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Evaluation of Cable Tension Using Static and Dynamic Test on R.H. Fisabilillah Cable-Stayed Bridge, Batam-Indonesia

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Abstract. R.H. Bridge Fisabilillah (Bridge I) is a cable-stayed bridge, included in the series of Barelang Bridges (Batam-Rempang-Galang), which were built from 1992 to 1998. With the service life of the bridge reaching 25 years, it is necessary to check the health condition of the bridge structure. Bridge cables are one of the most important elements of a cable-stayed bridge. These cable elements predominantly experience tensile forces when transmitting loads from the decks to the bridge pylons. Cable force inspection methods can be carried out using the direct measurement method (e.g., a static test using the lift-off method) or indirect measurement methods (e.g., a dynamic test using accelerometer sensors, electromagnetic (EM) sensors, and so on). This study aims to compare the cable tensile force based on the static test (lift-off method) in 2017 against the dynamic test (accelerometer sensors) in 2022. Evaluation of the cable tensile force based on the dynamic test was carried out using the taut string theory and beam string theory approaches. From the study, the two empirical approaches yielded insignificantly different results, with a difference in the mean difference of -1,71% and a maximum difference of 28,15%. The study also shows an increase in cable force capacity to a maximum of 47.20% UTS (ultimate tensile strength) based on the taut string theory and a maximum of 53.37% UTS based on the beam string theory. This value is greater when compared to the results of the cable force based on the static test (lift-off) in 2017, which was a maximum of 41.64% UTS. It is recommended to carry out further and more comprehensive studies to determine the effect of changes in cable force distribution on the behavior of the structure on the R.H. Fisabilillah Bridge.

.**Keywords**: static test, dynamic test, tension force, cable, cable-stayed bridge

INTRODUCTION

According to Presidential Decree No. 41 of 1973, Batam Island was designated as an industrial area, managed by the Batam Concession Agency (BP Batam). To support the island's development, a bridge linking Batam, Rempang, and Galang islands was constructed between 1992 and 1998. The BARELANG (Batam-Rempang-Galang) Bridge is composed of six bridges, one of which is the R.H. Fisabilillah Bridge, a cable-stayed bridge that spans 641.8 meters, connecting Batam and Tonton Island. The bridge has 112 cables that connect the decks to the two main pylons [1].

In accordance with the BMS Bridge Inspection Guide and Guideline No. 01/P/BM/2022 on Bridge Inspection, structural testing consisting of static and dynamic tests can be performed during special inspections, which are carried out when recommended by a detailed inspection to ensure the condition of the bridge elements. A detailed inspection is carried out every five years or when the Condition Value (NK) is equal to or greater than three. The cable elements are tested using direct measurement (static test) and indirect measurement (dynamic test with an accelerometer sensor or electromagnetic test [EM]) to determine the force occurring in the bridge cables [2]. Special inspection of cable elements aims to determine the force that occurs in bridge cables can be carried out through direct measurement (static test) and indirect measurement (dynamic test with accelerometer sensor or electro-magnetic [EM] test [3]. Each test method has test procedures, limitations, accuracy, and advantages that differ from one another.

The direct measurement method with a static test is frequently used as a controlled force for other test methods because the force is measured directly on the cable during lift-off work. The lift-off static test provides superior confidence in the cable force accuracy because it is measured directly. However, this method has longer execution times and requires a higher safety factor. The dynamic test method is widely used due to its practicality, relatively accurate results, and faster execution times. Several studies have investigated the validity and accuracy of the dynamic test method for measuring the force on bridge cables, such as those conducted on the Seohae cable-stayed bridge in Korea [4], cable hanger of the Siak II arch bridge - Riau [5] [6], the Merah-Putih cable-stayed bridge - Ambon [7], and the Padamaran I extra-dosed bridge - Riau [8].

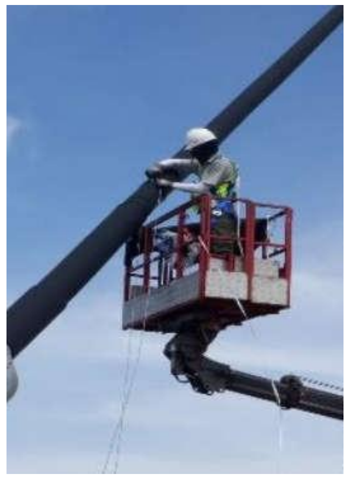

FIGURE 1. Preparation for the Dynamic Test by Installing the Accelerometer Sensor on the Bridge's Cable

The present study describes a dynamic test procedure for measuring the tensile force of bridge cables. The method involves installing accelerometer sensors on the cable to be measured (as shown in Figure 1), subjecting the cable to a vibrational load excitation, and recording the resulting vibration data. An empirical approach is then used to analyze the data and estimate the cable force. Previous research, such as that presented in [6] has demonstrated that the vibration method can accurately estimate the tensile force of hanger cable elements of steel arch bridges, with an accuracy of 4% - 6.71% compared to experimental results. In addition, [7] validated the cable force on the bridge using a dynamic, with a difference of only 0.28% - 9.23% compared to the cable control force. Various theoretical approaches have also been used to estimate cable tensile force with dynamic testing, with an error accuracy of less than 10.0%[9]. In more detail, [8] reviewed the use of several empirical formulations in the dynamic test of bridge cables and concluded that the taut string theory and beam string theory approaches provide precise results with a deviation of <7.0%.

