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Investigation of Cable Tension in Cable-Stayed Bridges Through Field Measurements and Numerical Simulation

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Abstract: This study investigates cable tension forces in a one-plane cable-stayed bridge in Vietnam using field measurements and numerical simulation. Cable forces obtained from the Finite element method (FEM) are compared with design values and field-measured data from lift-off and vibration-based method. Results show that field-measured forces generally deviate within 7% of the design values, confirming their reliability. Both measurement methods effectively capture cable force variations, with low tension in long cables and high tension in shorter ones. Numerical simulations accurately represent cable rigidity, with frequency discrepancies remaining below 3%. However, larger errors of 12% to 15% occur in shorter cables near the tower, while longer cables closely align with design values within 3%. Despite these differences, simulation-based preliminary analysis is acceptable for minimizing field measurements and serves as a valuable reference for structural assessments in service stage.

Keywords: cable, tension force, vibration-based method, lift-off test, FEM.

1. Introduction

Cables play a vital role in bridge engineering, serving as essential structural elements in both long-span cable-stayed and suspension bridges. Cable structures often have costly anchorage systems, as well as nonlinearity and complex geometry. Therefore, it is difficult to accurately predict their performance and align cable tension with theoretical design forces during construction. Over time, cable forces may vary due to temperature changes, dynamic loads, and steel relaxation. Thus, accurate cable tension measurements during both construction and maintenance stages are crucial for maintaining structural stability and safety.

There are various measurement methods for determining the tension in a cable-stayed bridge, including both direct and indirect approaches [1].

Direct methods involve using dynamometers or fiber optic sensors attached to the cables. Another option is employing hydraulic jacks, load cells, and displacement meters to measure cable force through lift-off testing. The lift-off method is a common technique for measuring cable tension; however, it can be particularly expensive for larger cables due to the high cost of specialized equipment. Meanwhile, the vibration-based method is a widely used indirect approach for estimating cable forces in practice [2-5]. In this method, the relationship between cable tension and frequency is established using empirical formulas or analytical expressions [6-8]. In 2020, the reliability of cable tension measurements obtained using the lift-off and vibration-based method was confirmed by comparing them with design values on a cable-stayed bridge [5]. The precision of cable tension estimation is further improved by considering factors such as the sag effect, flexural stiffness, and boundary conditions at the cable ends [9-15]. Although these methods provide reliable cable force measurements, they require physically attaching devices to the cable, which involves complex installation and calibration. Consequently, applying these techniques to all stay cables in a structure is both costly and time-consuming. Therefore, developing alternative non-contact methods for accurately determining cable forces is crucial.

In literature, finite element method (FEM) is a common approach to simulate the cable structure. This method represents the cable as a discretized system to analyze its mechanical behavior under various loading conditions [16]. In the numerical simulation of cable structures, cable elements can be modeled by modifying physical properties such as the elasticity modulus to account for the cable sag effect. In some studies, the nonlinearity of the cable structures is considered by using the truss element model [17, 18], while other researches incorporate interpolation functions to account for sag effects and the cable's shape [19-21]. Besides, the analytical expression of the cable shape was developed via the catenary system [22-24]. It can be observed that the finite element approach enables a more detailed assessment of cable responses and allows for precise tension force prediction. Most of the aforementioned studies have validated FEM simulations using only a single measurement method. Therefore, a comprehensive study comparing numerical simulations with other approaches, i.e., the lift-off method, vibration-based methods, and design values, is essential for a more thorough evaluation of cable tension measurement techniques.

This study investigates the cable tension force in a one-plane cable-stayed bridge in Vietnam using the lift-off method, an indirect vibration-based field test, and FEM simulation. The FEM simulation of cable tension follows the procedure of the vibration-based method used in the field test. The simulated tension forces for all cables are validated by comparing them with the design and the measured values obtained from the lift-off test and the indirect vibration-based method. The numerical simulation results serve as a reliable database for assessing cable forces during the service stage.

2. Materials and methodology

2.1. Field test

2.1.1. Target bridge

The target structure of the current work is Nguyen Tat Thanh bridge, a cable-stayed bridge located in Vinh Phuc province. It features a steel box girder with a height of 2.3 m and a bridge deck thickness of 250 mm. At the center of the girder, within the 3 m-wide median strip, an additional 200 mm concrete layer is applied, increasing the total cross-sectional height to 2.5 m. The bridge has a total width of 22.5 m in standard sections, expanding to 26.9 m in widened sections to accommodate landscape arrangements. The pylon comprises a steel bridge tower section and a lower reinforced concrete (RC) pier section. It supports the bridge girder through 18 stay cables arranged in a fan-shaped configuration, with a 7 m spacing between them, as shown in Fig. 1.

