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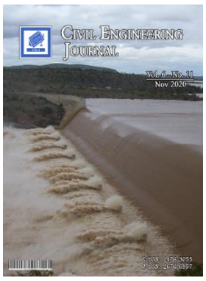

Evaluation of Cable Force Changes Effects on Cable Stayed Bridge

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Abstract

The proposed bridge, which is cable stayed bridge crosses the Hlaing River that flows through Western Yangon. It was completed in 2000 and is currently used to connect Insein Township with Hlaing Tharyar Township. It has the 20 years' service life. It requires the inspection and the evaluation of the real condition of the structure. As cable element plays an important role in cable structures, evaluation of the real state of the stay cable is one of the main focuses of the cable stayed bridge. Firstly, in the research work all cables are inspected to evaluate the current condition of the cables with included visual inspection and vibration-based cable force measurement method. With the help of static and moving load analysis, the effect of force change cables in which the successive force changes are considered, and the possible cable loss effect on the structural behavior of the bridge are also investigated. The finite element model of the cable stayed bridge is developed based on the geometric shape and material properties from MOC and is modelled with finite element software MIDAS Civil. The tension forces obtained by inspection over years (2000 to 2018) using vibration-based measurements method are compared with the measured intact cable forces. According to the results of the data analysis, it is observed that the cables force variations of the seven cables are abnormal conditions. In order to evaluate the condition of a bridge effected by cable force variation, the two parameters are considered; percentage increase in tension stress of all cables and percentage increase in deflection of the deck. The present study describes the structural response of the bridge in order to evaluate the actual safety of the bridge with abnormal force change cables, and also examines the consequences of one cable failure.

Keywords: Cable Stayed Bridge; Inspection; Cable Force Change; Parameters; Evaluate.

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1. Introduction

The basic structural form of a cable-stayed bridge is a series of overlapping triangles comprising pylon, girder, cable stay and cable anchorage [1]. Cable element plays an important role in cable structures such as cable stayed bridge, suspension bridge and extradosed bridge, during their life, the cables which are frequently exposed to severe environmental conditions. In Myanmar, old cable supported bridges was affected by severer corrosion in main cable which caused the collapse of the entire bridge with the exception of pylons during its service life [2]. Moreover, stayed cables comprise the main structural components of a cable-stayed bridge, and the changes in inclined cable force significantly affect the state of the whole structure [3]. The inspection of a bridge, especially the inspection of cables, after its completion, is critical to locate unreliable components and to ensure restoring its stability. The common methods to evaluate the condition of cables include visual inspection, vibration-based cable force measurement, laser-based force measurement, ultrasonic assessment, etc. [4].

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The bridge inspection is a detailed investigation and evaluation of damage and/or material properties of specified elements. The damage may be due to environmental impact (climate, saline soil, etc.), wear (insufficient maintenance), design and construction errors and overloading or similar conditions [5]. Visual inspection of the cable is of course the first action to be undertaken when starting with cable health assessment on a bridge. This can reveal obvious damages; unusual sag of the cable, revealing the loss of tensile force in the cable, heavy rust on external wire layers, wire failures, even cable rupture. This is of course the first, cheapest and easiest stage of the inspection. But this is not sufficient as some cables, especially parallel wire cables can experience gangrene effect. Another way to evaluate a cable health is the monitoring of the cable forces. Monitoring the cables forces can be very useful when assessing a structure as it gives indications on both the current situation and the evolution of the state of the cable [6]. The vibration monitoring system can detect the damage by determining the internal forces. The frequency of cable gathered by the sensors mounted on the cables can determine the static internal forces with the preconditions, which are the cable length, linear density and boundary conditions. The changes in internal forces can reflect the damaged condition of the cables [4]. A simple comparison method continues to be widely used for the evaluation of cable forces. According to the relative error value in each cable force is computed over year to reflect the condition of cable forces, such condition can be considered normal when the relative error value is less than a certain value (e.g., 5%) [7].

