Performance of bridge design under wind loading conditions

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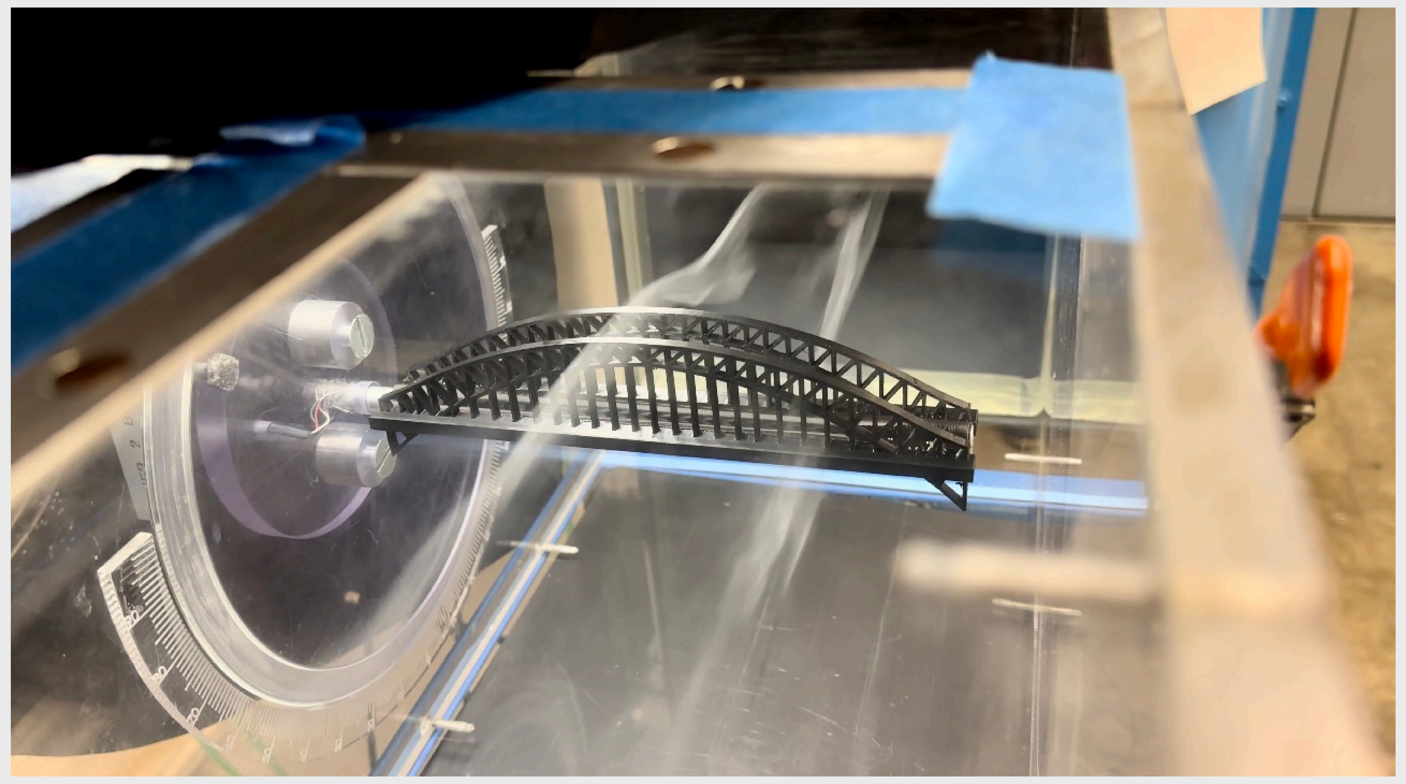
ABSTRACT

This wind tunnel experiment investigates the aerodynamic performance of three iconic bridges—Golden Gate, Bay Bridge, and Sydney Harbour Bridge—with a focus on drag coefficients under controlled wind loading conditions. To enhance the experiment's comprehensiveness, two 3D-printed replicas of the Sydney Harbour Bridge were created, allowing a comparative analysis. One model adheres to scale dimensions, while the other matches the size of the Golden Gate Bridge. This dual-print approach facilitates an examination of how the Sydney Harbour Bridge's shape responds in the Bay Area.

The methods involved subjecting the bridges to controlled wind speeds within a wind tunnel, reaching a maximum speed of 23 m/s. Observations focused on unique aerodynamic characteristics influenced by the diverse designs of the bridges, particularly the Golden Gate and Bay Bridge's cable suspension structure and the Sydney Harbour Bridge's arch shape. Analysis revealed similar drag coefficients for the Big Sydney Harbour Bridge and Golden Gate Bridge. The Bay Bridge exhibited higher coefficients, while the Small Sydney Harbour Bridge demonstrated even larger coefficients, suggesting comparable aerodynamic performance between the inverted truss design of the Sydney Harbour Bridge and the cable-stay structure of the Golden Gate.