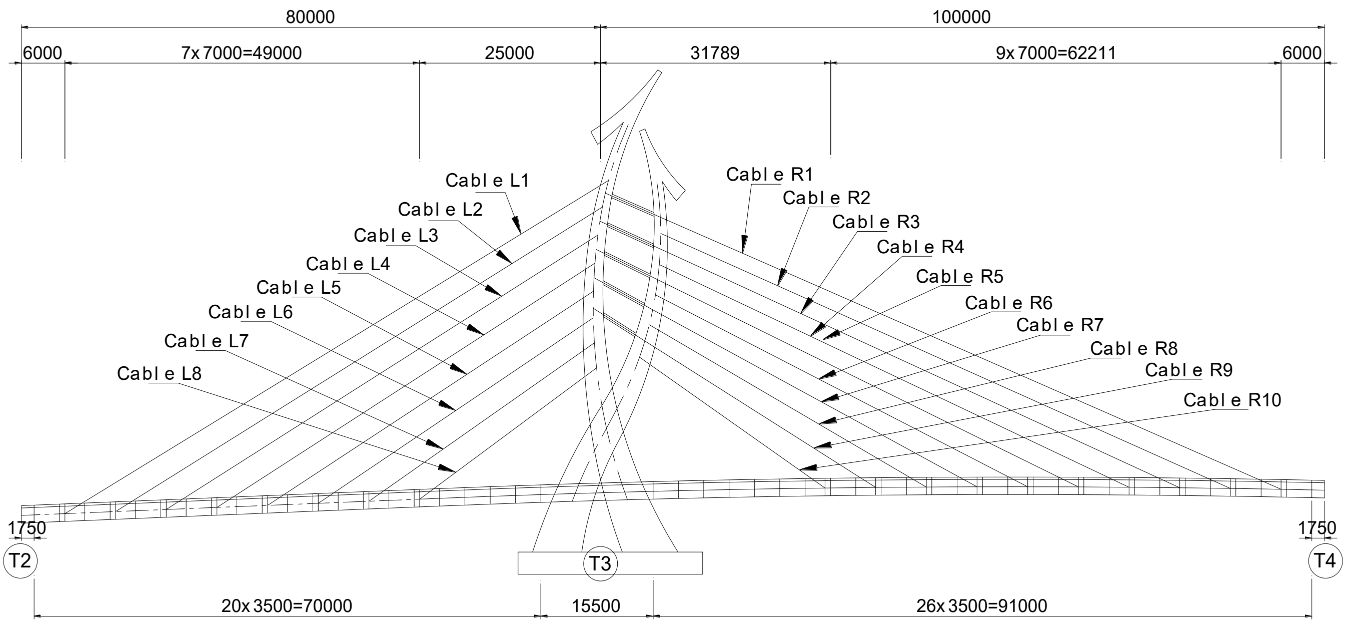


Fig. 1. The cable arrangements in Nguyen Tat Thanh bridge

Each stay cable consists of 15.7 mm diameter strands with a tensile strength of 1,860 MPa, anchored to both the girder and the tower. The cables have an elastic modulus of 195,000 MPa. The system consists of 8 cables on the left (side span) and 10 cables on the right (main span), with lengths from 30 m to 126 m, inclination angles between 23° and 45°, and varying cross-sectional areas. These structural features make Nguyen Tat Thanh bridge a representative case study for investigating cable tension forces in cable-stayed bridges.

2.1.2. Measurement of cable tension

The bridge structure was analyzed to evaluate the tension forces in the stay cables after the construction process was completed. This assessment was carried out using two standard measurement techniques, i.e., the lift-off and vibration-based methods. The lift-off test directly measures the tension by temporarily detensioning the stay cables, while the vibration-based method estimates the tension based on the cable's natural frequency. These methods provide an accurate evaluation of the stay cables of the completed bridge.

The lift-off test is a mechanical method used to assess cable tension forces in individual wires or strands. It employs a small-scale load cell, a hydraulic jack, and a displacement meter (Fig. 2). This test verifies tendon or cable forces after stressing and can be performed before cutting off the stressing tails of the tendons. The displacement meter has a tolerance of ±7%. The equipment and measurement procedure for the lift-off test and vibration-based method were presented in a previous study by the author [5].

Meanwhile, the vibration-based method determines cable tension by establishing the relationship between cable force and natural frequency while accounting for the sag effect and flexural rigidity. This approach is based on modal properties theory, which correlates natural frequencies with mode shapes [25]. Shimada and Nishimura [26] further developed this method by incorporating theoretical and experimental analyses, which serve as the basis for the present study. This study ultilizes a small-sized, oil damping type acceleration transducer (model AS-10GB of Kyowa) for measuring cable acceleration. It has a measurement range of ±10 G and a frequency range up to 220 Hz, with a sensitivity deviation of ±5%. The installation of the vibration equipment on the cables is presented in Fig. 3. The tension was assumed to be uniformly distributed on the anchorage base, perpendicular to the anchorage surface along the cable direction. To ensure data consistency, actual tension values were measured and used as input for computational models. The field test was performed in the morning during winter with temperatures ranging from 18^0C to 20^0C.

The simple equation used to calculate cable tension is derived from taut string theory [27], which assumes that the cable behaves as an ideal tensioned string without considering sag or bending stiffness:

Fig. 2. The equipment of lift-off test in Nguyen Tat Thanh bridge

Fig. 3. Set up the equipment for measuring the cable tension in Nguyen Tat Thanh bridge

$$T = \frac{4W(fL)^2}{g} \quad (1)$$

When considering the sag of cable , the cable tension can be calculated as [28]:

In case of $3 \le \xi \langle 17$

$$T = \frac{4W(fL)^2}{g}\left[0.875 - 10.89\left(\frac{C}{f}\right)^2\right] \quad (2)$$

In case of $17 \le \xi$

$$T = \frac{4W(fL)^2}{g}\left[1 - 2.2\left(\frac{C}{f}\right) - 2\left(\frac{C}{f}\right)^2\right] \quad (3)$$

Where $\xi = \sqrt{\frac{T}{EI}}L$ and $C = \sqrt{\frac{EIg}{WL^4}}$

where: T is the tension force in cable (kG);

f is the fundamental natural frequency of cable (Hz);

W is the weight of cable per meter (kG/m);

L is the length of cable (cm);

g is the gravitational acceleration (981 cm/s^2);

E is the elastic modulus of cable (kG/cm^2);

I is the inertia bending moment of cable (cm^4).

