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Safety of Suspension Cables of the Williamsburg Bridge

Sécurité des câbles du pont suspendu de Williamsburg

Sicherheit der Hängeseile der Williamsburg Brücke

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SUMMARY

The Williamsburg Bridge spanning New York City's East River has been attacked by salt air, which has corroded its steel main suspension cables. In 1988, the bridge was judged to be in need of replacement. Later, another study concluded the bridge was structurally sound. Methods are presented to estimate the current safety factor of the main cables, based on wire samples tested for tensile strength. The method uses the Ductile Wire Model and the Extreme Value Distribution approach and gives estimates for the cable safety factor.

RÉSUMÉ

Le Pont de Williamsburg sur le East River à New York a subi les attaques de la corrosion. En 1988, on estimait que le pont devait être remplacé. Puis une autre étude a montré qu'il était possible de garder le pont. Quelques méthodes utilisées pour l'évaluation des câbles sont présentées. Des essais sur des torons ont permis d'en estimer la résistance. Les méthodes, utilisant le "Ductile Wire Model" et "Extreme Value Distribution" donnent les facteurs de sécurité du câble.

ZUSAMMENFASSUNG

Die Williamsburg Brücke über den East River der Stadt New York war der Manhattaner Salzluft ausgesetzt, welche die Stahl-Haupthängekabel korrodiert hat; 1988 wurde beschlossen, die Brücke zu ersetzen. Später hat eine andere Untersuchung ergeben, dass die Brücke baulich sicher war. Basierend auf für Zugfestigkeit geprüften Drahtproben sind hier Methoden vorgestellt, den gegenwärtigen Sicherheitsfaktor des Hauptkabels abzuschätzen. Die Methode benutzt das Ductil Wire Model und gibt Schätzungen für den Kabelsicherheitsfaktor.

1. INTRODUCTION

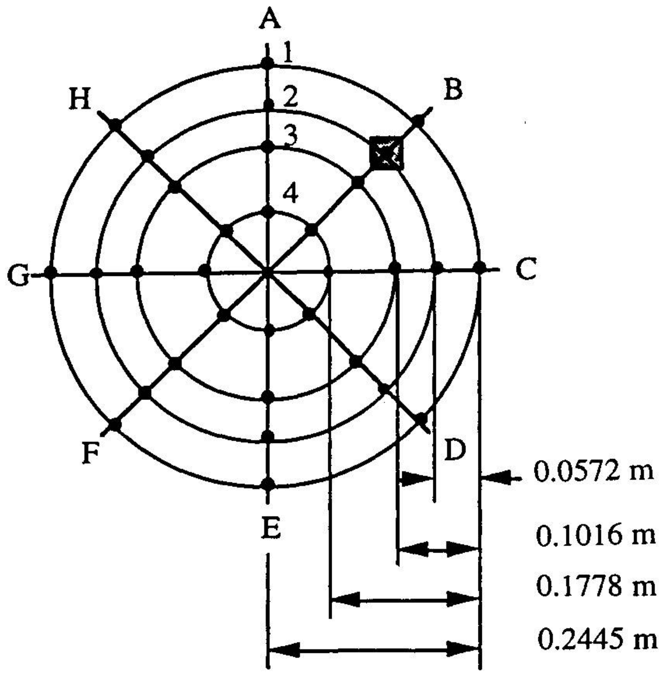
Nearly a quarter of a million people a day cross New York City's Williamsburg Bridge via car, truck, train, bicycle, and on foot [1]. At its opening in 1903, engineers and media hailed its record 488 m main span. Considered in 1988 structurally unfit for future use, it is now under large-scale rehabilitation after a later study concluded that the bridge was structurally sound. [5]. On the basis of previous work [4], this study re-evaluates the current strength of the main cables. By opening up the cables for inspection and wire sampling, inspectors visually evaluated and physically tested the cable wires. This study uses the existing data base and a new approach based on the Type I Asymptotic Distribution of the Smallest Value [2] to estimate the current value for the safety factor of the main cables.

