recently Li et al. (2018) conducted wind tunnel experiments to investigate the wind loading on two-plate billboards.

Results obtained from wind tunnel testing helped in developing wind load standards to guide the designing of structures for wind load (e.g. ASCE/SEI 7-10, EN 1991-1-4:2005, AS/NZS 1170.2:2002). Due to some drawbacks, they could not solely be used for the design of billboards. In the present study, two separate equations are developed to predict the drag force coefficients for the required aspect, clearance ratios, and wind angle for single-plate and two-plate billboards. Moreover, a simplified method to predict the maximum torsion about the base of the billboards is also proposed.

2. Code-Based Approach to Predict the Drag Force

In this study, three different design standards were examined to understand the analytical procedure to predict the drag force acting on a billboard.

2.1 Australian/New Zealand Standard

According to AS/NZS 1170.2:2002, the procedure to determine the wind action is to initially determine the site wind speed and the design wind speed, then the wind pressure is calculated and finally, the wind action is
calculated. Equation (1) can be used to determine the site wind speed ($V_{\text{site}}$):

$$V_{\text{site}} = V_{g} \, M_{d} \left( M_{\text{cat}} \, M_{t} \right)$$  \(\ldots \ldots \ldots \ldots (1)\)

Where $V_{g}$ is the regional gust wind speed, in meters per second, $M_{d}$ is the wind directional multiplier, $M_{\text{cat}}$ is the terrain/height multiplier, $M_{t}$ is the shielding multiplier and $M_{f}$ is the topographic multiplier. After determining $V_{\text{site}}$, the design wind speed is taken as the maximum cardinal direction site wind speed. Equation (2) is used to determine the design wind pressure, $p = (0.5 \, \rho_{\text{air}} \, V_{\text{des},\theta})^{2} \, C_{\text{fig}} \, C_{\text{dyn}}$  \(\ldots \ldots \ldots \ldots (2)\)

Where $\rho_{\text{air}}$ is the density of air, $1.2 \, \text{kg/m}^3$, $V_{\text{des},\theta}$ is the design wind speed, $C_{\text{fig}}$ is the aerodynamic shape factor and $C_{\text{dyn}}$ is the dynamic response factor. Finally, the design wind force is calculated by multiplying the design wind pressure by the area of the billboard.

### 2.2 European Standard

When considering the EN 1991-1-4 (2005), after determining the respective terrain category for the structure, mean wind velocity at the reference height is determined using Equation (3):

$$V_{m}(z) = C_{r}(z) \, C_{o}(z) \, V_{b}$$  \(\ldots \ldots \ldots \ldots (3)\)

Where $C_{r}(z)$ is the roughness factor, $C_{o}(z)$ is the orography factor and $V_{b}$ is the basic wind velocity. Next turbulence intensity is calculated using the equation (4),

$$I_{t}(z) = k_{t} / [ \, c_{o}(z) \, \ln(z/z_{0}) ]$$  \(\ldots \ldots \ldots \ldots (4)\)

$k_{t}$ is the turbulence factor, $c_{o}(z)$ is the orography factor and $z_{0}$ is the roughness length respective to the terrain category. Thereafter peak velocity pressure is calculated from the equation (5),

$$q_{d}(z) = (1 + 7 \cdot I_{t}(z)) \cdot (1/2) \cdot \rho \cdot V_{m}(z)^{2}$$  \(\ldots \ldots \ldots \ldots (5)\)

Finally, wind force acting on the billboard is calculated by multiplying the peak velocity pressure by the area of the billboard.

### 2.3 ASCE Standard

According to ACSE/SEI 7-10, initially, the category corresponding to the structure and the exposure class should be determined. Then the velocity pressure is computed using the equation (6),

$$q_{c} = 0.00256 \, K_{t} \, K_{a} \, K_{d} \, V^{2} \, \text{psf}$$  \(\ldots \ldots \ldots \ldots (6)\)

Where $V$ is the basic wind speed, $K_{a}$ is the topographic factor, $K_{t}$ is the wind directionality factor, and $K_{d}$ velocity pressure exposure coefficient. Thereafter design force acting on the structure is calculated from the equation (7),

$$F = q_{c} \, G \, C_{f} / A_{s}$$  \(\ldots \ldots \ldots \ldots (7)\)

Where $G$ is the gust effect factor, $C_{f}$ is the force coefficient, and $A_{s}$ is the gross area of the solid sign.

Therefore, it can be seen that the three design codes show some similarities in their methods of determining the design drag force acting on a billboard. The design codes consider the terrain and the exposure level of the structure but the design codes provide factors that are compatible with their countries and may not be suitable in the Sri Lankan context. Furthermore, the provided terrain categories only cover certain examples that may not be suitable in the modern context such as billboards that are put up on rooftops of buildings and where the existing terrain classes do not satisfy the actual case at the site. The design codes also do not consider the wind attack angle specifically, therefore making it unable to predict the drag force that acts when the wind is not flowing perpendicular to the billboard. In addition, the design codes do not provide any procedure to design the drag force acting on billboards of modern configurations such as two-plate, V-faced, or tri-sided billboards.