2.2. Cable tension calculation using Finite Element Method

In the present work, the procedure of the cable tension in finite element model follows the vibration-based method in the field test. The stay cable was modeled by three dimensional element Beam188 in ANSYS software. Assume that the cable has a total length of L meters. It was discretized into 100 equal segments to ensure simulation accuracy, with each segment measuring L/100 meters. The cable's endpoints were defined by coordinates (x_1,y_1,z_1) and (x_2,y_2,z_2), and the nodal coordinates along the cable were computed accordingly (Fig. 4). The boundary conditions at two end points of the cable are assumed as hinged supports. Due to its self-weight and pre-tension forces, the cable exhibited an initial sag. The sag value is automatically calculated in the software during the simulation process based on the input parameters.

The vibration of the stay cables was simulated using ANSYS software. The equation of motion, taking into account the effect of bending stiffness [29], is given by:

$$EI\frac{\partial_y^4}{\partial x^4} - H\frac{\partial_y^2}{\partial x^2} + \rho A\frac{\partial_y^2}{\partial t^2} = 0 \quad (4)$$

Where E is Young Modulus (MPa); I is the inertia moment of the cable (m^4); H is the cable tension force (N); ρ is the weight density (kg/m^3); A is the cross-section area of the cable; and *t* is the simulation time. Equation (4) describes the transverse vibration of a stay cable with bending stiffness, or equivalently, a classical beam subjected to axial tension. In this context, *y* denotes the transverse displacement function of the cable. The equation does not account for the inherent damping resistance component of the cable, as its value is theoretically considered negligible.

The cable in the target bridge has a Young's modulus of 195 GPa. The cross-sectional area of each strand is 150 mm², with the total strand count ranging from 27 to 37. Due to the difficulty in accurately determining the flexural rigidity of the cable, an equivalent modeling approach is employed in this study. This method preserves the cable's cross-sectional area while appropriately adjusting its flexural moment of inertia. The Beam188 element is modeled with a rectangular cross-section, with an area equivalent to that of the cable. The side length of the equivalent rectangle is determined as the square root of the cross-sectional area. As the bending moment of inertia of the cable strand is small and often neglected, the cable can be considered to have a width of 0.1 $\sqrt{A}$ and length of 10 $\sqrt{A}$. The initial tension force of each cable in the FEM simulation is from the calculated designed value in Table 1. The self-weight of the cable is specified using gravitational acceleration g=9.81 (m/s^2). The cable weight density ρ is determined from the mass per unit length ρ_L=1.3 (kg/m) and the crosss section area A:

$$\rho = \frac{\rho_L}{A} \quad (5)$$

Then, the angular frequency of the cable [29] can be calculated by:

$$\omega_n = \left(\frac{n\pi}{L}\right)^2 \sqrt{\frac{EI}{\rho_L}} \sqrt{1 + \frac{HL^2}{n^2\pi^2 EI}} \quad (6)$$