The need for a special inspection of the cable elements on the R.H. Fisabilillah bridge was first identified during a detailed inspection in 2016 by the Korea Infrastructure Safety and Technology Corporation (KISTEC), which is part of a collaboration between the Ministry of Public Works and Public Housing and the Ministry of Land, Infrastructure, and Transportation (MOLIT) of South Korea. The inspection revealed that several cables were damaged due to a lightning strike, loose cable deviator guides, and other issues [10].

In 2017, PT. VSL Indonesia performed cable maintenance work on the bridge, replacing cables damaged by lightning strikes and checking the cable force using the lift-off method. Figure 2 illustrates the cable force measurement by lift-off method using a mono-strand jack, with measurements taken on 112 cables in total. Specifically, 28 cables were measured on each of the BATAM side span, BATAM main span, TONTON side span, and TONTON main span. After inspection, it was found that the tensile force acting on the cable was still below 45.0% of the ultimate tensile strength (UTS), as presented in Table 2 [11].

FIGURE 2. Cable Force Measurement with Static Test Method (lift-off)

In 2022, the collaboration between the Ministry of Land, Infrastructure, and Transport (MOLIT) of South Korea and the Ministry of Public Works and Public Housing of Indonesia continued regarding the introduction of the bridge Structural Health Monitoring System (SHMS) system in South Korea and the installation of the SHMS system on the R.H. Fisabilillah. Therefore, before installing the SHMS sensors on the R.H. Fisabilillah Bridge, several tests were carried out to ensure the final condition of the bridge. One of the most important bridge elements to be tested is the cable element. Visual inspection of the cable elements is carried out to detect damage to the cable and the cable force is measured by a dynamic test to obtain the actual force that occurs in the cable.

Taut String Theory

This theory assumes that there is no effect of cable curvature (sag effect) and the influence of cable flexural stiffness (EI), so the cable force can be approximated by equation (1) [12]:

$$T = 4mL^2 (fn/n)^2 \tag{1}$$

where:
T = cable force (kN)
m = cable weight (ton/m)
L = cable length (m)
fn = frequency in mode n (Hz)
n = mode number

Beam String Theory

This theoretical approach is almost the same as the previous theory but has taken into account the effect of cable stiffness (EI), so the cable force can be determined using equation (2) [12]:

$$T = 4mL^2 (fn/n)^2 - (EI)eq\ (n\pi/L)^2 \tag{2}$$

where:
T = cable force (kN)
m = cable mass (ton/m)
L = cable length (m)
fn = frequency in mode n (Hz)
n = mode number

METHODOLOGY

The evaluation of cable force is to be carried out by comparing the results of cable force from static and dynamic tests. During the static test using the lift-off method, the initial force that occurs in the bridge cables is measured. On the other hand, the cable force during the dynamic test is obtained from the recorded data of the accelerometer sensors during the vibrational load excitation and analyzed using empirical formulas. The results obtained from both tests are then compared and evaluated. The lift-off method is considered as an initial reference due to its direct measurement of cable force during the jacking process. The difference between the static and dynamic test cable tensions is expressed as a percentage deviation value. The detailed research methodology is presented in a flowchart as shown in **FIGURE 3**.

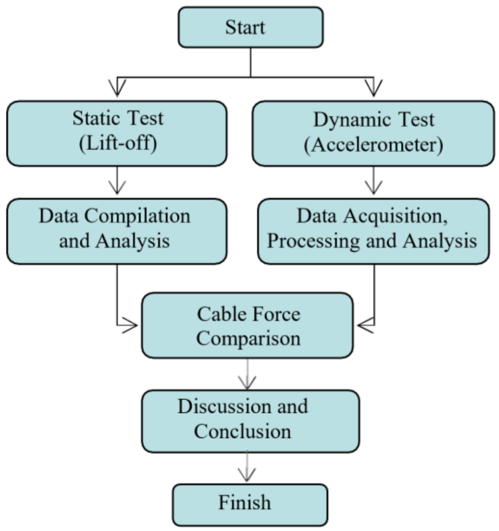

FIGURE 3. Research Flowchart

The research took a sample of 56 cables, where the location of the cables is on the left side of the bridge if we are from Batam to Tonton (North-East direction) as shown in **FIGURE 4**. A total of 56 cables were tested, both statically and dynamically. Cable names, cable lengths, and cable weights are presented in **TABLE 1**.