The bridge will run safely and be managed efficiently with the inspection of the cables' tension regularly. The inspection and safety evaluation provide strong guarantee for the bridge to run smoothly. A bridge over Yellow River is 2817.46m in total length, which is composed by south approach bridge, north approach bridge and the main bridge. Since 2000, multiple comprehensive inspections have been carried out. So structure adjustment and strengthening are used to guarantee the normal operation of the bridge. From 2008 to 2009, the department in charge of the bridge found that the expansion device plates connecting the main bridge and the approach bridge had significant down deflection. The expansion device plates' deflection leads to great impact on the main bridge deck with heavy loading wagons getting through. It seems that the variation of the bridge deck alignment can be seen by eyes. So it is necessary to inspect the main bridge structure, and to evaluate the structure situation and safety performance of the bridge [8].

The purpose of bridge evaluation is to help the engineer assess the capability of the bridge to safely carry its intended traffic. An analysis on the deformation and tension of the whole bridge is made according to the cables' tension variations. In the present study, the following method are employed in inspection of the cables; visual inspection, vibration-based cable force measurement method. The analysis and evaluation on all cable tension stresses and deck deflection of the bridge are done according to the cable tension force's variation. Moreover, the successive decreasing cable force is determined using regression analysis based on cable tension force' variation with time and then possible cable loss problem is considered to get safe operation of the bridge in future.

2. Case Study

2.1. Description of Bridge

The proposed bridge was built to connect the Insein and Hlaingtharya township across the Hlaing river in Western Yangon. The proposed bridge with 581.6 m span is a cable stayed bridge with double H-shaped pylons, double cable planes, semi-fan type and three span arrangements. The bridge span is side span 140.8 m + main span 300 m + side span 140.8 m, and three dimensional view are described as shown in Figure 1 and the numbering system for the cables and anchorage points are shown in Figure 2. The cables are numbered sequentially from left to right (Cable1 to Cable44). Both the upstream and the downstream have the same cables numbering order. The main structural system of bridge is composed of reinforced concrete pylon column with two numbers of transverse beam, steel truss girder, reinforced concrete deck slab, and new parallel wire strand type cable. The deck is supported by 88 stay cables with 44 on each half of the bridge. The bridge details longitudinal section is shown in Figure 3 and deck cross section is shown in Figure 4.