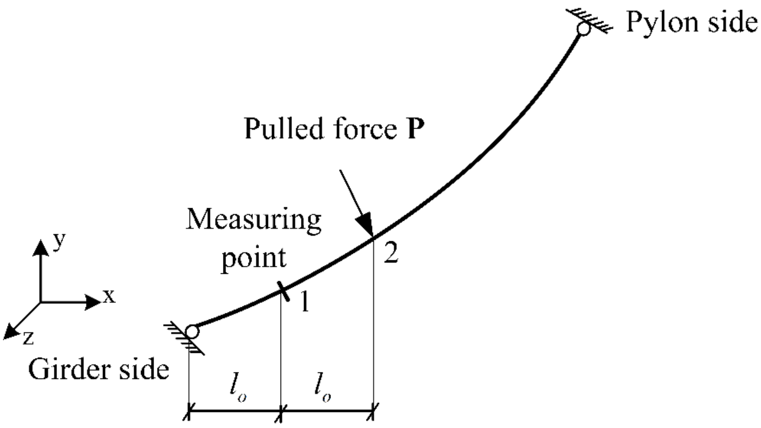


Fig. 4. Finite element model of the stay cable in ANSYS

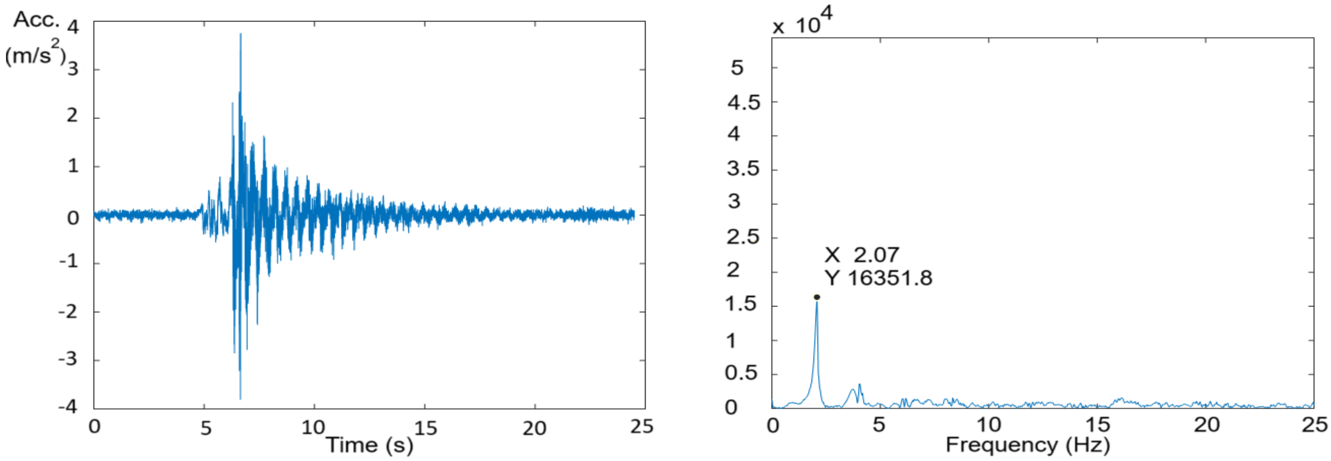
In the simulation, a pulling force of 500 N, equivalent to the force exerted by a human, is applied to the cable. The applied force is considered an impulsive force that varies over time. The force application point is selected based on its location in the vibration-based method (Fig.

4). Typically, in practice, this position is located at about 0.3 to 0.5 of the cable length from one end, and at a distance of approximately 2 to 3 meters from the vibration sensor. The impulse force stops after 4 seconds, after which the stay cable undergoes free vibration. The total analysis duration is 60 seconds, with a time step of 0.01 seconds. The structural damping of the stay cable is characterized by amplitude attenuation over time, with a default value of 0.5% in ANSYS software. In this study, the transient dynamic analysis in ANSYS software is performed to solve the equation of motion for the cable.

3. Results and discussions

3.1. Field test's results

In this study, the measurements were conducted using the vibration-based method, incorporating frequency analysis and Fast Fourier Transformation (FFT) to accurately determine the cable tension based on its dynamic characteristic (Fig. 5).



(a) Acceleration response (b) Frequency spectrum

Fig. 5. The cable tension of cable R10 measured by vibration-based method

Table 1. Comparison of the design cable force and measured cable tension using the lift-off test and vibration-based method

Cable No.	Length (mm)	Number of strands	Area (mm^2)	Inclination angle (degree)	Cable force (kN)			Difference between (II) and (I) (%)	Difference between (III) and (I) (%)
					Design value (I)	Lift-off method (II)	Vibration-based method (III)		
L1	87,621	75	11,250	31	6,975	6,765	6,714	3.10%	3.53%
L2	78,901	75	11,250	31.5	6,855	6,578	6,503	4.22%	3.71%
L3	70,271	75	11,250	32	6,623	6,368	6,273	4.00%	4.16%
L4	61,834	70	10,500	32.4	5,495	5,411	5,230	1.55%	5.67%
L5	53,566	70	10,500	32.8	5,642	5,663	4,999	0.37%	2.18%
L6	45,569	70	10,500	33.5	5,201	5,215	4,544	0.27%	1.79%
L7	37,826	70	10,500	34.6	5,264	5,600	4,868	6.00%	1.29%
L8	30,231	70	10,500	36	5,936	6,307	5,563	5.88%	1.16%
R1	126,576	45	6,750	23.3	2,232	2,354	2,273	5.16%	4.36%
R2	101,608	45	6,750	23.7	3,560	3,798	3,707	6.28%	2.32%
R3	85,957	50	7,500	24.3	4,185	3,945	3,922	6.08%	3.62%
R4	87,863	60	9,000	24.9	4,464	4,350	4,287	2.62%	1.69%
R5	71,569	65	9,750	25.8	4,973	5,057	4,458	1.67%	3.36%
R6	73,974	70	10,500	26.8	5,292	5,551	4,962	4.67%	3.78%
R7	57,623	70	10,500	28.2	5,138	5,187	4,778	0.94%	6.28%
R8	44,148	75	11,250	29.9	5,453	5,798	4,799	5.95%	1.60%
R9	45,953	75	11,250	31.9	5,340	5,580	4,952	4.30%	0.28%
R10	31,160	75	11,250	34.7	5,565	5,228	4,997	6.46%	0.85%

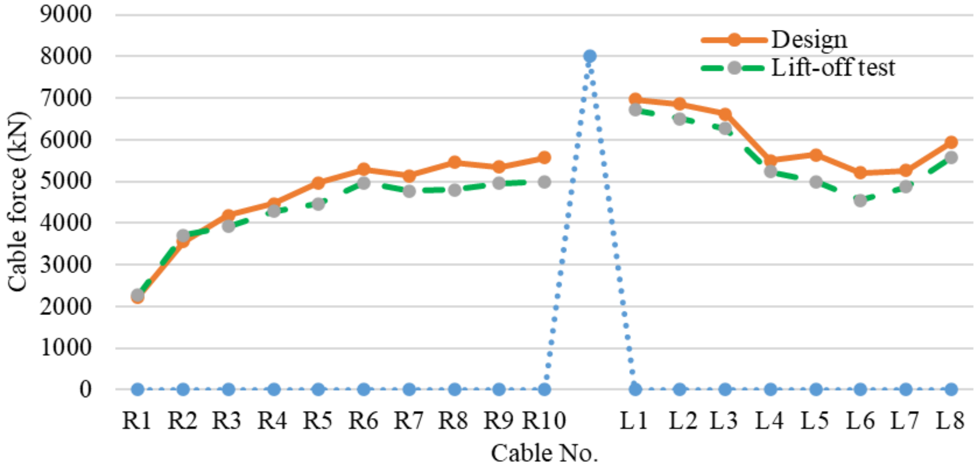


Fig. 6. Comparison of the design cable force and measured cable tension using the lift-off test

