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Static analysis of stay cables under the varying chord strength of the cable failure inspection in cable-stayed bridges

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Abstract

Purpose of research. *Bridge constructions are frequently subjected to harsh circumstances such as severe weather, earthquakes, traffic accidents, and even explosives. Bridge structures may lose some of their important structural parts (e.g., cables or piers) as a result of such intense external stresses, and further collapse is possible, as progressive collapse is often caused by the abrupt loss of one or more critical structural components. Cable-stayed bridges have very tiny cross-sectional areas and are subjected to high loads. Such strong pressures can destroy anchoring zones due to large stress concentrations, resulting in cable loss. Bridges with cable stays must be thoroughly investigated for the danger of progressive collapse induced by cable loss scenarios. Suggests considering the most common cable failure scenarios throughout the design process. To evaluate the effect of cable loss, do a static analysis with a (DAF) of two. There are two primary ways for avoiding progressive collapse. First, adopt structural or non-structural measures to provide a high level of safety against localized collapse. Second, prevent failures from spreading by establishing a solid foundation that allows for local failures.*

Methods. *Materials and methods. Damage to cables in the mathematical modeling of cable-stayed bridges. A continuous beam suspended from tension elements (cables) forms the basis of the conceptual model. His strength calculation plan is by comparing stiffness and flexibility matrices of intact and damaged systems. The stiffness matrix for an intact system is calculated using its reduced shape. The flexibility matrix is then calculated by inverting the reduced stiffness matrix. The conceptual model is interactive. As a result, the stiffness matrix is infinite. For direct analytical calculations, the parameter n is set as the ratio of the stiffness of the system ($\eta = \frac{k_{cable}}{k_{beam}}$), and a reduced form of the stiffness matrix is obtained to obtain an intact.*

Results. *The secant module seems to give a very good approximation, since the error remains less than 1% for cables up to 300 m long and less than 2% for cables up to 750 m long. Russians Russian Bridge has a length of 135.77 meters and the longest cable is 579.57 meters, as a result, the error rate of cables on the Russian Bridge will remain less than 1% for some cables and less than 2% for some cables. Considering that the modulus of elasticity of the steel material of the cable is rarely known with an accuracy of more than 2-3%, it is obvious that the method for determining the secant modulus would be suitable for all practical purposes. The tangent module is often easier to use than the secant module, since it is only necessary to know the voltage of the cable in its initial state. On the other hand, the tangent module can lead to erroneous conclusions with a long cable length and a large traffic-to-idle ratio, as shown in Figure 8.*

Conclusion. *The distance between two adjacent cables on modern bridges is significantly less than on older bridges. As a result, in the event of a car accident or explosion on the new bridge, several cables will fail. As a result, it was proposed that bridge designers take into account the rupture of all cables within a radius of 10 meters. Several studies have been conducted to find DAF in bridges. According to this study, having a father of two is not always safe. Although a recent study shows that the proposed DAD is safe for cable construction, that is, it is unsafe for structures of pylons or beams with negative moments.*

Keywords: *bridge structures; progressive collapse; cable-stayed bridges; load conditions; cable loss.*

Conflict of interest. *The authors declare the absence of obvious and potential conflicts of interest related to the publication of this article.*

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Статический анализ несущих тросов в условиях изменяющейся прочности хорды при проверке повреждения троса на вантовых мостах

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Резюме

Цель исследования. *Мостовые сооружения часто подвергаются воздействию суровых погодных условий, землетрясений, дорожно-транспортных происшествий и даже взрывчатых веществ. Мостовые сооружения могут потерять некоторые из своих важных конструктивных элементов (например, тросы или опоры) в результате таких интенсивных внешних воздействий, и возможно дальнейшее обрушение, поскольку прогрессирующее обрушение часто вызвано внезапной потерей одного или нескольких важных конструктивных компонентов. Вантовые мосты имеют очень малую площадь поперечного сечения и подвергаются высоким нагрузкам. Такое сильное давление может привести к разрушению зон крепления из-за высокой концентрации напряжений, что приведет к обрыву кабеля. Мосты с вантовыми опорами должны быть тщательно исследованы на предмет опасности постепенного обрушения, вызванного сценариями обрыва кабеля. Необходимо учитывать наиболее распространенные сценарии обрыва кабеля на протяжении всего процесса проектирования. Чтобы оценить последствия обрыва кабеля, выполняется статический анализ с использованием двух методов (DAF). Существует два основных способа избежать постепенного обрушения. Во-первых, принимаются конструктивные или неструктурные меры для обеспечения высокого уровня безопасности при локальном обрушении. Во-вторых, необходимо предотвратить распространение сбоев, создав прочную основу, допускающую локальные сбои.*

Методы. *Повреждения тросов при математическом моделировании вантовых мостов. Непрерывная балка, подвешенная к натяжным элементам (тросам), составляет основу концептуальной модели. Его план расчета прочности путем сравнения матриц жесткости и гибкости неповрежденных и поврежденных систем. Матрица жесткости для неповрежденной системы вычисляется с использованием ее уменьшенной формы. Матрица гибкости затем вычисляется путем инвертирования матрицы уменьшенной жесткости. Концептуальная модель является итеративной. В результате матрица жесткости бесконечна. Для прямых аналитических вычислений параметр η задается как отношение жесткости системы ($\eta = \frac{k_{cable}}{k_{beam}}$), и получается уменьшенная форма матрицы жесткости для получения неповрежденного состояния.*

Результаты исследования. *Модуль секущей, по-видимому, дает очень хорошее приближение, поскольку погрешность остается менее 1% для кабелей длиной до 300 м и менее 2% для кабелей длиной до 750 м. А поскольку длина самого маленького кабеля на Русском мосту составляет 135,77 метра, а самого длинного - 579,57 метра, в результате частота ошибок кабелей на Русском мосту останется для некоторых кабелей менее 1%, а для других кабелей менее 2%. Учитывая, что модуль упругости стального материала троса редко известен с точностью более 2-3%, очевидно, что метод определения секущего модуля был бы пригоден для всех практических целей. Касательный модуль часто проще в использовании, чем секущий модуль, поскольку необходимо знать только напряжение кабеля в исходном состоянии. С другой стороны, касательный модуль может привести к ошибочным выводам при большой длине кабеля и большом соотношении трафика к холостому ходу, как показано на рисунке 8.*

Заключение. *Расстояние между двумя соседними кабелями на современных мостах значительно меньше, чем на старых мостах. В результате в случае автомобильной аварии или взрыва на новом мосту несколько кабелей выйдут из строя. В результате было предложено, чтобы проектировщики мостов учитывали разрыв всех кабелей в радиусе 10 метров. Было проведено несколько исследований, чтобы найти DAF в мостах. Предложенный DAD безопасен для конструкции кабеля, то есть он небезопасен для конструкций пилонов или балок с отрицательными моментами.*

Ключевые слова: *мостовые конструкции; прогрессирующее обрушение; вантовые мосты; условия нагрузки; потеря кабеля.*

Конфликт интересов: *Авторы декларируют отсутствие явных и потенциальных конфликтов интересов, связанных с публикацией настоящей статьи.*

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Introduction

In cable-stayed bridges, major structural elements like towers, piers, or cables may be harmed or fail by severe loads, which might result in the collapse of the entire bridge. One of the more worrying failure types that might emerge from an unplanned cable loss in this kind of bridge is zipper-type collapse, commonly referred to as horizontal progressive collapse. Therefore, the recommendation made by PTI (2007) is that comparable static tests be used in conjunction with dynamic amplification factor (DAF) to thoroughly examine the effects of different cable loss situations. Existing standards and guidelines specify the common DAF value for building and bridge structures as DAF= 2.0; however, for cable-stayed bridges with considerable degrees of redundancy, the use of a constant DAF= 2.0 in conjunction with comparable static analysis has been questioned. One of the key objectives of this research is to investigate the abrupt loss of cables in cable-stayed and suspension bridges, which has lately attracted researchers' curiosity [1,2].

