Exploring the Limits of Cable Stayed Bridge Design and Performance

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Abstract

Across centuries, bridges have been vital to human development, furthering the capabilities of transportation. Today, with over 600,000 bridges in the United States alone, they are a crucial part of transportation and travel. Among the many types of bridges, cable-stayed bridges have recently become especially notable. These bridges are supported by positioned pillars and steel cables. Our project examined how statics principles play a role in the safety and stability of these bridges. By creating models and calculating load limits for each bridge component, we determined safe thresholds. To test these calculations, a physical model was constructed to conduct stress and structural assessments. The data from this model revealed how different weight distributions impact stability. This study aimed to show how statics can help prevent structural failures and increase the reliability of cable-stayed bridges, ultimately protecting lives and infrastructure.

1 Introduction

1.1 Bridge Evolution

Although technology has progressed much since the first cable-stayed bridge was constructed, the science remains the same. Furthermore, this progression in technology has led to the construction of more stable and safe bridges. This is obviously due to better practices and even the assistance of computers to conduct calculations that would otherwise be prone to human error. However, technology has also brought upon better ways of testing the safety and stability of these bridges, such as sensor-based systems (SBS), which use distributed optical fiber sensors in their process [1]. Before investigating the different methods of testing and their uses, the structure of a cable-stayed bridge must be explained first. A cable-stayed bridge is unique in its structure, using a deck that "is supported by a number of nearly straight diagonal cables in tension running directly to one or more vertical towers" [2]. The cables, mixed with a combination of support beams, hold up the weight of the bridge. For these bridges to remain intact, it is necessary to test the integrity of the bridge, not only before it is constructed, but after it is constructed as well.

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1.2 Testing Methods & Structural Analysis

46,154 bridges in the United States are considered structurally deficient [3]. Bridges go through several tests, such as static and dynamic testing. A static test would involve applying known weights or loads on the bridge and analyzing the load distribution as well as the stress on the cables, in the case of a cable-stayed bridge. In the experiment conducted by Innocenzi RD, Nicoletti V, Arezzo D, Carbonari S, Gara F, Dezi L. (2022), 12 fully loaded, medium-weight trucks were used to conduct the static test and analyze the load distribution on the bridge [4]. By measuring the effect of different loads on the bridge, much can be learned about the necessary factors that play into its structure. For example, the effect of the load on the cables can be analyzed, specifically the stress and tension of the cables. This is very important because although a cable-stayed bridge has multiple cables, it is usually the combined tension and compression that holds the structure together, with the highest-grade steel cables having a strength of 1800–2000 megapascals (1 MPa = 1,000,000 Pa) [5]. This means failure of even one of the cables can compromise the entire structure of the bridge, such as the collapse of the Morbi Bridge in India [6]. Another type of testing is simply visual testing (VT), making observations of the structure to look for any points of weakness, for example, warping or cracking of the structure [7].

Through the use of various testing methods, as well as knowledge and analysis of the forces in the structure, a stable bridge can be constructed. Once constructed, the testing methods referenced above will be conducted, and the effect of the tests on the bridge will be recorded and investigated.

2 Methodology

2.1 Materials

The materials chosen for this project were simple yet durable, balancing strength and cost-effectiveness. For the deck, a material of size 1in x 6in x 4ft was selected, providing a sturdy base for the structure. The towers were constructed from a 1.5in x 1.5in x 8ft piece of wood, which was cut down to size. Additionally, custom caps were 3D printed using PLA filament designed in SolidWorks to fit securely on top of the towers. For the cables, twisted nylon string was utilized. The string's tension was critical to the bridge's structural behavior, and the nylon material was the ideal candidate for the strings, due to its strength and cost effectiveness. To anchor the cables, i screws were secured into the deck and towers. The deck featured eight i screws on each side of the deck for a total of 16, and two larger i screws were installed towards the top of each tower to secure the upper cable connections.

2.2 Assembly

Construction began by securing the towers to the base support with four L brackets per tower, one on each side, fastened to the 2 x 4 support beneath. It was crucial to leave just enough room between the towers for the deck to fit snugly. Once secured with L brackets, a nail was driven through the underside of the support into each tower for added stability. The i screws were then carefully spaced along the deck, with the first screws on either side positioned 5.5 inches from the center and each additional screw spaced 5.5 inches apart, ensuring the final screws were 2 inches from the edge. A total of 16 i screws—eight on each side—were installed. After fastening the screws, the deck was positioned between the towers and leveled to ensure proper alignment on all axes. Two larger i screws were installed 1.5 inches from the top of each tower to anchor the cables from the deck, with careful alignment to ensure the forces acted correctly. Finally, custom caps, designed in SolidWorks and 3D printed with PLA filament, were attached to the top of each tower, and the bridge was painted to complete construction.