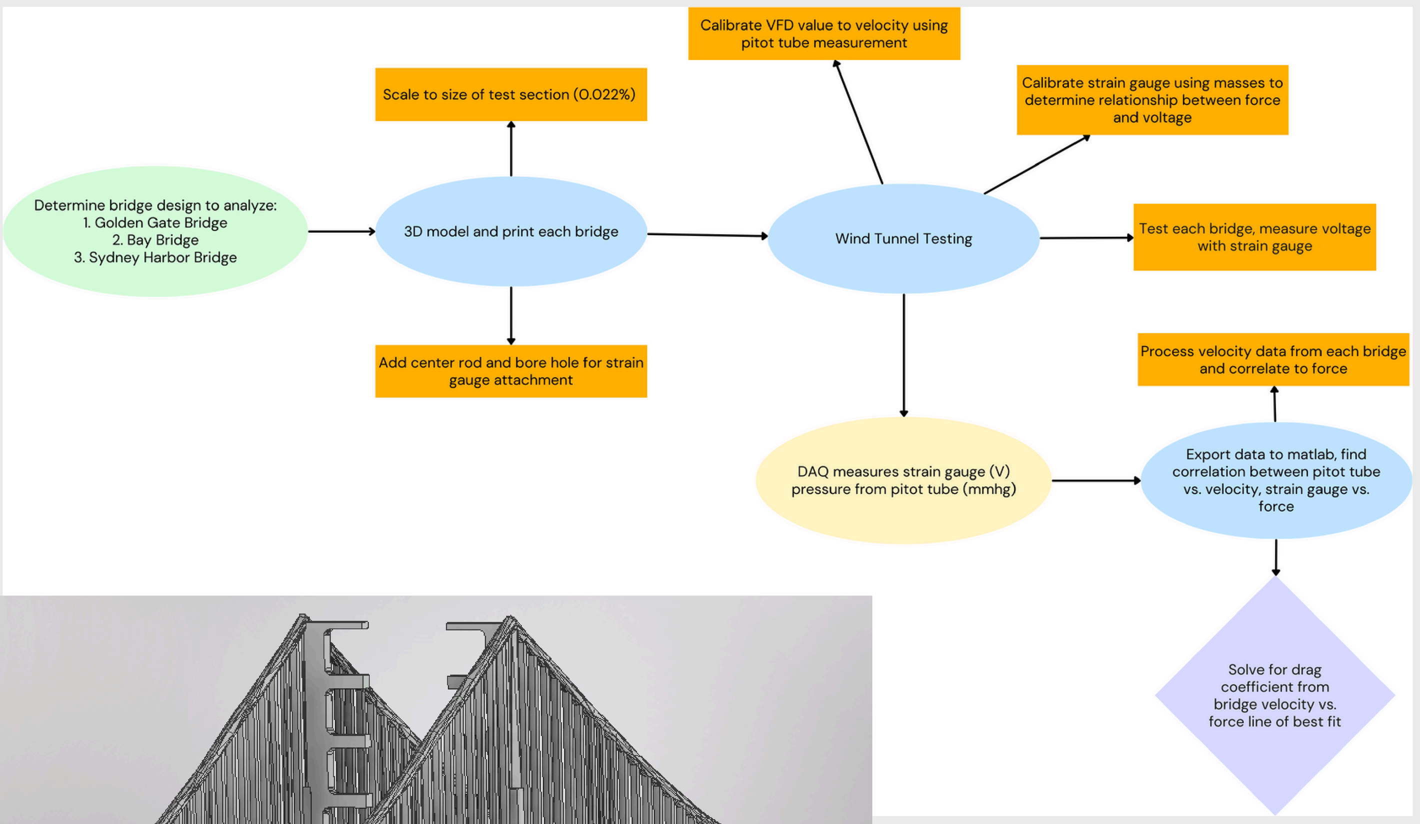
INTRODUCTION

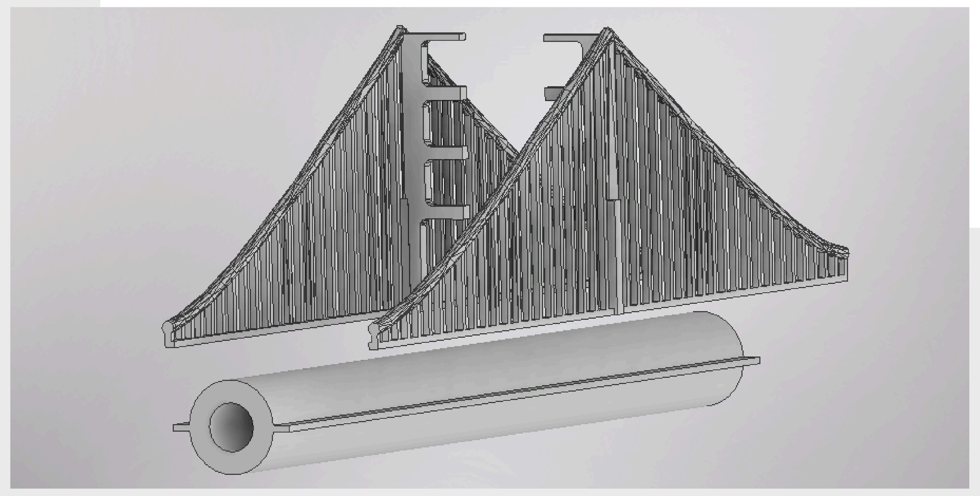
The Golden Gate Bridge, the Bay Bridge, and the Sydney Harbour Bridge host distinctive designs specifically chosen for their environment. This includes wind conditions, bridge span, and more, making them prime subjects for a comprehensive aerodynamic assessment.

These structures were analyzed to assess their resilience and drag coefficients. The Bay Bridge and Golden Gate Bridge, supported by cable-stays, withstand gusts up to 95 mph, while the Sydney Harbour Bridge, with an arch-shaped truss design, faces winds up to 132 mph. This experiment aims to determine the question in bridge design of where to optimize between structural robustness and minimal aerodynamic drag.

We hypothesize that the Sydney Harbour Bridge will exhibit a higher drag coefficient compared to the Bay Bridge and Golden Gate Bridge in this wind tunnel experiment. Our reasoning stems larger surface area of the Sydney Bridge's arch shape, resulting in higher aerodynamic resistance, leading to a greater drag coefficient. If our hypothesis holds true, it would suggest that the unique arch-shaped design contributes to a different aerodynamic performance profile compared to cable-stay structures under controlled wind loading conditions.