The cable in the pylon to the left of the picture is on the Batam Island side so the first code is given with the letter B, while the cable in the pylon to the right of the picture is on the Tonton Island side and is given the code T. For the second code, the name refers to the position of the cable from the cross-section bridge, where the right position is symbolized R and the left position is symbolized L. For the next code, cable names are given based on their position where the cables in the side span/edge are given the symbol S (side), and the cables in the middle span are given the symbol M (middle). For example, BL– S9 means that the cable is on the side of Batam Island (B) with a position on the left (L) and the position of the cable on the side span (S) with sequence number 9.

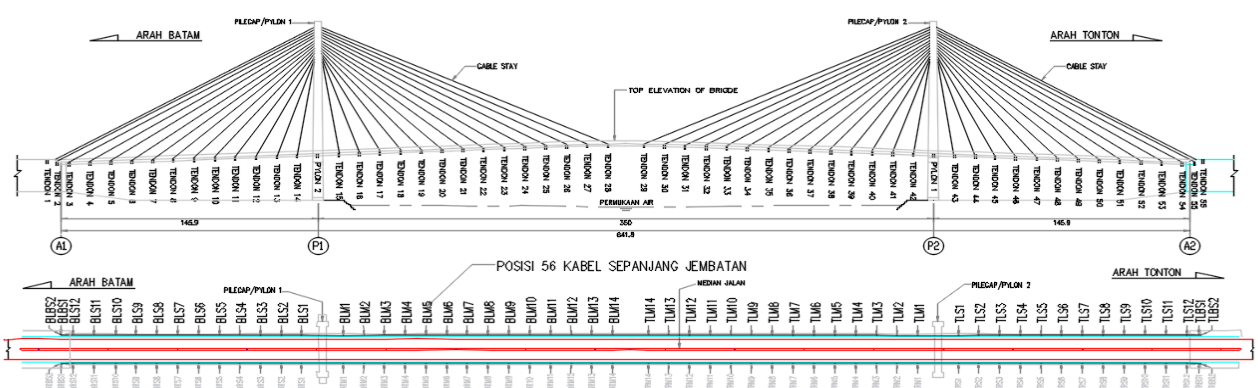

FIGURE 4. Locations of 56 Cable Samples

TABLE 1. Cable Properties

No	Cable Name	Cable Length (m)	Cable Weight (ton/m)	No	Cable Name	Cable Length (m)	Cable Weight (ton/m)
1	BL-BS2	185.75	0.1094	29	TL-M14	187.44	0.1008
2	BL-BS1	184.98	0.1094	30	TL-M13	177.09	0.0683
3	BL-S12	172.16	0.0727	31	TR-M12	164.46	0.0798
4	BL-S11	160.74	0.0798	32	TL-M11	153.29	0.0683
5	BL-S10	149.47	0.0636	33	TL-M10	142.30	0.0647
6	BL-S9	138.37	0.0636	34	TL-M9	131.53	0.0625
7	BL-S8	127.51	0.0592	35	TL-M8	121.03	0.0592
8	BL-S7	116.96	0.0570	36	TL-M7	110.90	0.0559
9	BL-S6	106.82	0.0570	37	TL-M6	101.23	0.0515
10	BL-S5	96.87	0.0504	38	TL-M5	91.83	0.0493
11	BL-S4	87.25	0.0504	39	TL-M4	82.85	0.0439
12	BL-S3	78.26	0.0428	40	TL-M3	74.62	0.0439
13	BL-S2	65.81	0.0364	41	TL-M2	63.38	0.0364
14	BL-S1	61.69	0.0636	42	TL-M1	60.48	0.0625
15	BL-M1	60.48	0.0625	43	TL-S1	61.69	0.0636
16	BL-M2	63.38	0.0364	44	TL-S2	65.81	0.0364
17	BL-M3	74.62	0.0439	45	TL-S3	78.26	0.0428
18	BL-M4	82.85	0.0439	46	TL-S4	87.25	0.0504
19	BL-MS	91.83	0.0493	47	TL-S5	96.87	0.0504
20	BL-M6	101.23	0.0515	48	TL-S6	106.82	0.0570
21	BL-M7	110.90	0.0559	49	TL-S7	116.96	0.0570
22	BL-M8	121.03	0.0592	50	TL-S8	127.51	0.0592
23	BL-M9	131.53	0.0625	51	TL-S9	138.37	0.0636
24	BL-M10	142.30	0.0647	52	TL-S10	149.47	0.0636
25	BL-M11	153.29	0.0683	53	TL-S11	160.74	0.0798
26	BL-M12	164.46	0.0798	54	TL-S12	172.16	0.0727
27	BL-M13	177.09	0.0683	55	TL-BS1	184.98	0.1094
28	BL-M14	187.44	0.1008	56	TL-BS2	185.75	0.1094

Data Acquisition and Processing

FIGURE 5. External Load Excitation on the Cable

After the accelerometer sensor is installed, the dynamic test on the cable is carried out by providing an external load excitation by pulling the cable with a rope, shaking it, and then releasing it. The process of excitation of the external load on the cable can be seen in **FIGURE 5**. The vibrations resulting from the excitation of the external load will then be recorded by the accelerometer sensor in the form of amplitude and time domains (**FIGURE 6. a**). The FFT (Fast Fourier Transform) method is applied to obtain the natural frequency value of the cable (**FIGURE 6. b**).