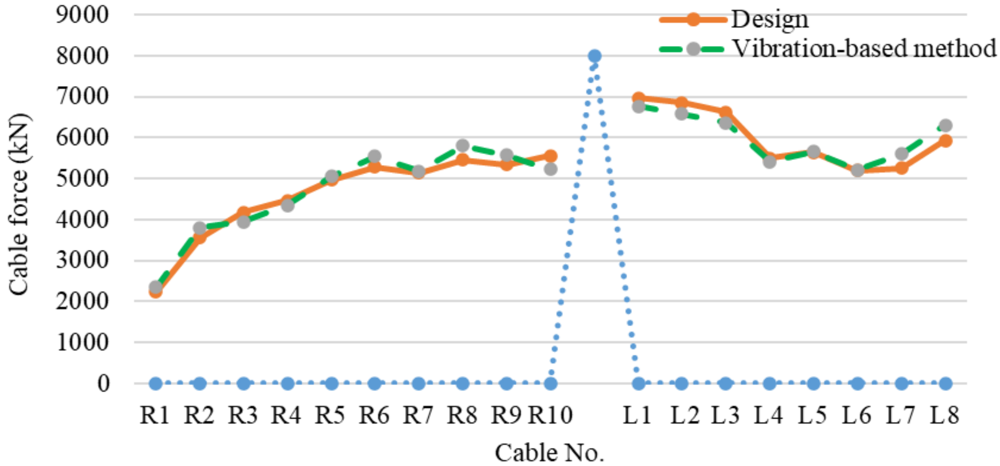


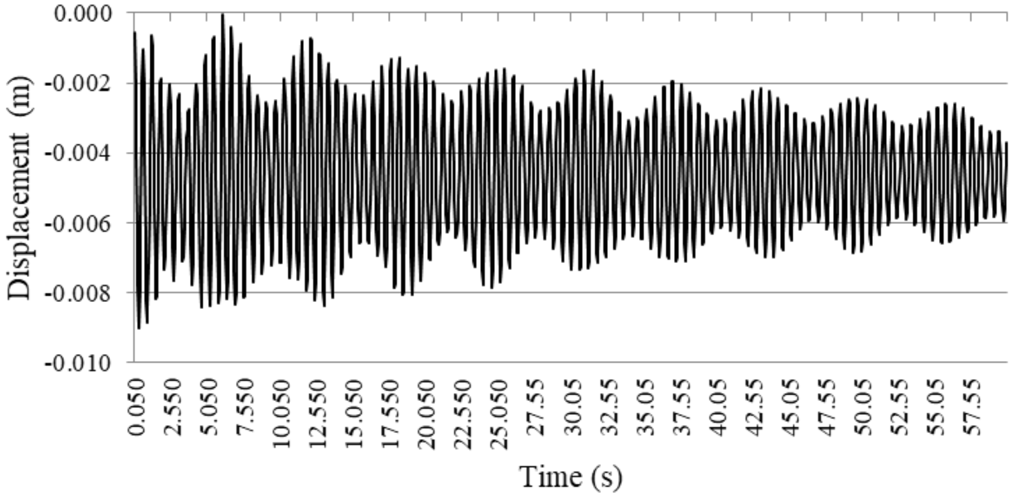
Fig. 7. Comparison of the design cable force and estimated cable tension using the vibration-based method

Table 1 compares the cable tension forces measured in field tests with the design values. The design tension force is calculated according to the guidelines of the French Interministerial Commissions [30]. Additionally, the table presents details of each cable in the Nguyen Tat Thanh Bridge, including length, inclination angle, number of strands, and cross-sectional area. The results show that the differences are relatively small. Specifically, the deviation between the lift-off method and the design values ranges from 1% to 6%, while the difference between the vibration-based method and the design values changes within 0.3% to 6%. Overall, the discrepancy between the measured and design data is generally within 7%, which is considered acceptable. This finding confirms the reliability and accuracy of both the measurement and design data.