### 3. Evaluation of the Drag Force Coefficient using Measured Forces

#### 3.1 Mean Drag Force Coefficient for Single-Plate Billboards

Six components of wind loads are acting on the billboard as shown in Figure 1, but only two of them are truly relevant for the structural design of a billboard: drag force $F_{x}$, and the torsion around the center axis of the supporting column, $M_{t}$. The other components are relatively low and can be discarded. For single-plate billboards, the mean drag force coefficient is given by the following expression:

$$C_{D} = \frac{F_{z}}{1/2 \, \rho \, \overline{U}^{2} \, b \, d}$$  \(\ldots \ldots \ldots \ldots (8)\)

where $F_{z}$ is the mean value of the force component normal to the board. The wind loading on a billboard, as shown in Figure 2, is highly dependent on its geometry and the wind attack angle ($\theta$). Since most of the billboards are rectangular, the geometry can be defined in terms of aspect ratio $(b/d)$ and clearance ratio $(d/h)$. $\overline{U}$ is the mean wind velocity which is set to 45 km/h for this study.

![Figure 1: Forces acting on the billboard](image-url)
Unlike for single-plate billboards, a very limited number of publications are available for two-plate billboards. Among them, no tabulated data are available for further analysis. In order to generate adequate data, CFD simulations were carried out.

3.3 Torsional Moment about the Column Base of Billboards

The torsion can be considered as the drag force acting at a horizontal eccentricity (e) from the geometric center of the board. Based on the results obtained, a conservative approach is presented to calculate the torsion in the Results and Discussion section.

So the designers will only have to plug-in the corresponding aspect and clearance ratios to the equation to find the drag force and the torsional moment.

4. Numerical Simulation

CFD offers a very powerful alternative to predict the wind-related phenomena on structures. Midas NFX software package was used for the analysis. CFD analyses were carried out considering the same parameters used for wind tunnel testing of billboards. A practical and economical approach to identify the wind loading on billboards is to test scaled-down models. Thus, for this paper, the 1:200 scale was used. The comparison of experimental results with the results obtained from the CFD simulation is shown in Figure 9.

4.1 Billboard Models

For the purpose of validating the CFD model, 9 single-panel rectangular billboards with an aspect ratio (b/d) of 1, 2, and 3 and clearance ratio (d/h) of 0.33, 0.5, and 0.67 (see Figure 2) were tested. Solidworks software was used to model the billboards. All models are 25cm high which corresponds to 50m in full scale. Each model was tested for wind attack angle θ of 0°, 15°, 30°, 45°, 60°, and 75°.

As used in the experimental setup, for the material of the billboard, balsa wood (ρ = 150kg/m³, E = 3.71GPa) was used. The density of air was taken as 1.225 kg/m³.

For the analysis of two-plate billboards, aspect, clearance ratios, and the angle between the plates were selected such that they represent almost all the possible configurations of two-plate billboards. All the models were tested for θ values 0°, 15°, 30°, 45°, 60°, 75°, 90° and each for θ 0°, 15°, 30°.

4.2 Navier-Stokes Equations

Wind flow around bluff bodies is governed by incompressible Navier-Stokes equations and continuity equations.

\[ \frac{\partial \rho}{\partial t} + \nabla (\rho \mathbf{u}) = 0 \]  

\[ \frac{\partial (\rho \mathbf{u}_i)}{\partial t} + \nabla (\rho \mathbf{u}_i \mathbf{u}_j) = - \frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j} \left( \mu \left( \frac{\partial \mathbf{u}_i}{\partial x_j} + \frac{\partial \mathbf{u}_j}{\partial x_i} \right) \right) \]
respectively. In these equations, Coriolis force, buoyance force are not included as their effect is negligible for micro-scale CFD simulations. In Direct Numerical Simulation (DNS), these equations are directly solved which requires very fine grids to capture all relevant scales in the flow. As its computational demand is too high for the Reynolds numbers typically encountered in wind engineering, it is not applicable in this area. The generally used approach for the computation of turbulent flows in wind engineering is the Reynolds Averaged Navier-Stokes equations (RANS). In this approach, the equations are averaged in time over all the turbulent scales to obtain a statistically steady solution of flow variables. So any variable in turbulent flow can be represented as a sum of mean value and a fluctuating value,

$$u_j = U_j + u'_j$$ .... (13)

where $U_j$ is the mean velocity and $u'_j$ is the fluctuating component in a turbulent flow. Substituting Equation (13) in Equation (12) and using the fact that the mean value of the fluctuating component, $\bar{u}_j = 0$

$$\frac{\partial (\rho u_j)}{\partial t} + \frac{\partial (\rho u_j U_j + \rho u'_j u'_j)}{\partial x_j} = -\frac{\partial P}{\partial x_j} + \frac{\partial}{\partial x_j} \left( \mu \left( \frac{\partial U_j}{\partial x_j} + \frac{\partial u'_j}{\partial x_j} \right) - \rho \bar{u}_j \bar{u}_j \right)$$ .... (14)