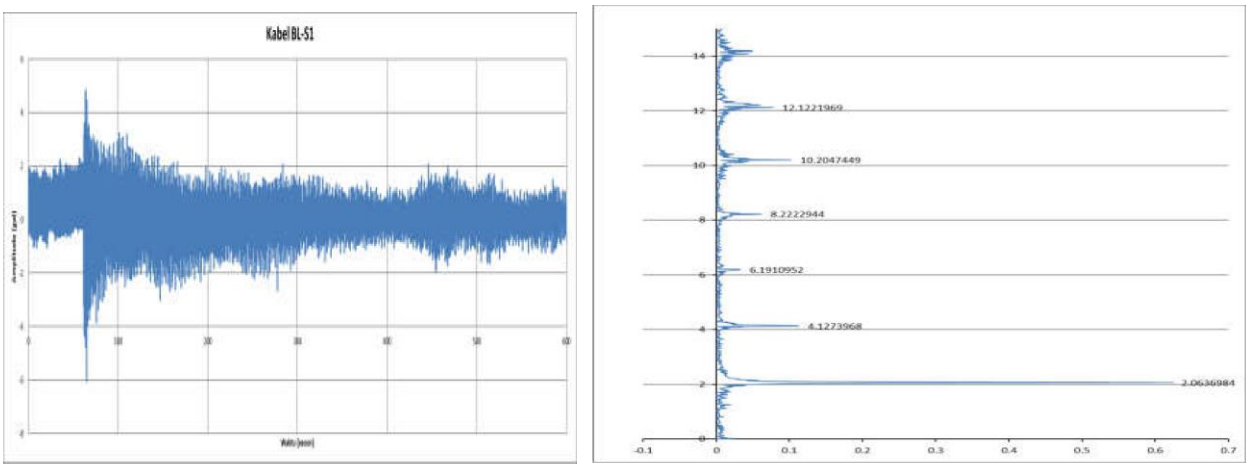

FIGURE 6. (a) BL-S1 cable Amplitude and Time Graph; (b) BL-S1 Cable Mode Number and Frequency Graph

The peak value of each frequency and its mode number are substituted into equations (1) and (2) to obtain an estimate of the cable force. Furthermore, the cable forces from several mode numbers are made into the modeling of the linear regression equation from equation (4).

$$(fn/n)^2 = [(EI)eq\ \pi^2/4mL^2]\ n^2 + T/\ 4mL^2 \quad (3)$$

$$y = ax + b \quad (4)$$

where:

y = $(fn/n)^2$
a = $[(EI)eq\ \pi^2/4mL^2]x = n^2$
b = $T/4mL^2$

Modes that provide R-square (R^2) values close to 1.0 can be used in further analysis, while modes that provide R-square (R^2) far below 1.0 can be evaluated regarding their use in the analysis. **FIGURE 7** is an example of a linear regression of cable mode and frequency on the BL-S1 cable.

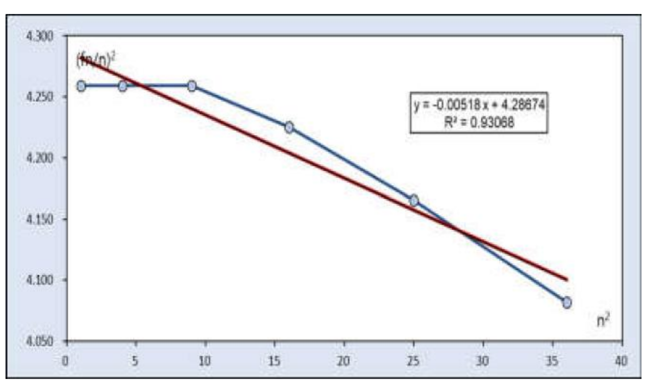

FIGURE 7. Linear Regression of Cable Mode and Frequency BL-S1

RESULT AND DISCUSSION

Cable Forces Based on Static Test (Lift-off Method)

Static test data were obtained from cable lift-off measurements in 2017 when the cable maintenance work was carried out. **TABLE 2** and **FIGURE 8** show the measured tension force on the cable during lift-off work.