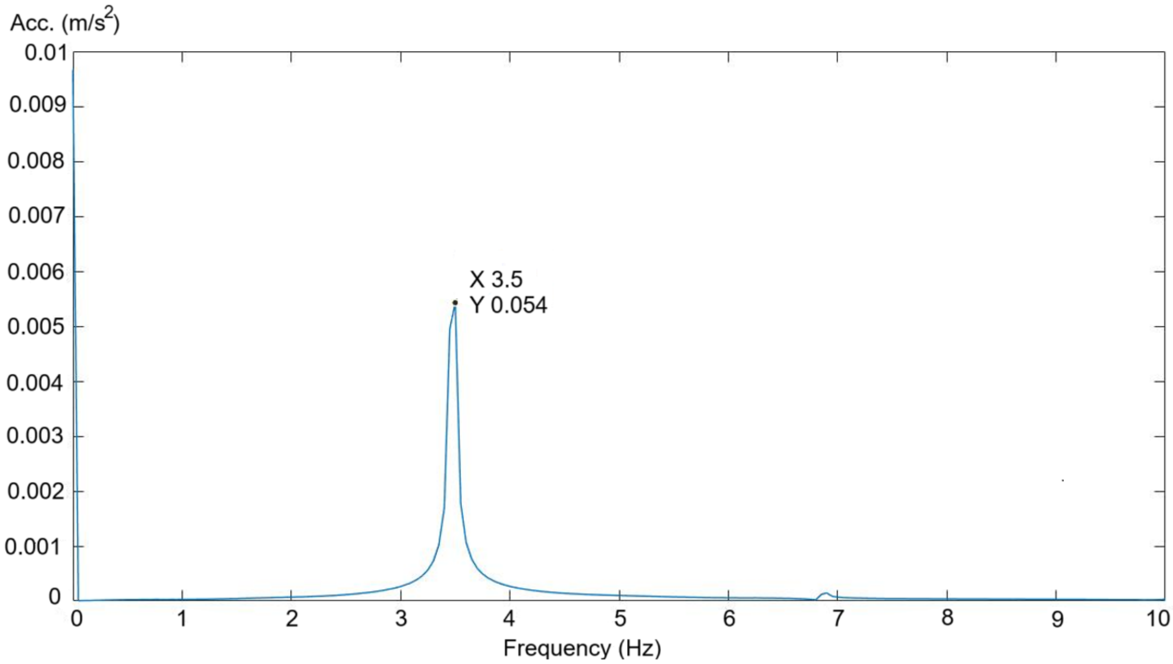
Figs. 6 and 7 compare the cable tension force obtained from the lift-off test and the vibration-based method with the design value. Although the methods for determining cable tension are different, both can capture the variations in cable tension across all cables. Similar to the design value, the cable force is lower in long cables and higher in short ones. It can be seen that both field tests provide reliable data on cable tension force. This dataset from field tests serves as a basis for assessing cable tension determined through numerical simulation in the following section.

3.2. Simulation results

The analysis results provide the time history of displacement at the measurement point on the stay cable R10 (Fig. 8a). Using the FFT, the natural frequency of the cable is determined, as shown in Fig. 8b. Based on the calculated natural frequency of the cable, the tension force is calculated using Equations (2) and (3).



(a) Time history of simulated displacement of stay cable R10



(b) FFT analysis of the simulated displacement of stay cable R10

Fig. 8. Time history and FFT analysis of the simulated displacement of stay cable R10

To verify the FEM simulation, the natural frequencies of the structure, calculated based on the design cable force values, are compared with the results from the simulation analysis. The results indicate that the discrepancies in natural frequencies for most cables are below 2%. However, certain cables, such as L4 and R7, show a larger deviation of approximately 3% (Table 2).

Fig. 9 presents a comparison between the frequencies obtained from the FEM simulation and those derived from theoretical calculations. The results indicate that the numerical simulation effectively captures the exact rigidity of each cable, demonstrating its accuracy in modeling the structural behavior and dynamic characteristics of the cable system.

The cable tension forces evaluated at the design stage, in the lift-off test, using the vibration-based method, and in the FEM simulation are compared in Table 3.

Table 2. Comparison of natural frequency calculated from the design value and FEM

Cable No.	Length (mm)	Number of strands	Area (mm²)	Inclination angle (degree)	Frequency from theory (Hz)	Frequency from FEM (Hz)	Discrepancy (%)
L1	87,621	75	11,250	31	1.53	1.50	1.71%
L2	78,901	75	11,250	31.5	1.68	1.65	1.81%
L3	70,271	75	11,250	32	1.86	1.82	2.03%
L4	61,834	70	10,500	32.4	1.99	1.93	2.73%
L5	53,566	70	10,500	32.8	2.32	2.35	-1.12%
L6	45,569	70	10,500	33.5	2.62	2.60	0.89%
L7	37,826	70	10,500	34.6	3.18	3.20	-0.66%
L8	30,231	70	10,500	36	4.22	4.20	0.56%
R1	126,576	45	6,750	23.3	0.77	0.79	-2.28%
R2	101,608	45	6,750	23.7	1.21	1.20	0.53%
R3	85,957	50	7,500	24.3	1.48	1.45	1.75%
R4	87,863	60	9,000	24.9	1.36	1.35	0.86%
R5	71,569	65	9,750	25.8	1.69	1.67	1.62%
R6	73,974	70	10,500	26.8	1.63	1.60	1.82%
R7	57,623	70	10,500	28.2	2.06	2.00	2.99%
R8	44,148	75	11,250	29.9	2.68	2.70	-0.80%
R9	45,953	75	11,250	31.9	2.55	2.55	-0.15%
R10	31,160	75	11,250	34.7	3.83	3.85	-0.42%