Methods

Cable failures in cable-stayed bridge mathematical models

Figure 1 shows the mathematical structure. The conceptual model is built on a continuous beam that is suspended by tension elements, such as cables. By comparing the stiffness and flexibility matrices of the damaged and undamaged systems, he intends to compute strength. Using its simplified form, the stiffness matrix of an undamaged system is computed. Next, the owered stiffness matrix is flipped to produce the flexibility matrix. Iterations are made to the conceptual model. The stiffness matrix is therefore infinite [3].

The intact state is achieved by using the reduced form of the stiffness matrix, which is given by specifying the parameter η as the system stiffness ratio ($\eta = \frac{k_{cable}}{k_{beam}}$), for direct analytical computations [4].

$$\underline{F}=\underline{\underline{K^{vv},^{red}}}*\underline{v}\,. \tag{1}$$

$$\underline{F}=(\ldots,F_{i-2},F_{i-1},F_i,F_{i+1},F_{i+2},\ldots). \tag{2}$$

$$\underline{v}=(\ldots,v_{i-2},v_{i-1},v_i,v_{i+1},v_{i+2},\ldots). \tag{3}$$

$$\underline{\underline{K^{vv,red}}}=3\sqrt{3}k_b\begin{pmatrix} & \vdots & \vdots & \vdots & \vdots & \vdots & \\ \cdots & \frac{k_2}{3\sqrt{3}} & \frac{k_1}{3\sqrt{3}} & \frac{k_2}{3\sqrt{3}} & \varepsilon^2 & (-\varepsilon)^3 & \cdots \\ \cdots & \varepsilon^2 & \frac{k_2}{3\sqrt{3}} & \frac{k_1}{3\sqrt{3}} & \frac{k_2}{3\sqrt{3}} & \varepsilon^2 & \cdots \\ \cdots & (-\varepsilon)^3 & \varepsilon^2 & \frac{k_2}{3\sqrt{3}} & \frac{k_1}{3\sqrt{3}} & \frac{k_2}{3\sqrt{3}} & \cdots \\ & \vdots & \vdots & \vdots & \vdots & \vdots & \end{pmatrix}, \tag{4}$$

where $\varepsilon=\sqrt{3}-2$; $k_1=\eta-4+3\sqrt{3}$; and $k_2=\frac{1}{2}(19-12\sqrt{3})$.

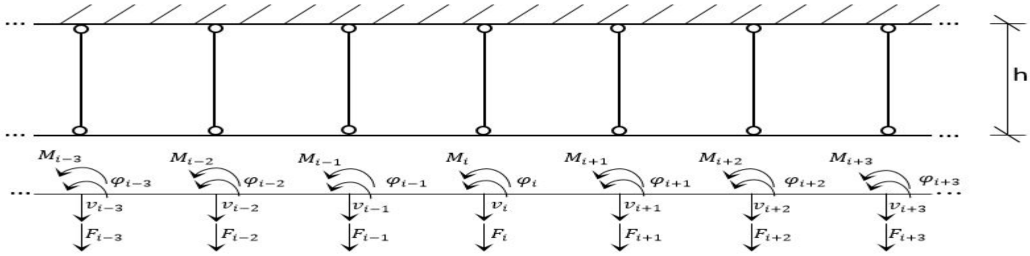


Fig. 1. Mechanism of Parallel Loading [3]

Conceptual model

A theoretical paradigm for long-span cable-supported bridges is the parallel load system. Examining the long span cable stayed bridges' structural resilience in the case of a cable failure is the aim of this research. The conceptual model is based on a beam that is suspended by cables, or tension components. By using load-bearing components of a similar sort and function, structures can be built using parallel load-bearing methods. One of these systems' unique features is its ability to offer additional load paths. Suspension and cable-stayed bridges are prime examples of this type of structural arrangement. Weights are supported by parallel sections called hooks and anchor cables in suspension and cable-stayed bridges [5].

On sometimes, torsion can be disregarded. When it comes to single-cable flat systems reinforced by box girders or double-cable cables flat equipment including edge girders, torsion has no impact. This work does not address torsion. Although the simplified model was first developed for a suspended bridge, it may be used for any paralleled load-bearing structure, including cable-stayed bridges. Every cable is thought to have the same axial durability, and the girder stiffness is the same in every cross-section. A true bridge's whole construction must be taken into account when calculating the cable's axial tension. The goal is to provide a general formula for the increase in stress related to a critical component as a result of cable failure. As a result, the quantity of cables may differ. First, an equation for the stress increase ratio of the critical cable is built assuming that there is only one failure of the cables. There are an increasing number of defective cables in the next phase. Finally, if cables break, an equation for a system with (2n) cables is established. The length L is the distance between two successive wires in the simplified form. The cable has an axial stiffness of K. K_b=12EI/L^3 is the supporting structure's bending stiffness. The whole system is symmetrical, with the broken cable located in the center. The load sustained by the failed cable is F; the absorption force in the critical cable as a result of a cable break is F1; and the corresponding absorbed load for the other cables on both sides of the site of failure is F2- Fn. The larger forces in the cables, and hence the anticipated bending moment in the girder, are generated by cable breaking [6, 7, 8].

Adapting the approximation function to provide a conceptual model with more specific details

All cables are considered to have the same axial stiffness. But in real buildings, this assumption is not correct. For instance, every cable in cable-stayed bridges has a distinct axial stiffness due to its particular length. This section makes the assumption that the axial stiffness of each cable is distinct in order to get the conceptual model one step closer to reality. The schematic representation of the model under study is shown in form 2 [5, 6].

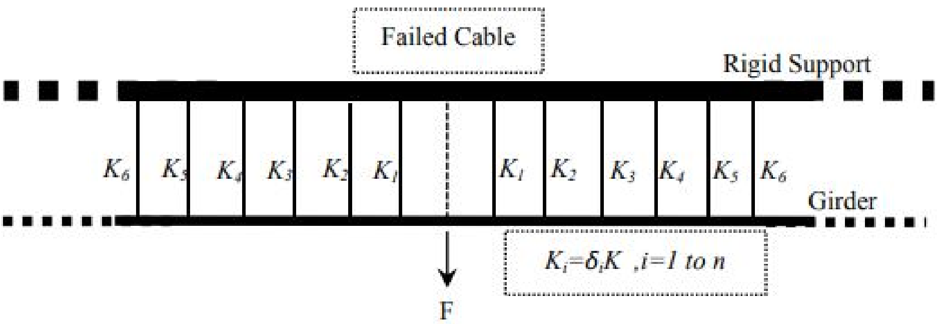


Fig. 2. Schematic representation of an elaborate model [5]

The new conceptual model takes each cable's individual axial stiffness into account, as seen in Fig. 2. In order to facilitate understanding of the mathematical process, a reference axial stiffness (K) is utilized, and the cables' stiffness is represented as a multiple of the reference stiffness ($K_i = \delta_i K$). There is just one hypothetical cable failure, and the model maintains its symmetry.