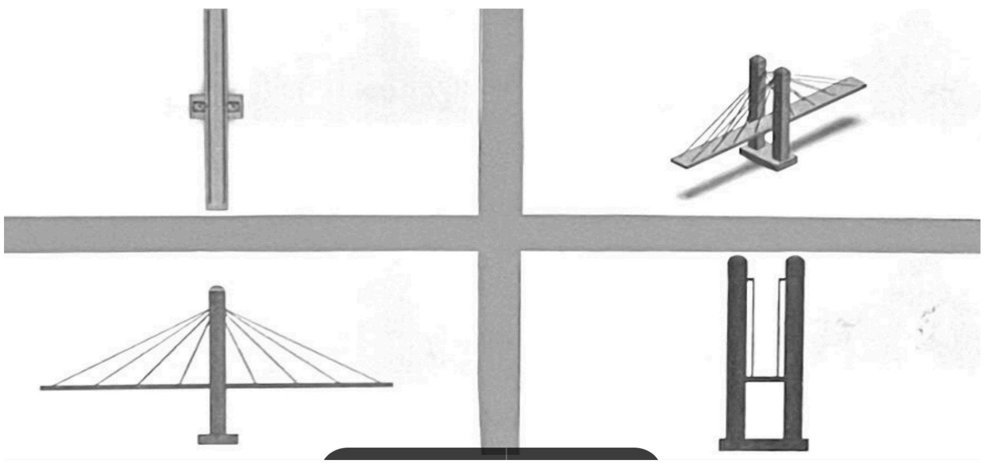

Figure 1: Final bridge design decided upon by the team [1]

3 Calculations

3.1 Cable Tension

Calculations began by determining the total weight of the bridge, which was 9.91 lbs, by summing the weight of each component. The tension in each set of wires was then calculated, with the symmetrical design ensuring equal forces on the four cable sections, corresponding to the deck's weight. To find the y-component of the force, the weight was divided by the sine of the measured angle, resulting in tensions of 0.381 lbs for the cables closest to the towers, 0.3205 lbs for the second closest, and 0.2595 lbs for the furthest. These calculations applied Newton’s second law, assuming the sum of forces on a stationary system equals zero.

$$\Sigma Fx = 0 \ \Sigma Fy = 0 \tag{1}$$

3.2 Reaction Forces in Tower

After calculating the tension in each of the cables, this provided the necessary information needed to find the reaction forces in the towers. The reaction force Ry was calculated by dividing the total weight of the deck by 2, as there are a total of two towers. This meant that Ry was equal to 4.955 lbs. Utilizing the fact that the forces in the x direction must also equal 0, the reaction forces in the x direction were set as the variable Rx, and plugged into the following equation.

$$-Rx + T1cos(\theta) + T2cos(\phi) + T3cos(\beta) = 0 \quad (2)$$

After plugging in our know values of T1, T2, T3, θ, ϕ, and β, the value for the reaction force in the x direction Rx was 0.4919 lbs. The last necessary calculation was finding the reaction moment produced at the base of each tower. The towers produce a reaction moment due to the fact that the towers are unable to rotate about any planes or points. Because all other forces in the system were already solved for, it was possible to create a single equation to solve for our reaction moment, denoted as Mr in the following equation.

$$Mr - (T1\,cos(\theta))(33) - (T2cos(\phi))(33) - (T3cos(\beta))(33) - (\frac{w}{2})(12) = 0 \quad (3)$$

Because the values of all variables in the equation are known besides Mr, solving this equation was as simple as plugging in our known values and isolating Mr, which resulted in a value of 75.69 lbs.

4 Results

The calculations provided a good start for the bridge's design, and testing verified the accuracy of our theoretical calculations. The bridge met all design goals, performing well under a variety of load conditions, with no noticeable deformation at higher loads (before exceeding maximum load for the cables). While the initial calculations focused on the weight of the deck alone (9.91 lbs), testing revealed that the maximum load the cables could safely handle before snapping was roughly 39.5 pounds. During testing, we found that the bridge responded better to a distributed load, which caused less stress on individual cables and helped maintain stability. In contrast, loads concentrated at specific points led to cable failure, highlighting the importance of load distribution in the design.

Despite this, the bridge's behavior closely matched our hypothesis, and there were no discrepancies between our calculations and the final model of the system. This validated our design, material selection, and construction methods, while providing valuable insights into how real-world applications align with theoretical models.

5 Conclusion

In this project, we successfully constructed a fan-shaped bridge with two towers, tested it under various loads, and found that it performed better than expected. The bridge met all goals outlined and defined by our calculations, validating our choice of materials and construction. Despite the success, several obstacles had to be overcome to achieve the desired results. The bulk of these problems were caused by initial material choices and the logistics of tensioning the cables. Much weaker i screws were initially installed, which caused them to shear under intense forces. To combat this, we opted for thicker i screws at the tower. Additionally, connecting and tensioning the cables proved to be challenging. We anchored the cables to the i screws and allowed each cable to be individually tensioned, but this method made it difficult to ensure proper alignment and prevent tilting. However, these obstacles were overcome, and the final design remained stable. This project provided valuable insights into the complexities of bridge design, material selection, and structural integrity. Improvements for future recreations may include refining the cable tensioning method and utilizing stronger materials. In the final analysis, this project provided valuable engineering experiences and highlighted the importance of material selection, precise design, and iterative problem-solving in structural engineering.

6 References

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