The extra fluctuating term $\rho \bar{u}_j \bar{u}_j$ is known as Reynold's stress. A turbulence model is used to represent this in terms of mean quantities. For this study, k-ω SST model was used.

### 4.3 k-ω SST Turbulence Model

The Shear-Stress Transport (SST) model was developed recently, for accurate prediction of aeronautics flows with adverse pressure gradients and separation. Over the decades, the existing models had consistently failed to compute these flows accurately. In particular, the otherwise popular k-ε model was not able to predict the behavior of boundary layers up to the separation. The k-ω model is substantially more accurate than k-ε in the near-wall regions.

It calculates two convective transport equations for specific dissipation rate of turbulent kinetic energy ($\omega$) and turbulent kinetic energy ($k$)

$$k = \frac{1}{2} \left( \overline{u'^2} + \overline{v'^2} + \overline{w'^2} \right)$$ .... (15)

where $u, v, w$ are wind velocity components, along, lateral and vertical directions. To calculate accurate values of the turbulence, the eddy kinetic energy and eddy length scale need to be defined according to the following equations;

**Eddy kinetic energy** = $1.5 \times (velocity \times turbulence \ intensity \ level)^2$ .... (16)

**Eddy length scale** = $ \frac{10 \times \text{viscosity}}{(\rho \sqrt{\text{Eddy kinetic energy}})}$ .... (17)

The Reynolds number of the flow was set to $1\times10^5$. The degree of accuracy of these components directly affects the accuracy of the simulation.

### 4.4 Computational Domain and Boundary Conditions

The computational domain is dependent on the size of the model billboard. However, the domain should be large enough to avoid the interference of the boundary with the flow. As the thickness of the billboard is not significant, the domain was selected based on the height and width (see Figure 4).

![Computational Domain](image1)

**Figure 4: Computational Domain**

![Boundary conditions](image2)

**Figure 5: Boundary conditions**

The boundary conditions represent the influence of the surrounding that has been separated by the computational domain. Boundary conditions incorporated for this study are depicted in Figure 5.

Inlet condition corresponding to the wind velocity is applied on the front face. The outflow is at atmospheric pressure. So 0 Pa was applied on the rear face. CFD analysis is the analysis of liquid or gas flow, thus solid parts are not directly considered in the analysis and wall condition should be used on faces which are in contact with solid parts and no-slip condition was applied on the walls. To represent the fact that, the air around is almost infinitely large, the normal velocity ‘0’ condition was applied to the faces at the boundary with the atmosphere.
4.5 Mesh Generation

In order to analyze fluid flows, the flow domain is split into smaller subdomains (elements) which is commonly known as mesh generation.

The accuracy of CFD results highly depend on the mesh being used. Both triangle and quadrilateral elements (hybrid) were used in the mesh generation. The most fundamental and accurate method for evaluating mesh quality is to refine the mesh until a critical result converges, which is known as a mesh sensitivity analysis. For each model, a sensitivity analysis was carried out and that for the case of clearance ratio=0.33 and aspect ratio=1 is shown in Table 1. It can be seen that, although the number of elements increases, the result remains constant (converged) around 1.29. As a mesh quality check, the aspect ratio was assured to be less than 3, for over 95% of the elements generated in the mesh.

Table 1. Sensitivity analysis for the case, clearance=0.33, and aspect=1

| Edge size control (mm) | No. of elements | Drag force coefficient |
|------------------------|-----------------|------------------------|
| 2.75                   | 984676          | 1.323                  |
| 2.40                   | 992486          | 1.297                  |
| 2.00                   | 1039590         | 1.304                  |
| 1.90                   | 1041899         | 1.291                  |
| 1.80                   | 1054653         | 1.296                  |

5. Results and Discussion

A simplified method to predict the drag force coefficient for single-plate billboards are generated using experimental databases in the literature. For two-plate billboards, data generated using CFD simulations are used. Regression analysis is a powerful statistical method that allows examining the influence of one or more independent variables on a dependent variable. Here, a function of independent variables is presented to predict the dependent variable, the drag force coefficient. RStudio package was used for the regression analysis.