A methodical approach is used to solve this system of equations, number five. Assumptions about the stiffness of each cable are made in the first stage (K1 = K2 = … = KN or $\delta_1 = \delta_2 = \ldots = \delta_n = 1$). The set of linear equations for the several cable systems is then solved, and the approximation function's unknown parameters are determined. The crucial cable's rigidity is adjusted in the second phase. As a result, all of the cables in this phase are equally stiff, with the exception of the essential cable ($\delta_2 = \delta_3 = \ldots = \delta_n = 1$). Ultimately, all cables have their stiffness adjusted in the last stage. As a result, the axial stiffness of each cable is different [5, 6].

$$\begin{cases} F_n+F_{n-1}+F_{n-2}+\cdots+F_1=\dfrac{F}{2} \\ F_n\left(6+\dfrac{6\beta}{\delta_n}\right)+F_{n-1}\left(1-\dfrac{12\beta}{\delta_{n-1}}\right)+F_{n-2}\left(\dfrac{6\beta}{\delta_{n-2}}\right)=0 \\ F_n(12)+F_{n-1}\left(6+\dfrac{6\beta}{\delta_{n-1}}\right)+F_{n-2}\left(1-\dfrac{12\beta}{\delta_{n-2}}\right)+F_{n-3}\left(\dfrac{6\beta}{\delta_{n-3}}\right)=0 \\ F_n(18)+F_{n-1}(12)+F_{n-2}\left(6+\dfrac{6\beta}{\delta_{n-2}}\right)+F_{n-3}\left(1-\dfrac{12\beta}{\delta_{n-3}}\right)+F_{n-4}\left(\dfrac{6\beta}{\delta_{n-4}}\right)=0 \\ F_n(24)+F_{n-1}(18)+F_{n-2}(12)+F_{n-3}\left(6+\dfrac{6\beta}{\delta_{n-3}}\right)+F_{n-4}\left(1-\dfrac{12\beta}{\delta_{n-4}}\right)+F_{n-5}\left(\dfrac{6\beta}{\delta_{n-5}}\right)=0 \\ \vdots \\ F_n(6n-12))+F_{n-1}(6(n-1)-12)+\cdots+F_3\left(6+\dfrac{6\beta}{\delta_3}\right)+F_2\left(1-\dfrac{12\beta}{\delta_2}\right)+F_1\left(\dfrac{6\beta}{\delta_1}\right)=0 \\ F_n(9n-7)+F_{n-1}(9(n-1)-7)+\cdots+F_2\left(11+\dfrac{6\beta}{\delta_2}\right)+F_1\left(3-\dfrac{6\beta}{\delta_1}\right)=0. \end{cases} \tag{5}$$

Based on the previous stages' results and the definitions of each approximation function parameter, the following conclusions can be drawn:

1. The parameter a represents the lowest coefficient of stress increase that happens when $\beta = \infty$, the girder is rigid, and all cables have the same displacement. As a result, it is simple to compute the parameter an as follows:

$$a=\frac{K_1}{2\sum_{i=1}^{n} K_i}=\frac{\delta_1}{2\sum_{i=1}^{n} \delta_i}, K_i=\delta_i K. \tag{6}$$

2. The highest voltage rise factor that happens when $\beta = 0$ is indicated by parameter b. The sole useful parameter for parameter b is thus the quantity of broken wires. It has been demonstrated that parameter b is 0.75 in the event of a single cable failure.

3. Parameter c has a growing value equal to δ_1 and is solely dependent on the crucial cable's axial stiffness.

4. A variety of systems have been studied, and the results indicate that the stiffness and quantity of cables have the most effects on parameter d. The effect of cable stiffness is negligible, though. Therefore, the effect of cable stiffness on parameter d value is disregarded in order to minimize the complexity of the approximation function.

With the aforementioned information in mind, the approximation function may be found as follows [5]:

$$\frac{F_1}{F}=a+\frac{\frac{3}{4}-a}{1+\left(\frac{\beta}{c}\right)^{d}}. \qquad (7)$$

For large values of n:

$$\frac{F_1}{F}=\frac{\frac{3}{4}}{1+\left(\frac{\beta}{\delta_1}\right)^{0.35}}, \qquad (8)$$

where equation (9). should be used to find the value d.

$$d=0.35+\frac{0.65}{1+\left(\frac{2n}{5}\right)^{1.1}} \quad 2n\geq 12. \qquad (9)$$

Three distinct systems, each with two alternative cable configurations, were investigated in order to confirm the correctness of the approximation function that was given (see Fig. 3).

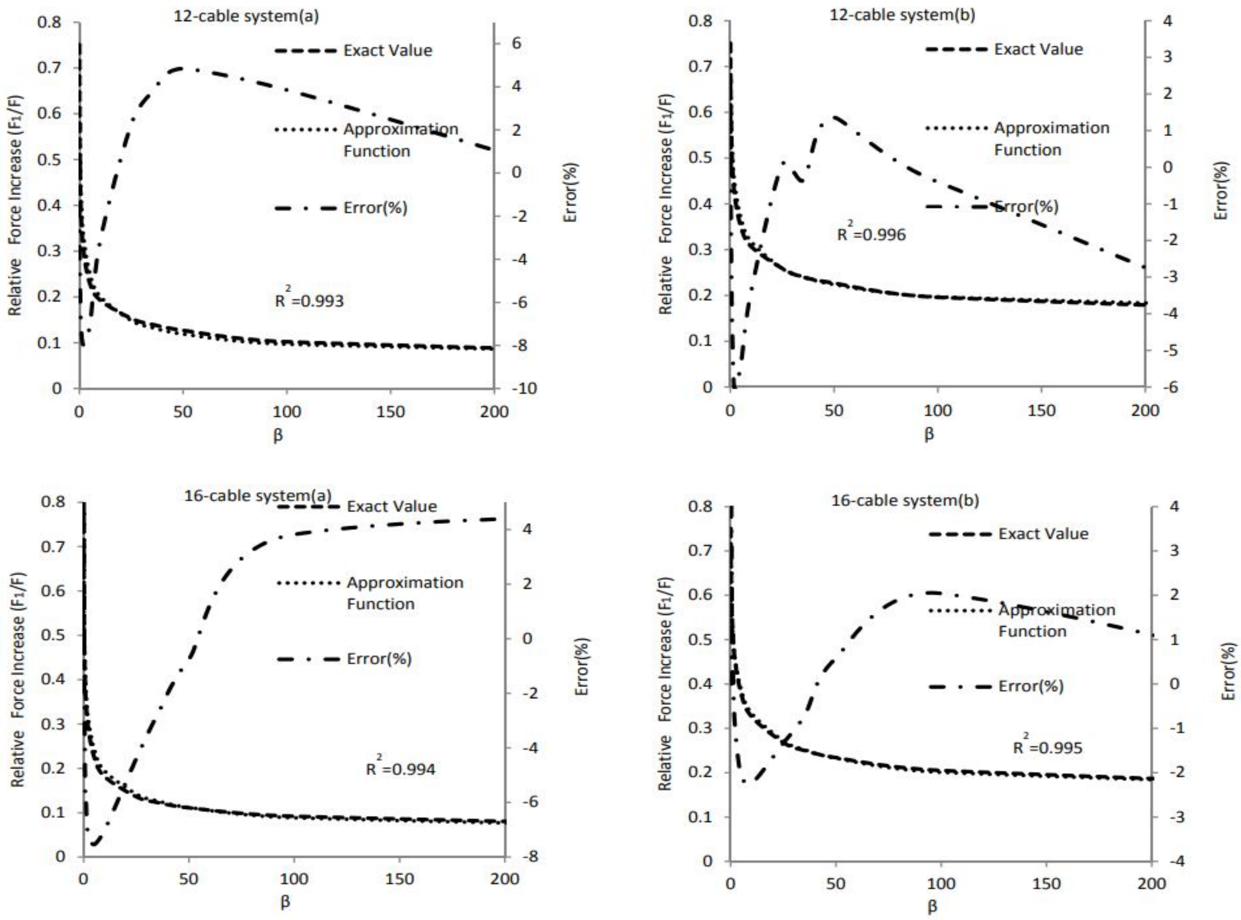


Fig. 3. The percentage of stress increase in different systems is shown through exact and estimated values

An Analytic Approach for Estimating the Stresses Increase Rate in an Important Cable Resulting from Cable Loss

When load-bearing components of similar sort and function are included into structural systems, it creates alternative load paths known as paralleled load-bearing structures. Bridges supported by cables are a prime illustration of this type of structural system. In the event that a cable or other parallel bearing element breaks, the weight it carries must be transferred to the rest of the structure. In this circumstance, the member next to the failing member bears the majority of the reallocated load and becomes the crucial member. If this component cannot sustain the redistributed weight, the collapse may spread to other members or possibly the entire building. Hence, considering the crucial significance of the key component in the durability of the bone structure, our study concentrates on it (cables)[1].