2. CABLE ANALYSIS OF THE WILLIAMSBURG BRIDGE

7,696 parallel wires with diameters of 0.0049 m comprise each of the four main cables of the bridge. 32 wire lengths were removed from each of five locations to estimate the current cable capacity and predict its reliability; data were collected from April to June of 1988. Engineers then cut each of the 32 wire samples into ten 0.3048 m segments to be tested in tension for breaking strength [1]. Figure 1 shows the locations of the 32 wire samples within the cable cross-section. The wire sample indicated by the shaded dot in Figure 1 is labeled B2 and will serve as an example in the following sections. For each one of the 32 wire samples, a mean and a standard deviation were computed for the tensile strength based on the ten 0.3048 m segments. The investigators assumed that the tensile strength follows a Gaussian distribution, with each wire sample having a different mean and standard deviation for each of these two parameters.

The data were used to develop contour maps depicting wire minimum breaking strength over the entire cable cross-section. The objective of this paper is to estimate the current safety factor of the main suspension cable, which is the ratio of its predicted strength divided by its ultimate load. The predicted strength is determined using the test results to estimate the average break load of the cable wires and then multiplying by the number of unbroken, ductile wires in the cross-section. The ultimate load is the maximum expected load and is calculated using structural analysis. The strength of the main cable is estimated using the Ductile Wire Model and an Extreme Value Distribution method, which can be implemented without using a computer.

<u>Fig. 1:</u> Wire sample positions in cable cross-section (Location I at mid span)



The Ductile Wire Model is based on the assumption that all wires within the cable cross-section, when over-stressed, have sufficient ductility to elongate plastically before breaking. On-site investigations produced clear indications of general ductile wire behavior and load redistribution among the cable wires. This model assumes elastic-perfectly plastic behavior and uses the tensile strength results to estimate the cable strength.

2.1 Average Wire Break Load: Extreme Value Distribution

The mean values and standard deviations are computed for each one of the 32 wires using ten 0.3048 m segments. Consequently, these values for the tensile strength and the elongation are valid only for wire segments that are 0.3048 m in length. Assuming, in each row vector of ten tensile strengths, the test results are arranged from smallest to largest (i.e., $X_{11} < X_{12} < X_{13} < \cdots < X_{1\,10}$), the first column of the matrix of test results (i.e., $X_{11}, X_{21}, X_{31}, \cdots, X_{32\,1}$) automatically provides the values of the break loads for the 32 wires.

However, the issue of the break load for a longer wire segment in the cable must be addressed using the idea of effective clamp length. Because of the clamping effect of cable bands and wrapping on the wires, the load of the broken wire is channeled to the remaining intact wires in the vicinity of the break and is channeled back to the broken wire as its ability to carry loads is regained away from the break location. It is this phenomenon that allows taking wire samples from the main cable without risking a significant drop in the cable load-carrying capacity over its full length. This indicates that the weakest point in each wire should not be sought over the cable's full length, but over a limited length known as the effective clamp length.

Retractions were measured for cut wires to estimate the effective clamp length. By measuring the retraction length after cutting a wire under tension, it is possible to compute the amount of tensile force carried by the wire at any location away from the cut. From these computations it is reasonable to estimate that a broken wire contributes only partially to the load-carrying capacity of the main cable for three panel lengths (or 18.3 m) in the vicinity of the break (a panel length is the horizontal distance between two successive cable bands). Outside this 18.3-meter zone, the wire regains nearly its full initial load carrying ability. Therefore the cable bands produce an effective clamp length of 18.3 m. The wrapping of wires, which is continuous along the entire length of the main suspension cable, applies additional pressure to the wires and produces friction. Theoretical values for similar cables are as low as 1.5 m [3]; however as a conservative measure, the influence of cable wrapping is neglected, and the effective clamp length for this study remains 18.3 m [4].

Denoting now by $X_{(1)}$ the random variable describing the wire break load, its probability distribution function will be given by the Type I Asymptotic Distribution of the Smallest Value:

$$F_{X_{(1)}}(x) \approx 1 - \exp\left(-e^{\alpha_1 (x-u_1)}\right) \tag{1}$$

where u_1 and α_1 are calculated from:

$$F_X(u_1) = \frac{1}{N} \tag{2}$$

$$\alpha_1 = N \cdot f_X(u_1) \tag{3}$$

In Equations (2) and (3), F_X and f_X are respectively the probability distribution and probability density functions of the initial distribution of random variable X; the value of N corresponds to the number of 0.3048 m segments in the effective clamp length of 18.3 m, or 60 units. Recall that X is a Gaussian random variable describing the tensile strength of 0.3048 m wire segments:

$$f_X(x) = \left(\frac{1}{\sqrt{2\pi} \cdot \sigma_X}\right) \cdot \exp\left[-\frac{(x-\mu_X)^2}{2\sigma_X^2}\right] \qquad -\infty < x < \infty \tag{4}$$