TABLE 2. Cable Forces Based on Static Test (Lift-Off Method)

No	Cable Name	Lift-Off Force (kN)	Ratio to UTS (%)	No	Cable Name	Lift-Off Force (kN)	Ratio to UTS (%)
1	BL-BS2	9.549	40,75	29	TL-M14	8.121	37,13
2	BL-BS1	8.117	34,63	30	TL-M13	5.321	36,74
3	BL-S12	3.672	23,51	31	TL-M12	6.189	32,90
4	BL-S11	5.425	32,05	32	TL-M11	4.367	29,95
5	BL-S10	5.394	39,09	33	TL-M10	4.572	32,52
6	BL-S9	4.682	33,92	34	TL-M9	4.019	29,68
7	BL-S8	4.580	35,89	35	TL-M8	4.295	33,66
8	BL-S7	4.110	33,59	36	TL-M7	3.936	32,86
9	BL-S6	3.406	27,83	37	TL-M6	3.447	31,52
10	BL-SS	3.309	30,99	38	TL-M5	2.942	28,24
11	BL-S4	3.550	33,25	39	TL-M4	2.929	31,24
12	BL-S3	3.022	33,16	40	TL-M3	3.078	32,84
13	BL-S2	2.598	33,25	41	TL-M2	2.856	36,56
14	BL-S1	4.412	31,97	42	TL-M1	4.156	30,69
15	BL-M1	4.419	32,63	43	TL-S1	4.464	32,35
16	BL-M2	2.890	37,00	44	TL-S2	2.692	34,46
17	BL-M3	3.015	32,16	45	TL-S3	2.616	28,70
18	BL-M4	2.931	31,27	46	TL-S4	3.445	32,26
19	BL-M5	3.384	32,49	47	TL-S5	3.429	32,12
20	BL-M6	3.896	35,62	48	TL-S6	3.619	29,57
21	BL-M7	4.254	35,52	49	TL-S7	3.799	31,04
22	BL-M8	4.086	32,02	50	TL-S8	3.894	30,52
23	BL-M9	4.130	30,50	51	TL-S9	3.683	26,69
24	BL-M10	4.503	32,02	52	TL-S10	5.620	40,72
25	BL-M11	4.814	33,01	53	TL-S11	6.170	36,45
26	BL-M12	7.048	41,64	54	TL-S12	3.627	23,22
27	BL-M13	5.604	36,66	55	TL-BS1	9.015	38,47
28	BL-M14	7.693	35,39	56	TL-BS2	8.347	36,13

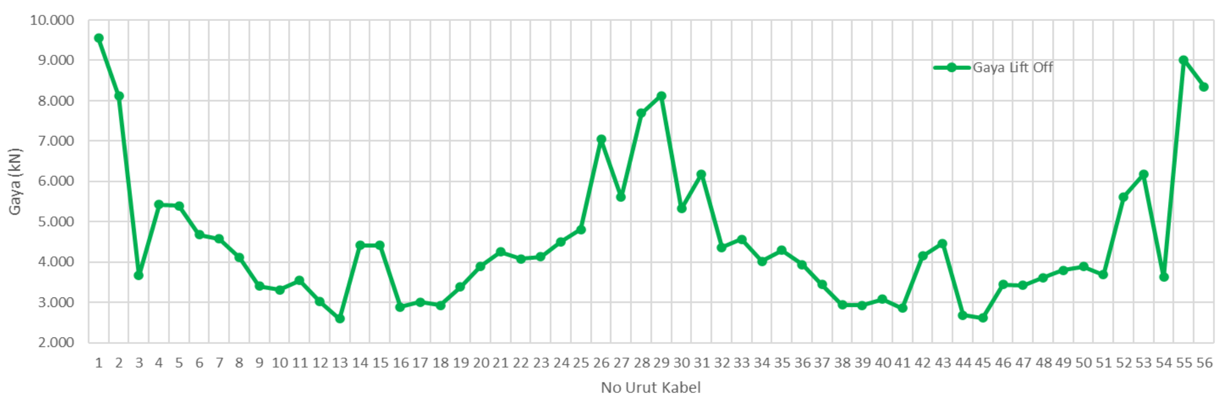

FIGURE 8 Cable Force Distribution Based on Static Test (Lift-off Method)

Cable Forces Based on Dynamic Test

TABLE 3 shows the recapitulation of cable force calculations using the formulation of equation (1) and equation (2). Furthermore, the cable forces from the two approaches (Taut String theory and Beam String theory) are presented in the graph in **FIGURE 9**.