The connection between the durability of chord F and the total length of chord c is the most important deformative characteristic in cable-stayed bridges with axial stress (Fig. 5). The dead load for the cable is equally spread around the curve. The examination of the Russky bridge (Fig. 4) will start with a catenary design rather than a parabola arrangement using a horizontal stay cable, as indicated in Fig. 6. Here, two circumstances defined by chord pressures F1 and F2 are considered [9, 10].

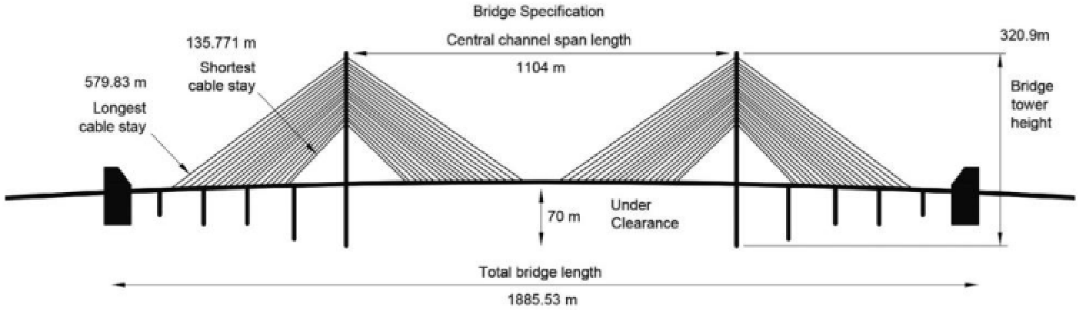


Fig. 4. Shows the bridge's primary dimensions and the positioning of important sections [7,10]

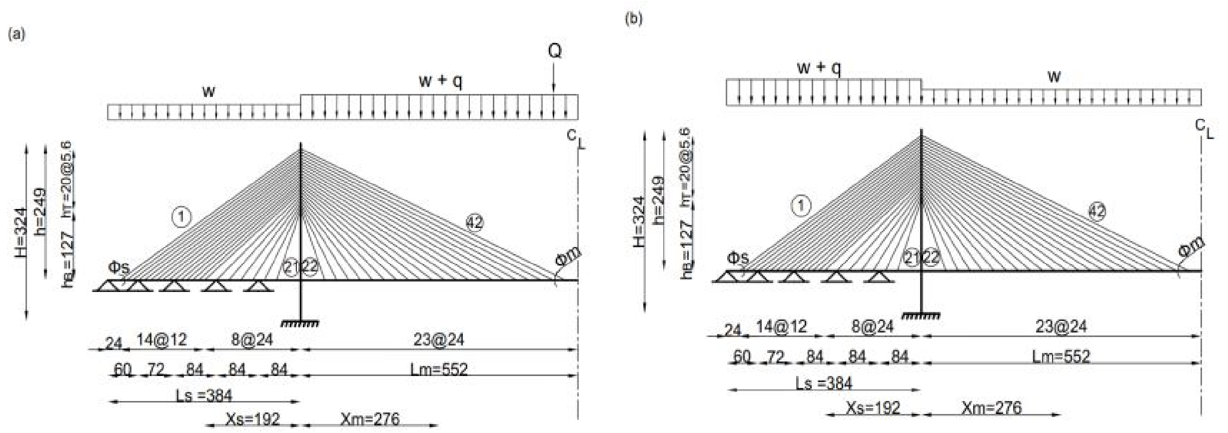


Fig. 5. Shows the stay cable's chord length (c) and chord force (F).

[1] Aoki Y. Analysis of the performance of cable-stayed bridges under extreme events (Doctoral dissertation), 2014.

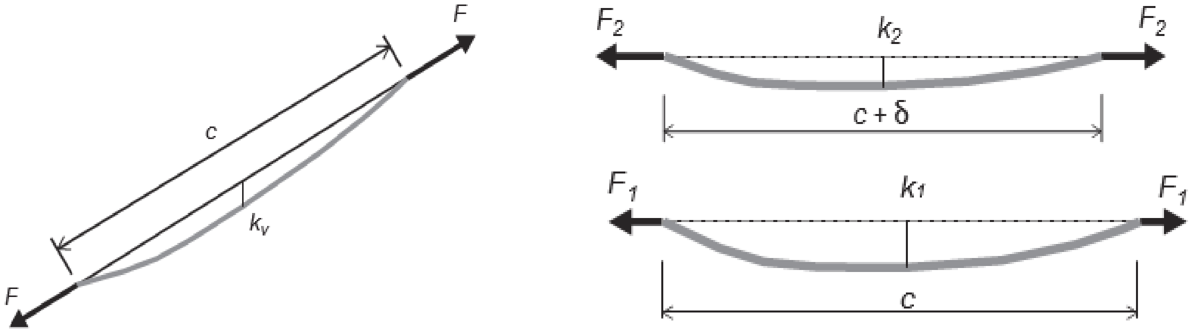


Fig. 6. A horizontal stay cable requires two requirements with F1 and F2 chord forces, respectively [9]

In case 1, the equation for the catenary is given by [9, 11]:

$$y_1=\frac{F_1}{w_{cb}\cos\phi}\left[\cosh\left(\frac{w_{cb}\cos\phi}{F_1}\left(x-\frac{1}{2}c\right)\right)-\cosh\left(\frac{w_{cb}\cos\phi\, c}{2F_1}\right)\right] \tag{10}$$

and in case 2:

$$y_2=\frac{F_2}{w_{cb}\cos\phi}\left\{\cosh\left[\frac{w_{cb}\cos\phi}{F_2}\left(x-\frac{c+\delta}{2}\right)\right]-\cosh\left(\frac{w_{cb}\cos\phi(c+\delta)}{2F_2}\right)\right\}. \tag{11}$$

Where w_{cb} is the dead load of the cable per unit length $w_{cb}=A_{cb}\gamma_{cb}$ and δ is the elongation of the cable, which is defined as the increase in the distance between the points of support, F is the force of the chord and c is the length of the chord.

Table 1 is parabolic approximation of the values for the correct cable curve in the Russky bridge (y_1, y_2) is a catenary and is utilized in most circumstances without causing an undesirable mistake.