Figure 1. Study area and three dimensional view of bridge

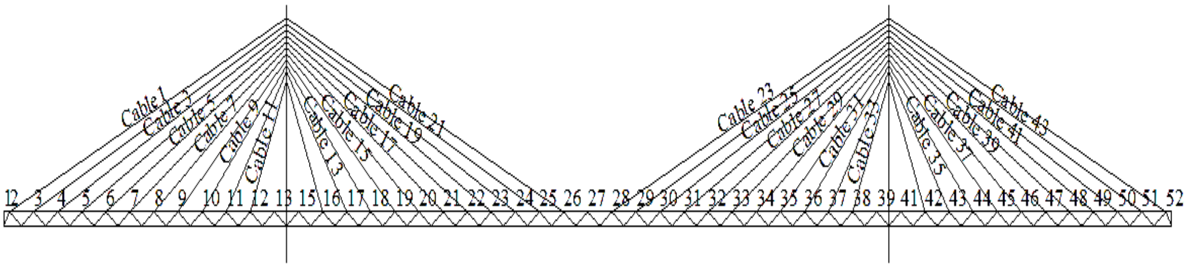

Figure 2. Names of cables and cable anchor points

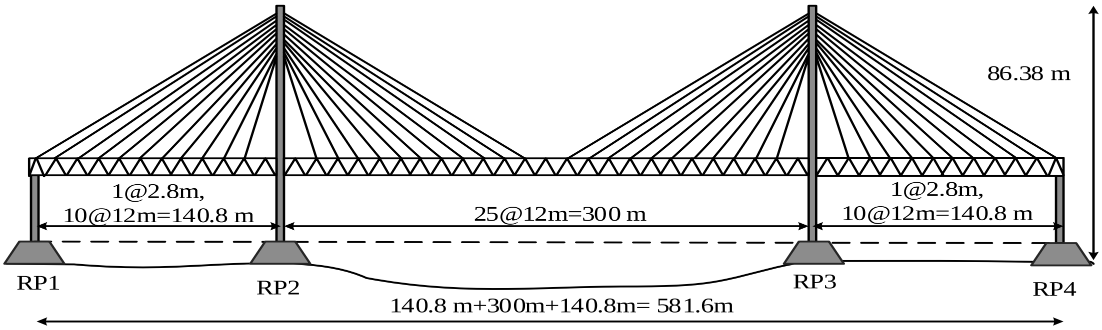

Figure 3. Longitudinal section of the bridge

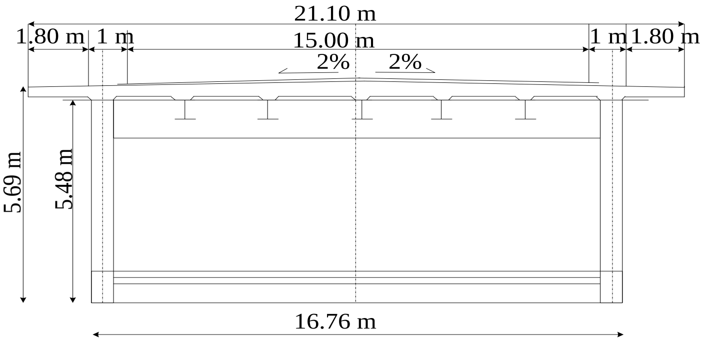

Figure 4. Cross section of bridge deck

The proposed bridge is developed as a three-dimensional finite element model in MIDAS Civil. The steel truss girders are modelled with beam elements and column with two numbers of transverse beams while the deck is modelled with plate element. The truss element is used to model the cables and the effect of cable sag in the cable is modelled with an equivalent elastic modulus obtained by Ernst Equation. The equivalent elastic modulus of the longest cable in the bridge, E_{eq} is $0.995E_c$. Boundary conditions at the base of the pylons are modelled with fixed end supports. The cross-sectional areas of cables are shown in Figure 5.

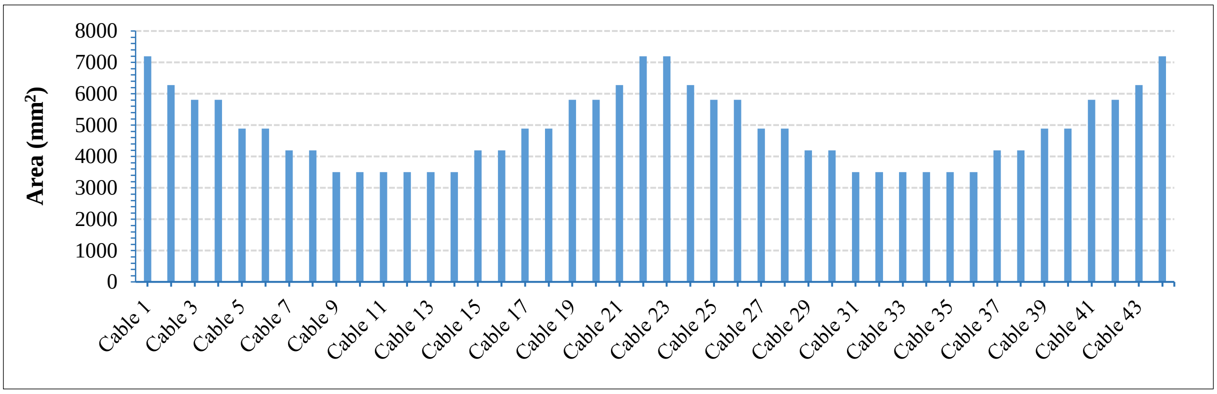

Figure 5. Cross-sectional areas of cables

2.2. Material Properties

The materials used for the bridge are reinforced concrete for pylon, steel for the girder and high-strength steel for the stay cables. Material properties for finite element model of the bridge are shown in Table1.