TABLE 3. Cable Forces Based on Dynamic Test

No	Cable Name	Estimate Cable Force (kN)		No	Cable Name	Estimate Cable Force (kN)	
		Taut String	Beam String			Taut String	Beam String
1	BL-BS2	8.764	8.936	29	TL-M14	7.860	8.736
2	BL-BS1	7.965	8.045	30	TL-M13	5.118	5.766
3	BL-S12	4.094	4.094	31	TL-M12	6.093	6.136
4	BL-S11	5.091	5.118	32	TL-M11	4.261	4.295
5	BL-S10	3.875	3.896	33	TL-M10	4.226	4.256
6	BL-S9	4.223	4.260	34	TL-M9	3.622	3.687
7	BL-S8	4.165	4.194	35	TL-M8	3.931	3.972
8	BL-S7	4.027	4.086	36	TL-M7	3.800	3.852
9	BL-S6	3.225	3.239	37	TL-M6	3.246	3.272
10	BL-SS	3.235	3.307	38	TL-M5	2.788	2.824
11	BL-S4	3.370	3.493	39	TL-M4	2.663	2.682
12	BL-S3	3.001	3.095	40	TL-M3	2.882	2.975
13	BL-S2	2.655	2.716	41	TL-M2	2.747	2.814
14	BL-S1	4.075	4.151	42	TL-M1	4.232	4.299
15	BL-M1	4.340	4.340	43	TL-S1	4.483	4.538
16	BL-M2	2.835	2.911	44	TL-S2	2.630	2.691
17	BL-M3	2.765	2.765	45	TL-S3	2.595	2.619
18	BL-M4	2.647	2.729	46	TL-S4	3.325	3.386
19	BL-M5	2.920	2.991	47	TL-S5	3.302	3.337
20	BL-M6	3.527	3.541	48	TL-S6	3.561	3.575
21	BL-M7	3.652	3.682	49	TL-S7	3.673	3.722
22	BL-M8	3.693	3.721	50	TL-S8	3.328	3.375
23	BL-M9	3.526	3.594	51	TL-S9	3.494	3.515
24	BL-M10	4.115	4.148	52	TL-S10	4.740	4.774
25	BL-M11	4.508	4.546	53	TL-S11	5.574	5.593
26	BL-M12	6.258	6.295	54	TL-S12	3.239	3.263
27	BL-M13	4.849	4.880	55	TL-BS1	8.972	9.049
28	BL-M14	7.371	8.158	56	TL-BS2	7.699	7.758

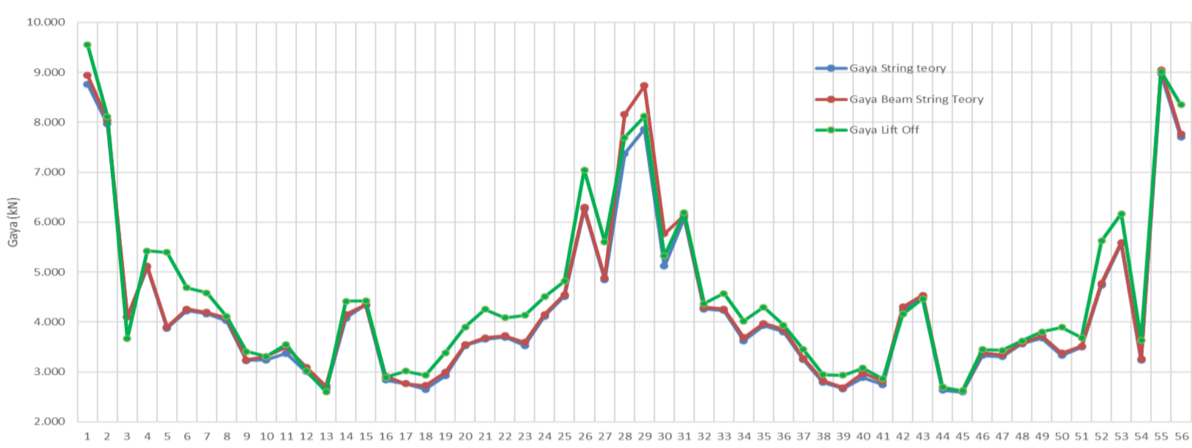

FIGURE 9. Comparison of Cable Force Distribution between Lift-Off with Taut String and Beam String Theory Approaches

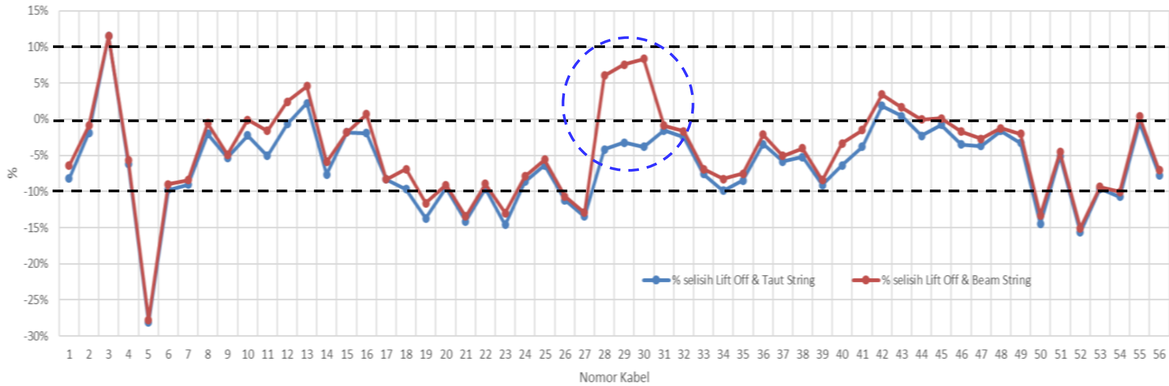

FIGURE 10. Percentage of Cable Force Deviation Between Static Test (Lift-Off) and Dynamic Test