Table 1. Correct cable curve values (y_1, y_2) for cables in the Russky bridge

NO	y_1	y_2	NO	y_1	y_2	NO	y_1	y_2
1	1.53437	1.16203	15	0.61924	0.45863	29	0.69597	0.51769
2	1.45742	1.10207	16	0.54044	0.3986	30	0.77222	0.57699
3	1.38247	1.0438	17	0.45909	0.33727	31	0.84785	0.63641
4	1.30954	0.98722	18	0.37498	0.27446	32	0.92369	0.6966
5	1.23861	0.93231	19	0.28776	0.20992	33	0.99865	0.75669
6	1.16967	0.87906	20	0.19729	0.14349	34	1.07562	0.81897
7	1.10139	0.82644	21	0.10859	0.07878	35	1.15254	0.88181
8	1.03522	0.77556	22	0.10859	0.07878	36	1.2293	0.94507
9	0.96992	0.72546	23	0.19729	0.14349	37	1.30791	1.01044
10	0.90798	0.67805	24	0.28776	0.20992	38	1.38835	1.07796
11	0.847	0.63149	25	0.37498	0.27446	39	1.46843	1.1457
12	0.78714	0.58589	26	0.45909	0.33727	40	1.55025	1.21551
13	0.72953	0.54212	27	0.54044	0.3986	41	1.63268	1.28638
14	0.67323	0.49945	28	0.61924	0.45863	42	1.71676	1.35929

Table 2 shows the horizontal distance between the pylon and the cable (a) and the length of inclined cable (c) in the Russky bridge [12].

Table 2. Distance (a) and cable length (c)

NO	a	c	NO	a	c	NO	a	c
1	360	432.11	15	192	250.31	29	216	272.54
2	348	419.02	16	168	228.58	30	240	295.15
3	336	405.94	17	144	207.5	31	264	318.07
4	324	392.87	18	120	187.29	32	288	341.22
5	312	379.82	19	96	168.27	33	312	364.57
6	300	366.77	20	72	150.89	34	336	388.08
7	288	353.74	21	48	135.77	35	360	411.73
8	276	340.73	22	48	135.77	36	384	435.48
9	264	327.73	23	72	150.89	37	408	459.33
10	252	314.76	24	96	168.27	38	432	483.26
11	240	301.81	25	120	187.29	39	456	507.26
12	228	288.89	26	144	207.5	40	480	531.31
13	216	275.99	27	168	228.58	41	504	555.42
14	204	263.13	28	192	250.31	42	528	579.57

Total elongations from the non-stressed state

The lengths of the cables l_1 determined by [10,11]:

$$\mathrm{l}_1=2\frac{F_1}{\mathrm{w_{cb}}\cos\phi}\sinh\left(\frac{\mathrm{w_{cb}}\cos\phi\, c}{2F_1}\right) \tag{12}$$

and l_2 determined by:

$$l_2=2\frac{F_2}{w_{\mathrm{cb}}\cos\phi}\sinh\left(\frac{w_{\mathrm{cb}}\cos\phi(c+\delta)}{2F_2}\right). \tag{13}$$

In Table 3, the lengths of the cables in the Russky bridge as a result of the force of the chord, taking into account the dead loads.

Δl_1 and Δl_2, the total elongations from the non-stressed state, is calculated using [13]:

$$\Delta l_1=\frac{F_1^2}{2\mathrm{EA}w_{cb}\cos\phi}\times$$

$$\times\left[\sinh\left(\frac{w_{\mathrm{cb}}\cos\phi\, \mathrm{c}}{F_1}\right)+\frac{\mathrm{w_{cb}}\cos\phi}{F_1}\right]; \tag{14}$$

$$\Delta l_2=\frac{F_2^2}{2\mathrm{EA}w_{cb}\cos\phi}\times$$

$$\times\left[\sinh\left(\frac{w_{\mathrm{cb}}\cos\phi\, \mathrm{c}}{F_2}\right)+\frac{\mathrm{w_{cb}}\cos\phi\, \mathrm{c}}{F_2}\right]. \tag{15}$$

Table 4 shows the value of the total elongations from the unstressed condition of the cables used in the Russky bridge.

The graph shows (7) the cable lengths in the Russky bridge as a result of the force of the chord and total elongation from the case of unstressed cables used in the Russky bridge, that the cable steels do not have a plastic plateau and that the elongation at rupture is much less than that of typical structural steel.

Table 3. Lengths of the cables in the Russky bridge

NO	l_1	l_2	NO	l_1	l_2	NO	l_1	l_2
1	432.16	433.82	15	250.32	251.29	29	272.55	273.61
2	419.06	420.68	16	228.59	229.48	30	295.17	296.31
3	405.98	407.55	17	207.5	208.31	31	318.09	319.32
4	392.91	394.42	18	187.29	188.02	32	341.25	342.57
5	379.85	381.31	19	168.27	168.93	33	364.6	366.01
6	366.8	368.22	20	150.89	151.48	34	388.12	389.62
7	353.77	355.14	21	135.77	136.3	35	411.77	413.36
8	340.75	342.07	22	135.77	136.3	36	435.54	437.21
9	327.75	329.02	23	150.89	151.48	37	459.39	461.16
10	314.78	316	24	168.27	168.93	38	483.33	485.19
11	301.82	303	25	187.29	188.02	39	507.34	509.28
12	288.9	290.02	26	207.5	208.31	40	531.41	533.44
13	276	277.07	27	228.59	229.48	41	555.53	557.65
14	263.14	264.16	28	250.32	251.29	42	579.7	581.91

Table 4. Total elongation of cables in Russky bridge

NO	Δl_1	Δl_2	NO	Δl_1	Δl_2	NO	Δl_1	Δl_2
1	0.62569	1.68649	15	0.35724	0.97686	29	0.38975	1.06362
2	0.60605	1.63539	16	0.32563	0.89204	30	0.42302	1.15188
3	0.58647	1.58433	17	0.29513	0.80977	31	0.45694	1.24132
4	0.56697	1.53331	18	0.26604	0.73091	32	0.49144	1.3317
5	0.54753	1.48234	19	0.23878	0.65667	33	0.52643	1.42285
6	0.52817	1.43142	20	0.21396	0.58883	34	0.56194	1.51463
7	0.50886	1.38056	21	0.19245	0.52983	35	0.59787	1.60694
8	0.48962	1.32977	22	0.19245	0.52983	36	0.63417	1.69967
9	0.47045	1.27904	23	0.21396	0.58883	37	0.6709	1.79279
10	0.45137	1.2284	24	0.23878	0.65667	38	0.70808	1.88621
11	0.43237	1.17786	25	0.26604	0.73091	39	0.74553	1.97991
12	0.41344	1.12741	26	0.29513	0.80977	40	0.78339	2.07385
13	0.39461	1.07709	27	0.32563	0.89204	41	0.82154	2.168
14	0.37588	1.0269	28	0.35724	0.97686	42	0.86009	2.26233

Because it is not acceptable to have permanent (irreversible) elongation of the wires for loads that will occur with a large number of repetitions throughout the bridge's lifetime, the available plastic strains (characterized by a minimum elongation at rupture of 4% in a gauge length of 250 mm) are generally sufficient to allow a local redistribution of forces between wires with different initial stresses due to imperfections during erection [14, 15].