5.1 Equation to Predict the Drag Force Coefficient and Torsion for Single-Plate Billboards

First, a linear regression was carried out treating first-order terms of aspect ratio, clearance ratio, and wind attack angle as predictor variables and drag coefficient as the predicted variable. The adjusted R2 value was 0.685 and the model did not turn out to be a good one.

Then another equation (18) with different forms of the terms was tested. Then R2 value was increased to 0.827 and so as the significance of the terms.

\[ C_D = -0.364 - 0.13 \log_{10} AR - 0.308(CR)^3 + 4.138 \cos(\theta) - 2.315 \cos^2 \theta \]  \hspace{1cm} \text{(18)}

Since the R2 value alone doesn’t show the big picture on the accuracy, the proposed equation was compared with experimental data. The comparison is shown in Figure 6.

Based on the plot of e/b versus wind angle shown in Figure 7, the value of 0.6 can be recommended as a conservative value for e/b. Hence, the torsion can simply be calculated by multiplying drag force by the eccentricity (0.16).

5.2 Equation to Predict the Drag Force Coefficient and Torsion for Two-Plate Billboards

With the validated CFD model for single-plate billboards, CFD simulations were done for two-plate billboards, for varying aspect and clearance ratios. For the angle between the plates (φ), 0, 15° and 30° were used and all the configurations were tested for wind attack angle (θ), 0, 15°, 30°, 45°, 60°, 75° and 90°. Then a data base was created, from the CFD analysis results for further analysis. Then a similar expression by using the CFD database. An expression for total force coefficient is presented in terms of Aspect, Clearance ratios, wind attack angle and the angle between the plates. For simplicity, two separate expressions were formulated for θ from 0-45° and 45°-90°.

\[ C_F = 1.787 - 0.041AR - 0.228CR - 1.246 \cos \phi + 1.214 \cos \theta \hspace{1cm} \text{............... (19)} \]

\[ 45°<\theta<90° \]

\[ C_F = 2.514 - 0.103AR - 0.389CR - 1.881 \cos \phi + 1.4 \cos \theta \hspace{1cm} \text{............... (20)} \]

When considering the torsional effects for two-plate billboards, the Figure 8 shows the variation of e/b against wind attack angle for various configurations. The behavior of φ=0 case is identical to that of single plate billboards. So, to calculate the torsional moment, e/b=0.16 can be used. For both φ=15 and φ=30 case, maximum e/b can be identified as 0.22. Therefore, torsion about the base can easily be obtained by multiplying the total force by 0.22 for two plate billboards with non-parallel plates.
Figure 7. Variation of Peak eccentricity ratio with wind angle for single-panel billboards

Figure 8. Peak eccentricity ratio of two-panel billboards

Figure 9. Validation of the CFD model for single panel billboards.
Figure 7. Variation of Peak eccentricity ratio with wind angle for single panel billboards.

Figure 8. Peak eccentricity ratio of two panel billboards

- $b/d = 2$, $d/h = 0.5$
- $b/d = 1.5$, $d/h = 0.33$
- $b/d = 1$, $d/h = 0.4$
- $b/d = 3.5$, $d/h = 0.25$
- $b/d = 2.8$, $d/h = 0.28$

Figure 9. Validation of the CFD model for single panel billboards.

Legend
- ▲ Experimental
- ○ CFD

Figure 9. Validation of the CFD model for single panel billboards.
5. Conclusions and Recommendations

Numerous wind tunnel experiments have been done to find the wind loading on single-plate billboards. A database was formed using the tabulated data available in the literature for further analysis.

Unlike for single-plate billboards, limited researches have been done on two-plate billboards. To generate adequate data and to form a database, CFD analyses were done.

Using the database generated, two separate equations were formulated to easily predict the drag force coefficient and hence the drag force. With the results obtained, the following conclusions can be made:

1. A code-based approach cannot be used to see the big picture of the wind effects on different configurations of billboards.
2. CFD can be used as an effective alternative for wind tunnel testing of billboards
3. Out of the different turbulence models available, the k-ω SST model overcomes almost all the shortcomings in predicting the wind loads on billboards
4. From mesh sensitivity analyses carried out, it was found that 2mm edge-size control and 2cm 3D mesh size is appropriate for the selected billboards.
5. Proposed Equation (18) accurately predicts the drag force coefficient for single-plate billboards
6. Proposed Equations (19) and (20) accurately predict the total force coefficient for two-plate billboards
7. The torsional response of single-plate billboards and parallel-plate billboards can be found by multiplying the drag force by 0.16b
8. The torsional response of non-parallel two-plate billboards can be found by multiplying the total force with 0.22b

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Numerous wind tunnel experiments have been done to find the wind loading on single billboards. Proposed Equation (18) accurately predicts the drag force coefficient for single plate billboards, size is appropriate for the selected billboards. Found that 2

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