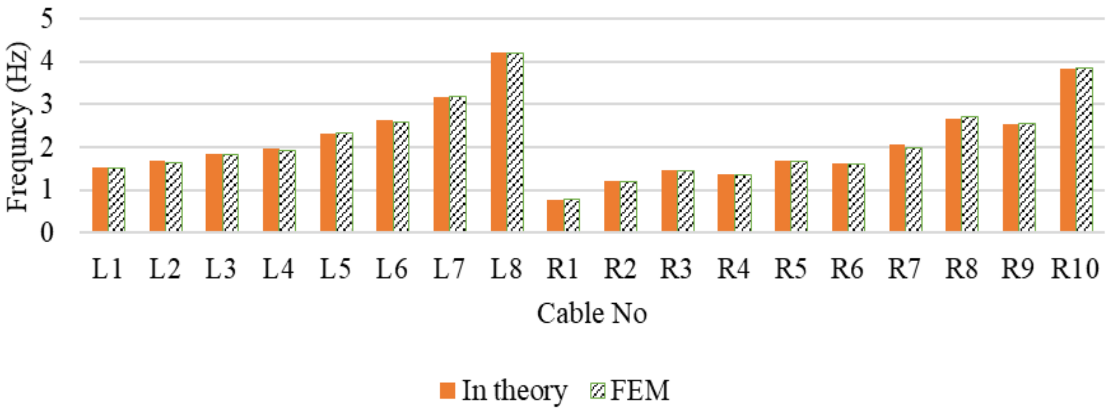


Fig. 9. Comparison of calculated natural frequency in theory and FEM simulation

The results show that the error in tensile force values determined by the numerical simulation method, compared to the design values, ranges from approximately 2% to 8% for most cables. However, for cables L5, L6, R5, R8, and R10, the error falls within the range of 11% to 15%. The discrepancy in cable force between the lift-off test and FEM simulation is below 5% for most cables, while some cables exhibit higher errors. Specifically, the error for cables L5 to L8, R5, R6, and R9 ranges from approximately 11% to 15%, with the highest value reaching 20.81% in cable R8. Meanwhile, the difference in cable tension force between the numerical simulation and the vibration-based method is approximately 2% to 3% for most cables. However, this value increases to 8% to 10% for cables R5, R9, and L7, and further rises to 12–15% for cables L5, L6, R8, and R10.

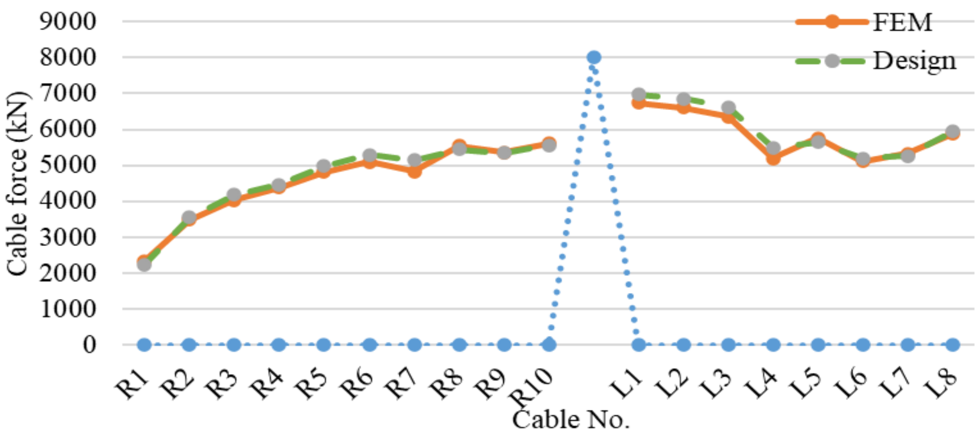
Fig. 10 plots the cable tension values from the FEM simulation, design, lift-off test, and vibration-based method. A similar trend is observed when comparing the tension differences between the numerical simulation and the design, as well as those measured using the vibration method.

Significant discrepancies occur in the second to fourth cables from the tower and in cables positioned close to the tower. In contrast, longer cables located farther from the side span closely match the design values, with deviations of only about 3%. Meanwhile, cables near the tower, which are shorter and stiffer, exhibit larger discrepancies, around 12% to 15%. This suggests that cable stiffness has a considerable impact on the dynamic analysis results. The short cables in the side span near the tower tend to have relatively high errors.

The analysis results suggest that, when compared to the design tension values, the FEM simulation exhibits larger errors for shorter cables located near the tower than for longer cables positioned farther from the tower. This discrepancy becomes even more significant for cables situated in the main span, highlighting the influence of cable length and stiffness on the accuracy of numerical simulation.

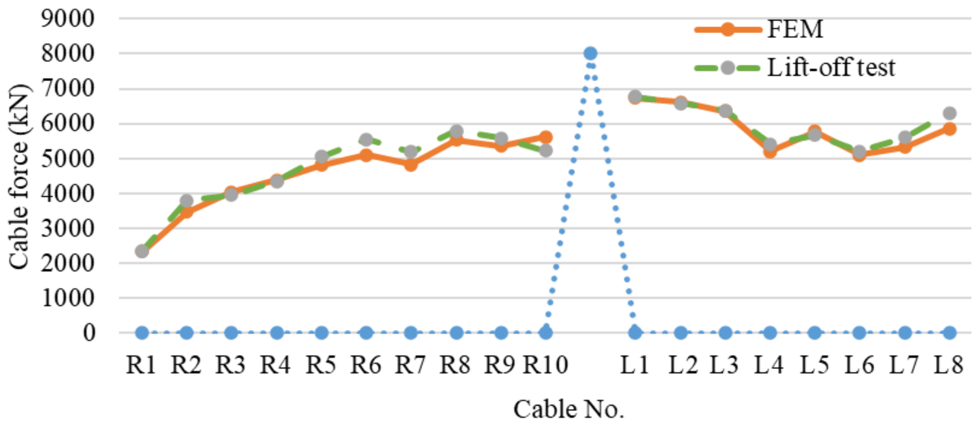
Table 3. Cable tension force by lift-off and vibration-based method