Table 1. Material properties of the bridge

Structural Member	Elastic Modulus, E (N/mm^2)	Poisson's ratio, *v*	Weight Density (kg/m^3)	Strength (N/m^2)
Deck & Tower	3.45E+04	0.2	2500	50
Girder	2.06E+05	0.3	7850	345
Cable	2.00E+05	0.3	8362	1670

3. Research Methodology

The required data of existing cable-stayed bridge is collected and obtained from MOC (Ministry of Construction). The bridge is modelled using MIDAS CIVIL software. To properly assess the condition of cable sheathing surface, visual inspection is done. The tension forces obtained from inspection over years using vibration-based measurements method are compared with the measured intact cable forces. All the cables on the bridge are evaluated according to the visual inspection results throughout the cable sheathing surface and the cables' tension inspection results of the bridge. And then, it describes the behaviour of the bridge in order to evaluate the actual safety with defected cables, and also examines the consequences of a cable failure. Figure 6 shows the flow chart of the study.

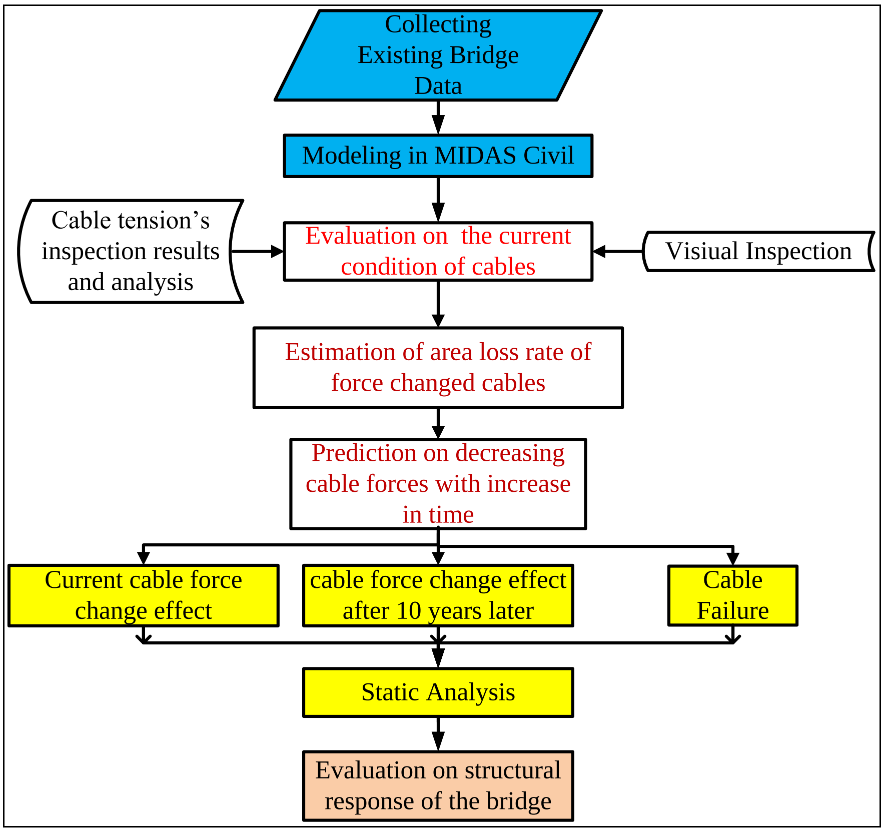

Figure 5. Flow chart of the study

3.1. Estimation of Area Loss Rate of Force Changed Cables

O.A. et al (2015) validated corrosion analysis method by modeling the cables as solid elements and introducing corrosion by area loss. In this research, a parallel wire cable has been modeled as solid elements to estimate the effect of corrosion which leads to reduced cross sectional area on the cable force. The results obtained shows that the percentage of corrosion is proportional to force left in the cable after the area is reduced. Therefore, the percentage of area wasted due to corrosion can be modelled as percentage drop in the cable force [10]. O.A. et al (2015) model shows that tension force drop in cable is directly proportional to cable area lost without considering other phenomena. Consider mechanisms of cable force drop result in the reduction in cable cross sectional area. Therefore, cable area changes relative to force left in the cable is introduced in the following equation 1 based on cable force measurement.

$$F_0/A_0 = F_1/A_1 \tag{1}$$

$$A_1 = F_1/F_0 \times A_0 \tag{2}$$

The area loss rate defines the amount of metal loss at a given location on a bridge member. It relates the amount of section loss to the original section of the member as the following Equation 4 [16].

$$\text{Area loss rate } \% = (1- A_1/A_0) \times 100 \tag{3}$$

Where F_0 is the cable force in the intact cable, F_1 is the cable force in the force change cable, A_0 is the cross sectional area of intact cable and A_1 is the cross sectional area of the force change cable.