FIGURE 8 shows the cable force during lift-off work in 2017 which will be used as a reference force in the estimation of cable force based on the dynamic test in 2022. Referring to **FIGURE 9**, it is generally seen that the difference in cable force estimation resulting from the approach to Taut String theory and Beam String theory is not significant. The mean difference between the two empirical approaches is 1.71%. This low difference value can be caused by the influence of the cable length (L) which is greater than the cable stiffness (EI), as shown in equation (2). The maximum difference value of the estimated cable force between these two theoretical approaches can be seen in the cable numbers 28 (BL-M14), 29 (TL-M14), and 30 (TL-M13) of 10.24%, 10.78%, and 12.19% (see **FIGURE 10**). This difference can occur because the value of R^2 is low, which is 0.16, 0.19, and 0.15 respectively. If you look further at the amplitude-frequency graph on each cable, there are difficulties in determining the frequency below 1 Hz. This can be caused by interference or noise recorded by the sensor as shown in **FIGURE 11**.

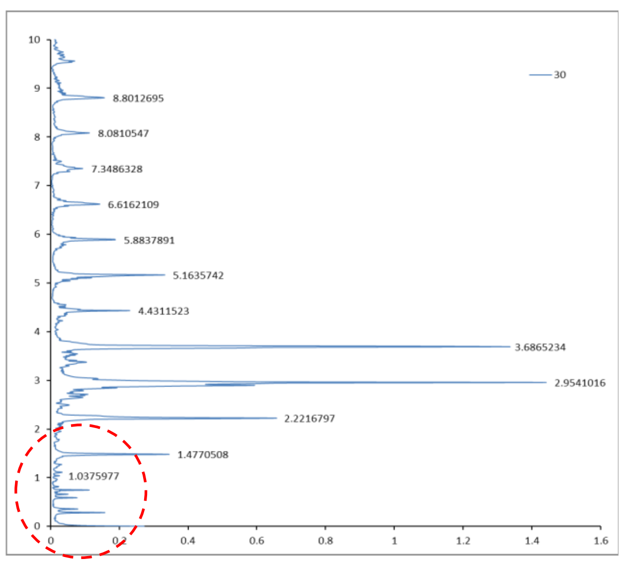

FIGURE 11. TL-M13 Cable Mode Number and Frequency Graph (Cable No. 30)

Furthermore, **FIGURE 10** shows a comparison between the cable forces based on the static test (lift-off method) and the dynamic test, using either the Taut String theory approach or the Beam String theory approach. The difference in the comparison of the cable forces is expressed in percentage deviation. The Beam String theory equation gives a relatively smaller percentage of deviation when compared to the Taut String theory. This can happen because the Beam String theory has accommodated the influence of cable stiffness (EI) in it. The average percentage deviation using Beam String theory is -4.49%, with a minimum deviation value of -27.78% for cable number 5 (BL-S10) and a maximum of 11.49% for cable number 3 (BL-S12). While the Taut String theory equation gives an average deviation percentage of -6.20% with a minimum value of -28.15% for cable number 5 (BL-S10) and a maximum of 11.49% for cable number 3 (BL-S12). The minimum and maximum deviation values in these two theories occur in the same cable, namely cable number 5 (BL-S10) and number 3 (BL-S12). This can be caused by interference or noise, such as rain, wind, or passing vehicles that have a frequency close to the natural frequency of the cable as shown in Figure 11, so determining the cable frequency becomes more difficult. With a small difference in lift-off force, we can evaluate the frequency of the cable by comparing a cable that has the same length and weight as cable number 5 (BL-S10). Referring to **TABLE 4** and **FIGURE 12**, it can be seen that the frequency value on cable number 5 (BL-S10) is below the frequency of identical cables, especially at frequencies < 1Hz where there are many peaks of the same frequency as shown in **FIGURE 13**.