Cable No.	Length (mm)	Cable force (kN)				Discrepancy between (IV) and (I) (%)	Discrepancy between (IV) and (II) (%)	Discrepancy between (IV) and (III) (%)
		Design (I)	Lift-off (II)	Vibration-based (III)	FEM (IV)			
L1	87,621	6,975	6,765	6,714	6,737	3.89%	0.76%	0.34%
L2	78,901	6,855	6,578	6,503	6,610	5.41%	1.15%	1.64%
L3	70,271	6,623	6,368	6,273	6,358	5.57%	1.51%	1.36%
L4	61,834	5,495	5,411	5,230	5,200	5.07%	3.46%	0.57%
L5	53,566	5,642	5,663	4,999	5,768	12.86%	13.28%	15.38%
L6	45,569	5,201	5,215	4,544	5,110	14.46%	14.77%	12.45%
L7	37,826	5,264	5,600	4,868	5,333	8.13%	15.04%	9.55%
L8	30,231	5,936	6,307	5,563	5,868	6.71%	13.37%	5.48%
R1	126,576	2,232	2,354	2,273	2,334	1.80%	3.54%	2.68%
R2	101,608	3,560	3,798	3,707	3,479	3.98%	2.45%	6.16%
R3	85,957	4,185	3,945	3,922	4,039	6.71%	0.59%	2.98%
R4	87,863	4,464	4,350	4,287	4,390	4.13%	1.47%	2.40%
R5	71,569	4,973	5,057	4,458	4,811	11.54%	13.44%	7.92%
R6	73,974	5,292	5,551	4,962	5,099	6.65%	11.87%	2.76%
R7	57,623	5,138	5,187	4,778	4,834	7.53%	8.56%	1.18%
R8	44,148	5,453	5,798	4,799	5,541	13.62%	20.81%	15.47%
R9	45,953	5,340	5,580	4,952	5,355	7.84%	12.68%	8.14%
R10	31,160	5,565	5,228	4,997	5,613	11.37%	4.61%	12.32%

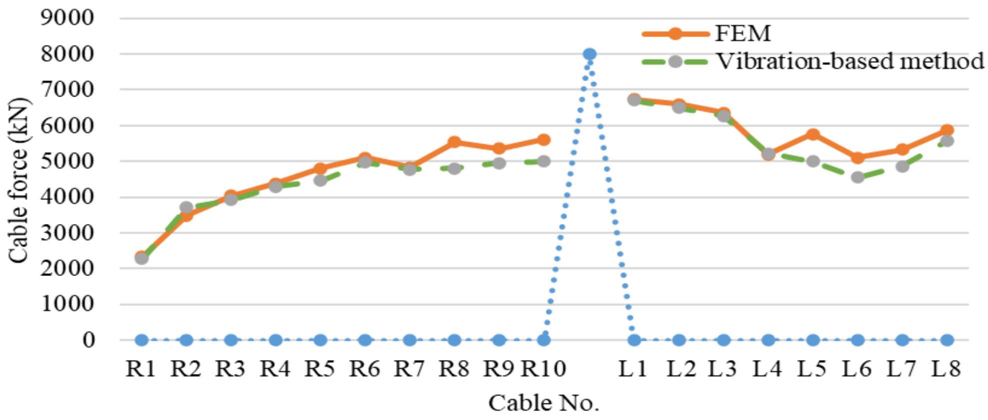


(a) Comparison of cable force between FEM simulation and design values

Fig.10. Comparison of cable force in FEM simulation with design values, lift-off test and vibration-based method



(b) Comparison of cable force between FEM simulation and lift-off test



(c) Comparison of cable force between FEM simulation and vibration-based method

Fig.10. (continued)

4. Conclusions

This study examines the cable tension forces in a one-plane cable-stayed bridge in Vietnam using both field measurements and numerical simulations. The cable tension forces derived from the finite element model are evaluated by comparing them with the design tension forces and field-measured values obtained through the lift-off and vibration-based methods.

The following conclusions can be summarized from the results of the current work:

- The discrepancy between field-measured cable forces and design data is generally within 7%, confirming the reliability and accuracy of both the measurement and design data.
- Both the lift-off test and vibration-based method effectively capture variations in cable tension across all cables. Similar to the design values, longer cables exhibit lower tension forces, while shorter cables experience higher forces.
- The numerical simulation accurately represents the rigidity of each cable. The discrepancy between the natural frequencies of cables, calculated based on design tension force values, and those obtained from simulation analysis is less than 3%.
- Numerical simulations show greater errors for shorter cables near the tower than for longer cables farther from it. Significant discrepancies of around 12% to 15% are observed in the second to fourth cables from the tower and in cables positioned close to the tower. In contrast, longer cables in the side spans closely match the design values, with deviations of only about 3%.

Despite these discrepancies, preliminary analytical values obtained from the simulation are considered acceptable, as they help reduce the need for extensive field measurements, especially in cases where direct measurement is impractical. The proposed numerical model can be applied to various cable-stayed bridges to establish a comprehensive database for tension assessment under different load cases. This database can aid in optimizing cable force adjustments during the design and construction phases. Additionally, it can provide an initial assessment of structural performance and serve as a valuable input for further analyses, including AI-based structural evaluations using machine learning.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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