The equation of case $l_2 - l_1 = \Delta l_2 - \Delta l_1$ of the cable leads to δ [9, 16]:

$$\delta=\frac{\dfrac{(F_2-F_1)c}{2EA}+\dfrac{1}{2EAw_{cb}\cos\phi}\left[F_2^2\sinh\left(\dfrac{w_{cb}\cos\phi\, c}{F_2}\right)-F_1^2\sinh\left(\dfrac{w_{cb}\cos\phi\, c}{F_1}\right)\right]}{\cosh\left(\dfrac{w_{cb}\cos\phi\, c}{2F_2}\right)}+$$

$$+\frac{\dfrac{2}{w_{cb}\cos\phi}\left[F_1\sinh\left(\dfrac{w_{cb}\cos\phi\, c}{2F_1}\right)-F_2\sinh\left(\dfrac{w_{cb}\cos\phi\, c}{2F_2}\right)\right]}{\cosh\left(\dfrac{w_{cb}\cos\phi\, c}{2F_2}\right)}. \tag{16}$$

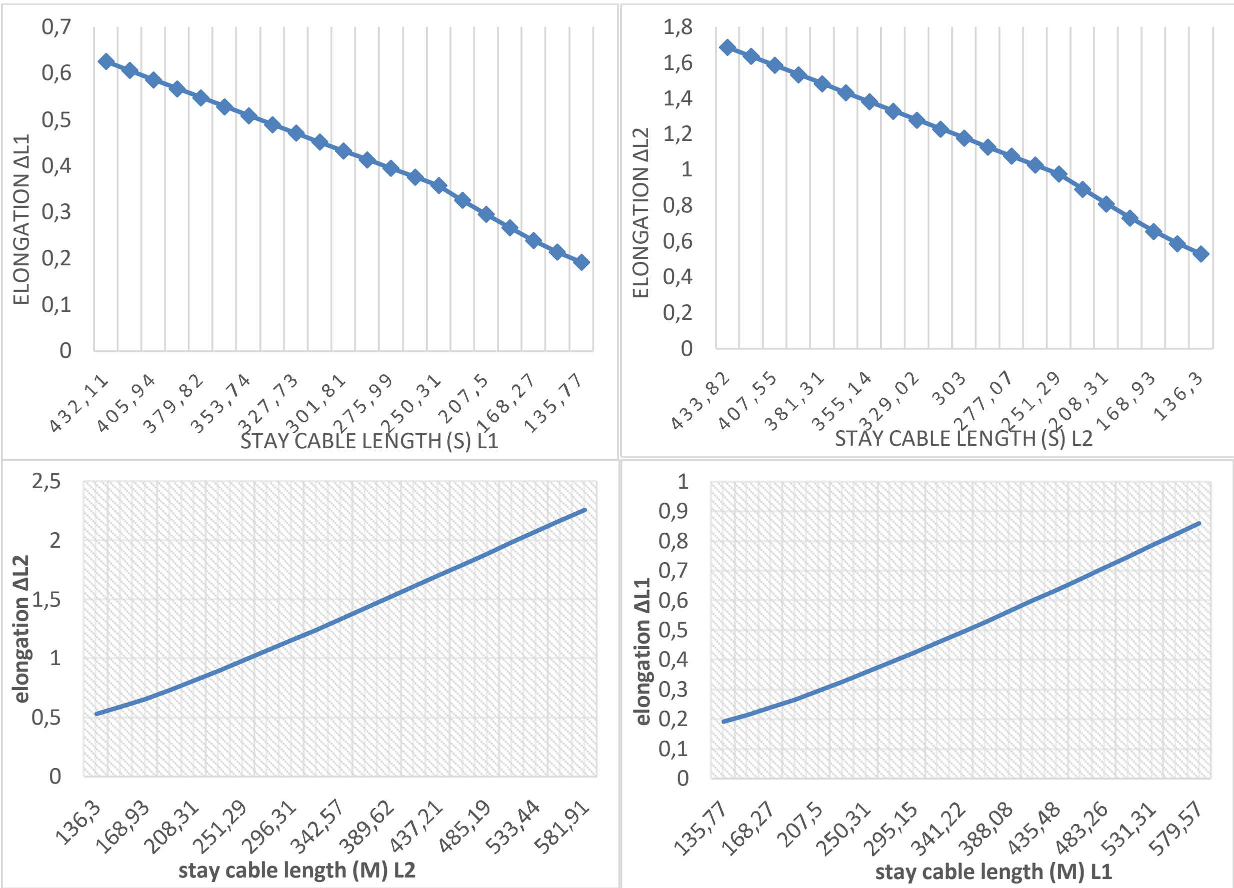


Fig. 7. Shows the lengths of the cables in the Russky Bridge

For an inclined stay cable, the transverse load which results in the sag has an intensity of $w_{cb}\cos\phi$, as indicated in Fig. 8. The deformational characteristics of an inclined cable will be very close to those of a horizontal cable with the same chord length c, but subject to a dead vertical load $w_{cb}\cos\phi$.

Introducing $F_1=A\sigma_1$, $F_2=A\sigma_2$, $w_{cb}=A_{cb}\gamma_{cb}$ leads to [9, 17]:

$$\frac{\delta}{c}=\frac{(\sigma_2-\sigma_1)\gamma_{cb}\cos\phi+\frac{1}{c}\left[\sigma_2^2\sinh\left(\gamma_{cb}\cos\phi\frac{c}{\sigma_2}\right)-\sigma_1^2\sinh\left(\gamma_{cb}\cos\phi\frac{c}{\sigma_1}\right)\right]+4\frac{E}{c}\left[\sigma_1\sinh\left(\gamma_{cb}\cos\phi\frac{c}{2\sigma_1}\right)-\sigma_2\sinh\left(\gamma_{cb}\cos\phi\frac{c}{2\sigma_2}\right)\right]}{2E\gamma_{cb}\cos\phi\cosh\left(\dfrac{\gamma_{cb}\cos\phi\, c}{2\sigma_2}\right)}, \tag{17}$$

where A_{cb} is the cross-sectional area of the stay cable, γ_{cb} the density of the cable material (weight per unit volume), σ_1 is the cable stress in case 1, σ_2 is the cable stress in case 2 and E modulus of elasticity.

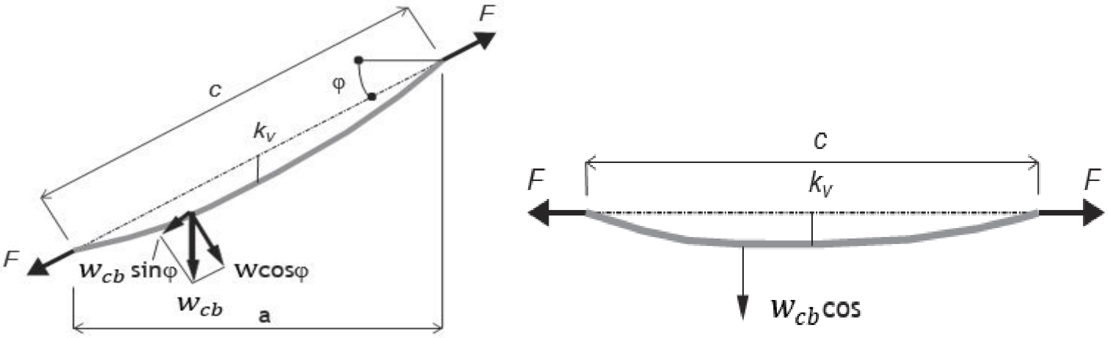


Fig. 8. An inclined stay cable and a parabolic horizontal stay cable with equal deformational characteristics [9, 18]

According to Equation 17, Table 5 expresses the elongation based on the correct configuration and the exact catenary-based solution. But the solution is approximate, depends on the parabola-based solution and will be easier to use.

For large values of σ_2, it is the stress-strain relationship of a straight rod of the same unstressed length as the cable. Given that sag is inversely proportional to cable stress, it is well understood that, for large values of σ_2, the sag effect will ultimately wear off and the cable behaves more and more like a straight rod [19].