with μ_X and σ_X the mean value and standard deviation of X, respectively, and:

$$F_X(x) = \int_{-\infty}^{\infty} f_X(u)\,du = \Phi\left(\frac{x-\mu_X}{\sigma_X}\right) = \Phi(z) \tag{5}$$

with $\Phi(z)$ denoting the Standard Normal Distribution. The average wire break load is the mean value of random variable $X_{(1)}$, since $X_{(1)}$ describes the wire break load. The mean value and standard deviation of $X_{(1)}$ are given by:

$$E\left[X_{(1)}\right] = u_1 - \frac{0.57721}{\alpha_1} \tag{6}$$

$$\sigma_{X_{(1)}} = \sqrt{\frac{\pi^2}{6\alpha_1^{\,2}}} \tag{7}$$

The average wire break load is now computed for wire B2 using the Extreme Value Distribution. For wire type B2, the mean value and the standard deviation of the initial distribution are:

$$\mu_X = 28{,}976 \text{ N} \quad \text{and} \quad \sigma_X = 262.9 \text{ N} \tag{8}$$

Considering that the effective clamp length is 18.3 m, the value of N is 60. Using now Equations (2) through (5), the numerical values of parameters, u_1 and α_1 are:

$$u_1 = 28{,}416 \text{ N} \quad \text{and} \quad \alpha_1 = 0.0094 \tag{9}$$

Having computed u_1 and α_1, the probability distribution function, the mean value and the standard deviation of the wire break load are:

$$F_{X_{(1)}}(x) \approx 1 - \exp\left(-e^{0.0094(x-28{,}416)}\right) \tag{10}$$

$$E\left[X_{(1)}\right] = 28{,}355 \text{ N} \tag{11}$$

$$\sigma_{X_{(1)}} = 136.3 \text{ N} \tag{12}$$

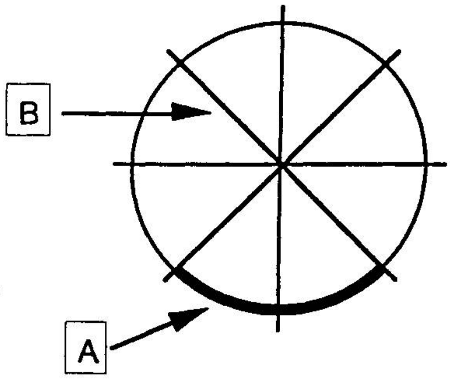
2.2 Number of Unbroken Wires in the Cable Cross-Section

The broken wires must be discounted from the main cable cross-section. The bottom surface of the main cable contained the greatest number of wire breaks, where water infiltrating into the cable wrapping tended to collect [4]. The wires in the cross-section are divided into two groups: (A) the 78 surface wires of the bottom quadrant (where corrosion and wire breaks occurred to a high degree), and (B) the remaining 7,618 interior and surface wires. These two groups are shown in Figure 2.

Fig. 2: Two wire groups in cable cross-section

A 78 surface wires in bottom quadrant

B 7,618 remaining interior and surface wires



The probability that a wire will be broken in either one of the two groups is based upon on-site inspections. The investigators found 15 broken wires among the 78 wires inspected in group A. Three broken wires were found in group B; although there are 7,618 wires in group B, only 1,057 could actually be inspected from the limited number of wedged cable openings. Therefore,

$$p_A = \frac{15}{78} \quad \text{and} \quad p_B = \frac{3}{1{,}057} \tag{13}$$

The number of broken wires in groups A and B are two random variables, NBW_A and NBW_B, respectively. Following the Binomial Distribution with the number of trials $N_A = 78$ and $N_B = 7{,}618$, respectively, the corresponding mean values and variances are:

$$E(NBW_A) = N_A \cdot p_A = 15 \tag{14}$$
$$E(NBW_B) = N_B \cdot p_B = 21.62 \tag{15}$$
$$Var(NBW_A) = N_A \cdot p_A \cdot (1 - p_A) = 12.12 \tag{16}$$
$$Var(NBW_B) = N_B \cdot p_B \cdot (1 - p_B) = 21.56 \tag{17}$$