METHODOLOGY

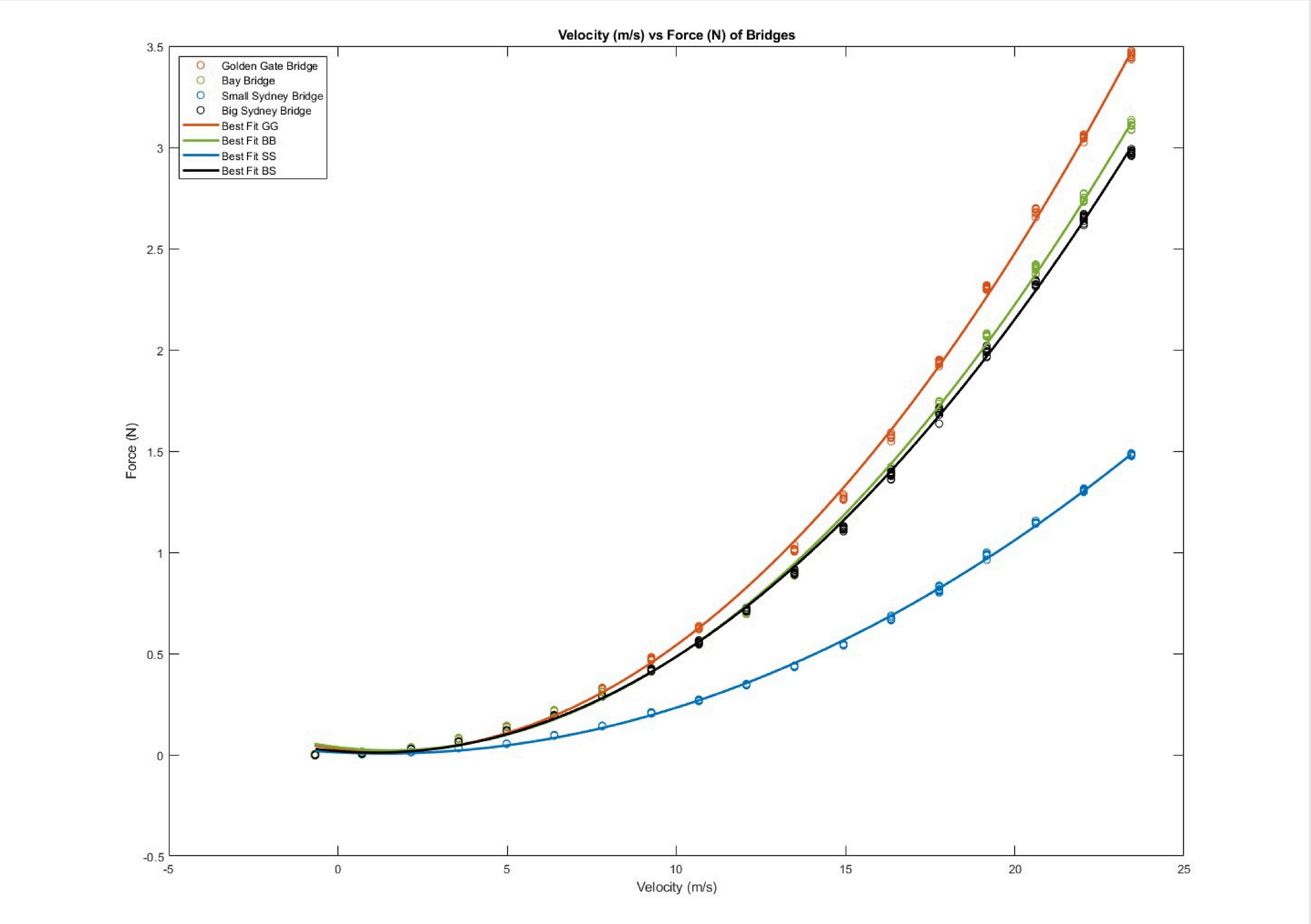




The design of our procedure revolved around the usage of the wind tunnel, specifically defining a max test section area of 6 in^2. Our bridge models optimized this required area with reference to the strain gauge in order to measure aerodynamic response to varying wind velocities. The bridges proved difficult to re-create in one piece on 3D printers. As a result, each bridge was printed as a composite and pieced together after printing.

RESULTS

Analyzing the data yields some interesting results. The drag coefficient and wind response for each distinct design can be calculated from velocity and strain gauge calibration, as shown below. Our main interest in the drag coefficient is calculated through the area of the face parallel to the wind, air density in the wind tunnel, and wind velocity.



The equation below translates a quadratic correlation between the drag force and the velocity.

$$F_d = \frac{\rho v^2 C_d A}{2}$$

Manipulating the above equation, we obtain the drag coefficient as a function of the force and velocity squared:

$$C_d = \frac{2F_d}{\rho v^2 A}$$

Finding the coefficients of the drag force equation reveals,

$$F_d = av^2 + bv + c$$

where

$$a = \frac{\rho C_d A}{2}$$

Therefore, the drag coefficient is

$$C_d = \frac{2a}{\rho A}$$

Table 2: Determining Drag Coefficient C_d From F_d and Velocity

Bridge	Line of Best Fit	Area $[m^2]$	Air Density $[kg/m^3]$	C_d
Golden Gate	$F_d = 0.0071v^2 - 0.0199v + 0.0295$	0.0048	1.18836	2.4894
Bay Bridge	$F_d = 0.0065v^2 - 0.0199v + 0.0373$	0.0035	1.18836	3.1256
Big Sydney	$F_d = 0.0060v^2 - 0.0133v + 0.0182$	0.0042	1.18836	2.4043
Small Sydney	$F_d = 0.0030v^2 - 0.0082v + 0.0120$	0.0012	1.18336	4.2075