The sag $k_c$perpendicular to the chord for an inclined stay cable (Figure 9), is given by [9, 11]:

$$k_c = \frac{g_{cb}c^2\cos\phi}{8T} = \frac{\gamma_{cb}c^2}{8\sigma}\cos\phi. \tag{18}$$

Table 5. Elongation of cables in Russky bridge based on correct configuration

NO	δ	δ/c	NO	δ	δ/c	NO	δ	δ/c
1	0.459437	0.001063	15	0.269006	0.001075	29	0.292123	0.001072
2	0.445689	0.001064	16	0.246285	0.001077	30	0.315519	0.001069
3	0.431965	0.001064	17	0.224129	0.00108	31	0.339105	0.001066
4	0.418264	0.001065	18	0.202784	0.001083	32	0.362813	0.001063
5	0.404585	0.001065	19	0.182601	0.001085	33	0.386627	0.00106
6	0.390928	0.001066	20	0.164064	0.001087	34	0.41044	0.001058
7	0.377297	0.001067	21	0.147881	0.001089	35	0.434288	0.001055
8	0.363685	0.001067	22	0.147881	0.001089	36	0.458197	0.001052
9	0.350095	0.001068	23	0.164064	0.001087	37	0.48203	0.001049
10	0.336523	0.001069	24	0.182601	0.001085	38	0.505732	0.001047
11	0.322974	0.00107	25	0.202784	0.001083	39	0.529529	0.001044
12	0.309445	0.001071	26	0.224129	0.00108	40	0.553187	0.001041
13	0.295939	0.001072	27	0.246285	0.001077	41	0.576865	0.001039
14	0.282458	0.001073	28	0.269006	0.001075	42	0.600374	0.001036

The relative sag k/c appears to be proportional to the cable length c with a proportionality factor: $\gamma_{cb}/8\sigma$ vertical sag k_v:

$$k_v = \frac{k_c}{\cos\phi} = \frac{\gamma_{cb} c^2}{8\sigma}. \quad (19)$$

Note that the vertical sag k_v is unaffected by the stay cable's inclination.

In the dead load state, the factor $\gamma_{cb}/8\sigma$ typically has a value of approximately 25×10^{-6}, resulting in a relative sag k/c of less than 1/100 for cable lengths up to 400 m. As a result, a stay cable's relative sag is less than one-tenth of that of cable stay bridge main cables. This is demonstrated in Table 6 values of sag kc perpendicular to the chord and vertical sag k_v of cables used on the Russky bridge.

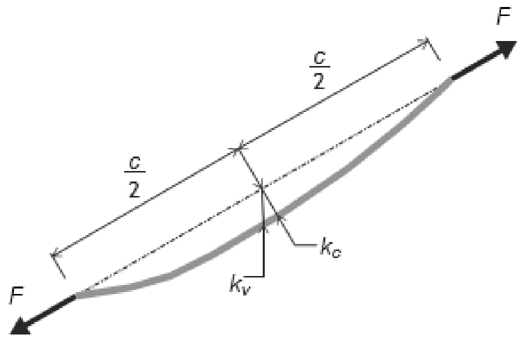


Fig. 9. Sag of stay cable measured perpendicular to the chord (k_c) and perpendicular (k_v) [9, 15]

Table 6. k_c, k_v for cables used in Russky Bridge

NO	k_c	k_v	NO	k_c	k_v	NO	k_c	k_v
1	2.0417	2.4507	15	0.6311	0.8224	29	0.7726	0.9749
2	1.9131	2.3045	16	0.5042	0.6858	30	0.9299	1.1434
3	1.7892	2.1629	17	0.392	0.5651	31	1.1023	1.3278
4	1.6699	2.0258	18	0.2949	0.4604	32	1.2905	1.5282
5	1.5551	1.8934	19	0.2122	0.3716	33	1.4924	1.7445
6	1.4448	1.7656	20	0.1427	0.2988	34	1.7122	1.9768
7	1.3374	1.6424	21	0.0857	0.2419	35	1.9463	2.225
8	1.2346	1.5238	22	0.0857	0.2419	36	2.1939	2.4891
9	1.135	1.4098	23	0.1427	0.2988	37	2.4588	2.7692
10	1.0415	1.3003	24	0.2122	0.3716	38	2.7411	3.0652
11	0.9513	1.1955	25	0.2949	0.4604	39	3.0357	3.3772
12	0.8645	1.0953	26	0.392	0.5651	40	3.3473	3.7051
13	0.7826	0.9997	27	0.5042	0.6858	41	3.673	4.049
14	0.7044	0.9088	28	0.6311	0.8224	42	4.0154	4.4088

Results and Discussion

The danger of slow collapse due to cable loss scenarios in bridges with cable supports has to be thoroughly investigated. There are two main approaches to stopping a slow collapse. First, use structural or nonstructural measures to ensure a higher level of safety against localized collapse. Second, provide a solid structure that permits local failure in order to stop failures from spreading. The weight carried by each parallel force-bearing cable must be transmitted to the remaining structure in the event that it fails. The member who is next to the failing member in this scenario becomes the key member and receives the majority of the transferred load. The collapse will likely affect other components of the structure as well as this one if it is unable to support the weight that has been shifted. As a result, because the crucial component plays such an important role in the structural system's resilience, our study focuses primarily on this member.

The effect of variable sag under different loading conditions indicates that there is no linear relationship between force and deformation, but a linearization may be achieved by adding a secant modulus of elasticity, E_{sec}, defined by:

$$E_{sec}=\frac{\Delta\sigma}{\Delta\varepsilon}=\frac{\sigma_2\text{-}\sigma_1}{\delta}c. \quad (20)$$

Substituting the value of δ/c, the following expression for E_{sec} is derived:

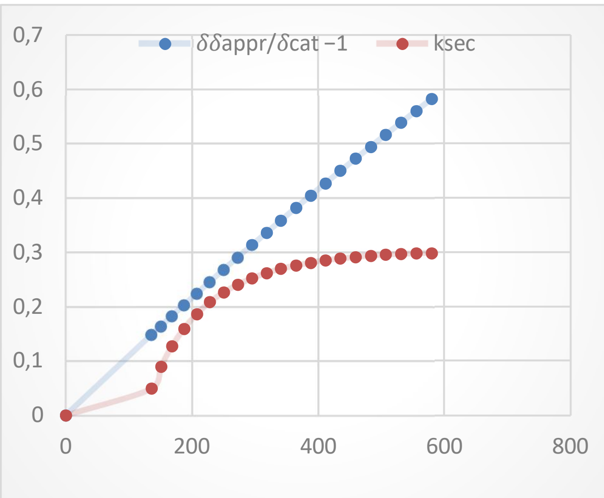
$$\frac{1}{E_{sec}}=\frac{1}{E}+\frac{\gamma_{cb}^2a^2}{24}\left(\frac{\sigma_1+\sigma_2}{\sigma_1^2\sigma_2^2}\right). \quad (21)$$

The secant modulus might be substituted by a tangent modulus Etan obtained from (21) with $\sigma_2=\sigma_1$ for cable-stayed bridges with low traffic-to-dead load ratios:

$$\frac{1}{E_{tan}}=\frac{1}{E}+\frac{\gamma_{cb}^2a^2}{12\sigma_1^3}. \quad (22)$$

The secant modulus appears to give a very good approximation as the error remains less than 1% for cable lengths up to 300 m and less than 2% for cable lengths up to 750 m.

And because the smallest cable in the Russky bridge is 135.77 meters long and the longest cable is 579.57 meters, as a result, the error rate of cables in the Russky bridge will remain for some cables less than 1% and for some cables less than 2%. Considering that the cable steel material's modulus of elasticity is rarely known with greater than 2-3% precision, the secant modulus approach would be appropriate in all realistic cases. Since just the cable stress in the starting condition has to be known, the tangent modulus is frequently simpler to use than the secant modulus. However, as Figure 10, 11 illustrates, the tangent modulus may yield inaccurate results for high cable lengths and significant traffic-to-dead load ratios.