The sum of these two random variables is a new random variable, NBW_{tot}, representing the total number of broken wires in the cable cross-section:

$$NBW_{tot} = NBW_A + NBW_B \tag{18}$$
$$E(NBW_{tot}) = E(NBW_A) + E(NBW_B) = 36.62 \approx 37 \tag{19}$$
$$Var(NBW_{tot}) = Var(NBW_A) + Var(NBW_B) = 33.68 \approx 34 \tag{20}$$

In view of the fact that the values of p_A and p_B shown in Equation (13) are estimated from the inspection of a single cable cross-section along the length of the main suspension cable, it is necessary to establish a sufficiently conservative value for the total number of broken wires in the cable cross-section. This is achieved using Chebyshev's inequality:

$$P\{|NBW_{tot} - E[NBW_{tot}]| \geq \delta\} \leq \frac{Var(NBW_{tot})}{\delta^2} \tag{21}$$

and an upper bound of 1% yielding the following value for δ:

$$\frac{Var(NBW_{tot})}{\delta^2} = 0.01 \quad or \quad \delta = 58.31 \tag{22}$$

Consequently, a sufficiently conservative value for the total number of broken wires in the cable cross-section is estimated as:

$$E[NBW_{tot}] + \delta \approx 96 \text{ broken wires} \tag{23}$$

The corresponding number of unbroken wires is 7,600.

3. SAFETY FACTOR ESTIMATION

The procedure to compute the safety factor of the main suspension cable using the Ductile Wire Model is described using an effective clamp length of 18.3 m (or 60 units).

(1) The average wire break load for the cable cross-section is estimated as 26,751 N.
(2) The conservative value for the total number of broken wires in the cable cross-section is estimated as 96 (Equation 23). The corresponding number of unbroken wires is 7,600.
(3) The strength of the main cable is the average wire break load multiplied by the number of unbroken wires, or 203,307,600 N.
(4) The ultimate load, or maximum expected load, on the main cable was determined as 48,485,400 N using structural analysis.
(5) Finally, the safety factor is the ratio of the cable strength divided by the ultimate load:

$$\text{Safety Factor} = \frac{203{,}307{,}600\ N}{48{,}485{,}400\ N} = 4.19$$

Table 1 displays the corresponding safety factor values for effective clamp lengths of 6.1 m (20 units) and 12.2 m (40 units).

Table 1: Safety Factors of Main Suspension Cable using the Ductile Wire Model

Effective Clamp Length	6.1 m (20 units)	12.2 m (40 units)	18.3 m (60 units)
Safety Factor	4.23	4.21	4.19

Note: 1 unit = 0.3048 m.

4. CONCLUSIONS

Wire break loads are directly described by Type I Asymptotic Distributions of the Smallest Value with parameters that can be easily determined from the test data. The assumptions considered in the computation of the safety factor of the main cable are generally conservative. Recall, for example, that the influence of cable wrapping on the effective clamp length was neglected and that Chebyshev's inequality was used to estimate a conservative value of the total number of broken wires.

When using the Ductile Wire Model, the effect of the effective clamp length on the value of the safety factor is minimal (see Table 1). On-site investigations produced clear indications of general ductile wire behavior and load redistribution among the cable wires. Consequently, engineers concluded that all unbroken wires should be considered ductile. The values for the safety factor of the main suspension cable shown in Table 1 indicate a range between 4.19 and 4.23. These values are sufficiently high to support the conclusion to rehabilitate, and not replace, the main suspension cables of the Williamsburg Bridge.

REFERENCES

1. LEVINE, R. and JOHNSON, K. Chronicle of City's Neglect of Williamsburg Bridge, The New York Times, June 10, 1988, pp. A1 and B4.

2. MATTEO, J. A., DEODATIS, George, and BILLINGTON, D. P. Safety Analysis of Suspension-Bridge Cables: Williamsburg Bridge, Journal of Structural Engineering, ASCE, Vol. 120, No. 11, 1994, pp. 3197-3211.

3. RAOOF, M. and HUANG, Y. P. Wire Recovery Length in Suspension Bridge Cable, Journal of Structural Engineering, ASCE, Vol. 118, No. 12, 1992, pp. 3255-3267.

4. STEINMAN BOYNTON GRONQUIST & BIRDSALL in association with COLUMBIA UNIVERSITY. Williamsburg Bridge Cable Investigation Program: Final Report, submitted to the New York State and New York City Departments of Transportation, October 1988.

5. WILLIAMSBURG BRIDGE TECHNICAL ADVISORY COMMITTEE. Technical Report to the Commissioners of Transportation of the City and State of New York, June, 1988.