DISCUSSION

As anticipated, the different designs do respond differently under wind currents. The challenges of design do contribute to some uncertainty in the results. In particular, the 3D printing limitations and the difference in scale greatly complicate the ability to accurately measure drag force. Nevertheless, solutions presented (composite printing, accurate scaling, etc.) help mitigate this to make the data better suited for comparison.

All bridges were tested at speeds of up to 50mph. At these speeds, it seems the drag coefficient is inversely proportional to the bridge size. When scaled down, the drag coefficient was observed to increase significantly (25-50%). The bridge design (inverted truss vs. suspension bridge) did not have a significant effect on the drag coefficient.

For engineers designing with wind load as a primary consideration, the span of the bridge should be taken into account. Structures such as the smaller Sydney Harbour Bridge are much less aerodynamic than their larger spanning counterparts. The engineer should weigh this with other factors (structural integrity, cost, etc.) to find the optimal solution.

It should be noted that material choice and cable geometry is likely to have a large impact on the aerodynamic properties of bridges. While it was not explicitly tested in this experiment, it is possible that small changes in geometry have a large effect on drag. The cable and center-deck geometry were likely to have an effect on drag, especially for the smaller bridges tested.

REFERENCES/ACKNOWLEDGEMENTS

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Bay Bridge Design Criteria Report - https://files.mtc.ca.gov/A354_report/A354/Appendix_F_Design_Criteria_and_Specifications/F1%20Self-