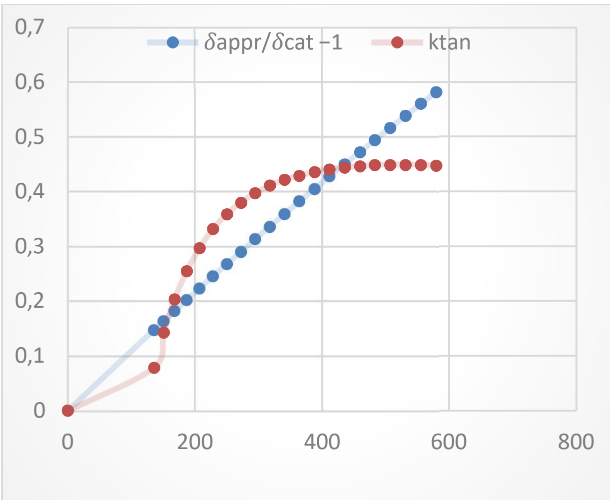


Fig. 10. Indicated the effect of using an equivalent modulus of elasticity based on the parabolic approximation rather than the correct catenary solution for cables. Looking at the results in Table (7), the maximum stress ratio for cables is 0.75, and accordingly, the stress ratio for cables K will be considered 0.8 and 0.5, respectively. The error is defined as $\delta_{appr}/\delta_{cat}$, where $\delta_{appr}=(\sigma_2-\sigma_1)c/E_{eq}$ for a horizontal cable with varying length

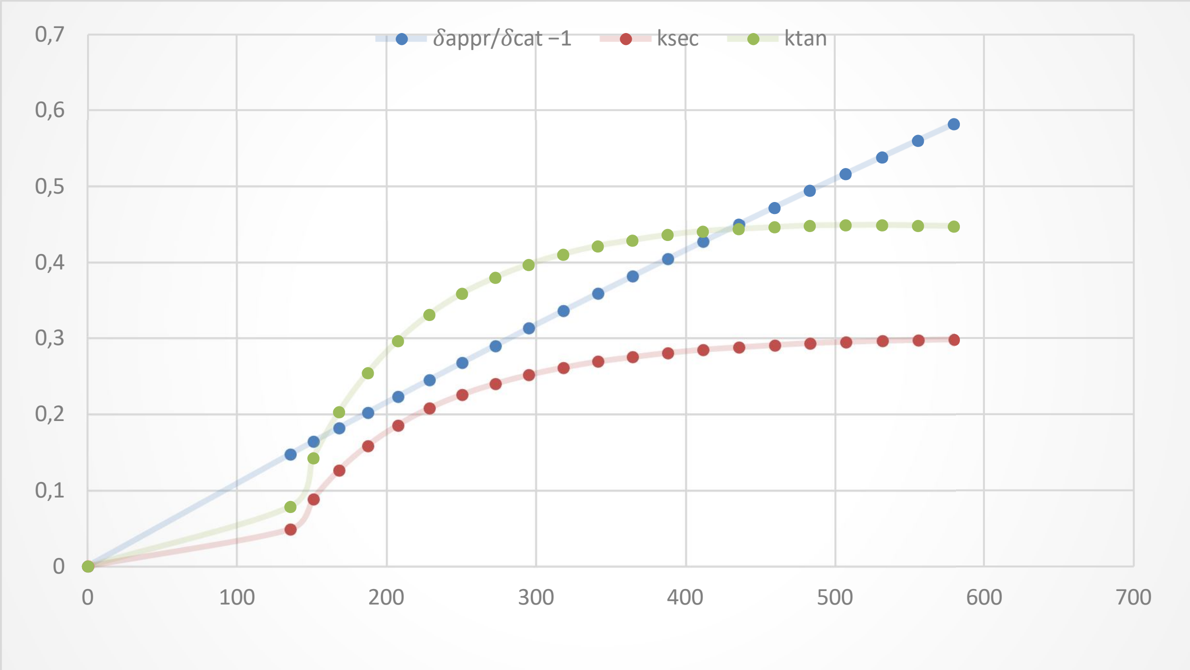


Fig. 11. $(\delta_{appr}/\delta_{cat} - 1)$ shows an error by applying the tangent modulus or secant modulus of the stay cables in the Russky bridge with the following Parameters: $E = 205\text{GN/m}^2$, $\gamma_{cb} = 0.08\text{MN/m}^3$ (including corrosion protection), $\sigma_2 = 720\text{MN/m}^2, \kappa = 0.5$ and 0.8, respectively

The structural details for every system are displayed in Table 7. The findings further demonstrate that the accuracy of the final approximation function is little affected when the impact of cable stiffness (S) on the d parameter is disregarded. The rounding error is smaller than 5%, with the exception of tiny values of β. All systems' computed R-square values are higher than 0.970, which is acceptable. The matching system of linear equations must be solved in order to determine the precise values for systems with 12 and 16 wires. As a result, the analytical method was looked at once again.

Table 7. The structural details for every system are displayed

Stiffness of the Cables	12 cable system (a)	12 cable system (b)	16 cable system (a)	16 cable system (a)
S_1	S	$3S$	S	$4.5S$
S_2	$1.4S$	$2.6S$	$1.5S$	$4S$
S_3	$1.8S$	$2.2S$	$2S$	$3.5S$
S_4	$2.2S$	$1.8S$	$2.5S$	$3S$
S_5	$2.6S$	$1.4S$	$3S$	$2.5S$
S_6	$3S$	S	$3.5S$	$2S$
S_7			$4S$	$1.5S$
S_8			$4.5S$	S

Conclusions

The space between two neighboring cables in modern bridges is significantly less than in older bridges. As a result, in the case of a vehicle accident or an explosion on a new bridge, several cables are going to fail. As a result, it was suggested that bridge designers consider the bursting of all cables inside 10 meters. Several investigations have been done to find DAF in bridges. According to this research, having a DAF of two is not always safe. Although a recent study shows that the suggested DAF is secure for cable design, which is it is not safe for pylon or girder designs with negative moments.

DAF = 2.0 is a popular DAF measurement for buildings and bridge structures that is accepted by current standards and guidelines (PTI, 2007); however, the consistency of DAF = 2.0 has been questioned for bridges that are cable-stayed with considerable degrees of redundancy. When used with a comparable static evaluation, the comparable static evaluation with DAF = 2.0 is occasionally conservative in measuring bending moments inside an edifice following the absence of a single stay. As a result, it is strongly advised to conduct a comprehensive dynamic study to estimate the increasing collapse of bridges due to cable loss. Static linear evaluation using DAF is a frequent method in actual projects for solving the challenges listed above. Precise calculation of DAF is critical when utilizing linear static analysis. abrupt wire loss A sudden loss of cable can cause a gradual "zipper-type" collapse, making it one of the most severe loading scenarios for a bridge with cable stays. Some of the subsequent conclusions may be derived. * The bridge's location has a significant impact on how it responds dynamically to an unexpected cable loss. Especially for multi-DOF constructions like cable-stayed bridges, dynamically amplifying factors (DAFs) can be more than two when fast forces are applied. Because of this, the DAF=2 building plan for this kind of bridge is not always cautious, and there's a chance that important sections will have lower load factors.

* Each section and reaction component (such as internal forces, deflection, etc.) requires a different DAF, and each DAF must accurately represent the impact of the technique and structure type.

* The stay arrangement, loading groups, deck stiffness, and damping ratio have an effect on DAFs in cable-stayed bridges.

* It is considered and highly suggested to do a fluid assessment of big structures that are prone to unexpected component failure, given the diversity of mathematical tools available for analyzing structures. This is because an easier comparable static evaluation strategy employing DAF = 2 can be unusual.

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