TABLE 4. Frequency Rating on Cable Identical to Cable Number 5 (BL-S10)

Model Number	**1**	**2**	**3**	**4**	**5**
Cable Name	**Frequency (Hz)**				
BL-S10	0,8287	1,6575	2,4699	3,3149	4,1274
BR-S10	0,9399	1,8921	2,8320	3,7597	4,7119
TL-S10	0,9155	1,8311	2,7466	3,6621	4,5654
TR-S10	0,9155	1,8311	2,7588	3,6621	4,5654

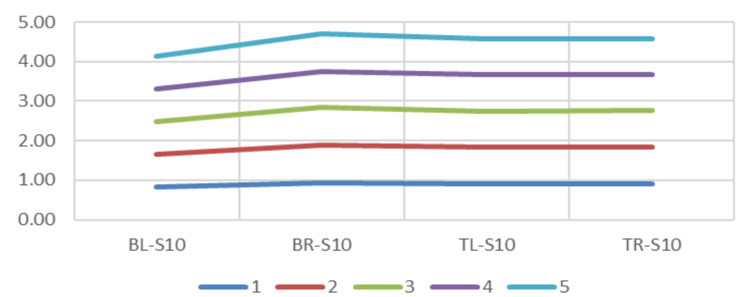

FIGURE 12. Frequency Rating on Cable Identical to Cable Number 5 (BL-S10)

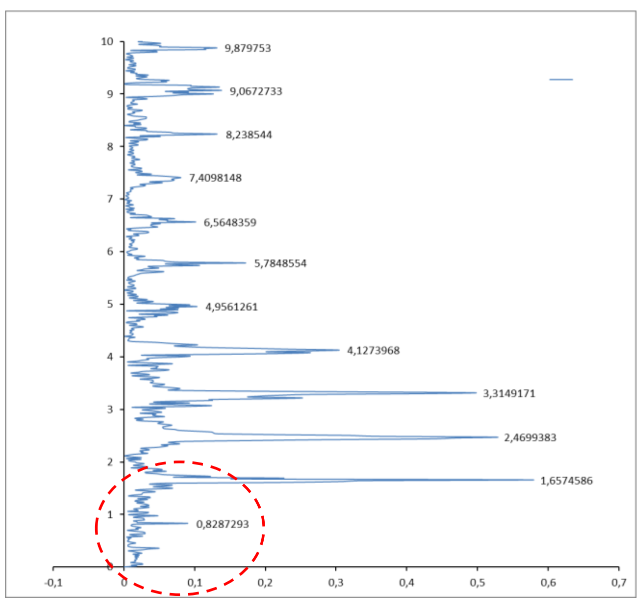

FIGURE 13. BL-S10 Cable Mode Number and Frequency Graph (Cable No. 5)

In addition, from **FIGURE 11** it is found that 10 cables have a deviation percentage above the 10% range. Factors that cause large deviations are influenced by the same factors as cable number 5 (BL-S10). Therefore, data from the accelerometer sensor needs to be filtered to eliminate the noise that occurs [13].

In general, the difference in the percentage of force deviation that occurs is in the range below 10%, both positive (+) and negative (-). This could indicate a change in cable force between the static test (lift-off) in 2017 and the current conditions based on the dynamic test in 2022. The change in cable force that occurred resulted in an increase in cable force capacity to a maximum of 47.20% UTS based on the Taut String theory and a maximum of 53.37% UTS based on the Beam String theory. This value is greater than the maximum cable capacity based on the 2017 static test (lift-off), which is a maximum of 41.64% UTS. Based on these facts, it is recommended to carry out further and more comprehensive studies to determine the effect of changes in cable force on the behavior of the bridge structure. In addition, cable force adjustment (tuning) can be an alternative solution to redistribute the forces that occur in the bridge cables before the SHMS sensor installation work is carried out on the R.H. Fisabilillah Bridge.

CONCLUSION

Cable force measurements on cable-stayed bridges can be obtained by direct and indirect methods, i.e., static test using the lift-off method and dynamic test methods using accelerometer sensors and electromagnetic sensors. The indirect method using dynamic tests is commonly preferred due to its practicality and relative accuracy. The taut string theory and beam string theory are widely used empirical approaches to estimate cable forces based on dynamic tests. Our study found that the mean difference between these two approaches was -1.71%, with a maximum difference of 28.15% observed in cable number 5 (BL-S10).

The evaluation of cable force using the beam string theory approach showed an average percentage deviation of -4.49%, with a minimum deviation value of -27.78% for cable number 5 (BL-S10) and a maximum of 11.49% for cable number 3 (BL-S12). Meanwhile, the taut string theory approach yielded an average deviation percentage of -6.20%, with a minimum deviation value of -28.15% for cable number 5 (BL-S10) and a maximum of 11.49% for cable number 3 (BL-S12). Ten cables showed deviations with range values above 10%. Therefore, further evaluation is needed to determine the selected frequency value, and the data should be filtered to remove any noise. For cables with deviations below 10%, an increase in cable force resulted in a maximum of 47.20% UTS based on the taut string theory and a maximum of 53.37% UTS based on the beam string theory, compared to the maximum of 41.64% UTS obtained from the static test (lift-off method) in 2017. Before the SHMS sensor installation work is carried out on the R.H. Fisabilillah Bridge, it is recommended to conduct further and more comprehensive studies to determine the effect of changes in cable force on the behavior of the bridge structure.

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