3.2. Prediction on Decreasing Cable Forces with Increase in Time

Regression analysis is a statistical tool used to model the relationship between a dependent variable and one or more independent variables. The linear regression analysis is used to predict successive decrease cable forces of defected cables with increasing time. In the studied linear model, successive cable force drop is dependent variable and time is independent variable. The linear model is expressed using the following Equation 4 [11].

$$Y = a + b\,X \tag{4}$$

Where; Y is cable forces at time t, kN, X is time of service, years, and a and b are constants.

3.3. Evaluation of Cable Force Change Effects

In order to evaluate the condition of a bridge affected by decreasing cable force, the following parameters are considered;

The percentage increase in stress of cables is used in the study in order to evaluate the effects of force decrease on the corresponding cables or on other adjacent cables. The percentage increase in deflection is used in the study in order to evaluate the effects of force decrease on structural response [16].

4. Field Inspections and Discussions

Visual inspection of the cables is the first action to examine the sign of damage on the cables. Then, the cable tension forces have been monitored with Vibration-Based Cable Force Measurements method from 2000 to 2018 by Ministry of Construction (MOC) which is an appropriate method in cable stayed bridge. Visual inspection examines the thorough cables to be combined with Vibration-Based Cable Force Measurements method.

4.1. Visual Inspections

A lot of literature shows that the damage of cable stayed system mainly appears in anchorage systems, guide pipes and cable sheathing (NCHRP Synthesis 353). Therefore, anchorages, guide pipes and cable sheathing are mainly inspected. Figure 6 show the condition of cable anchorage portion observed by inspection team of MOC in June, 2015. Drain blockage conditions are occurred on the top chords and cable anchorage zone due to garbage. If an effective water drainage system is not provided, crevice corrosion and pitting can occur at the anchorage because of water runoff and debris accumulation [16].

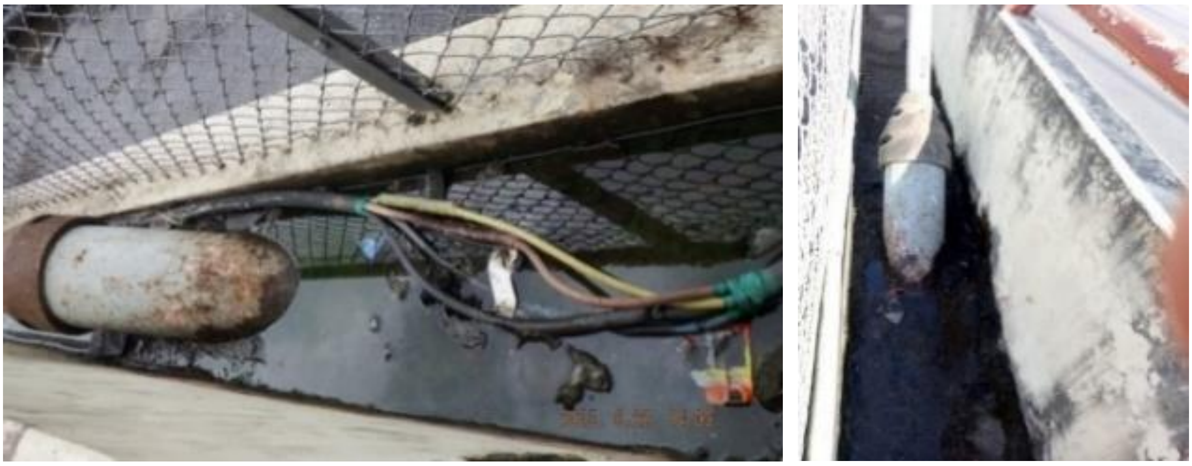

Figure 6. Drainage blockage in cable anchorage zones (MOC, 2015)

Figure 7. Poorly drain condition and cable anchor zone in damp condition and cracks and damage in sheathing of cable3 D/S in December 2018

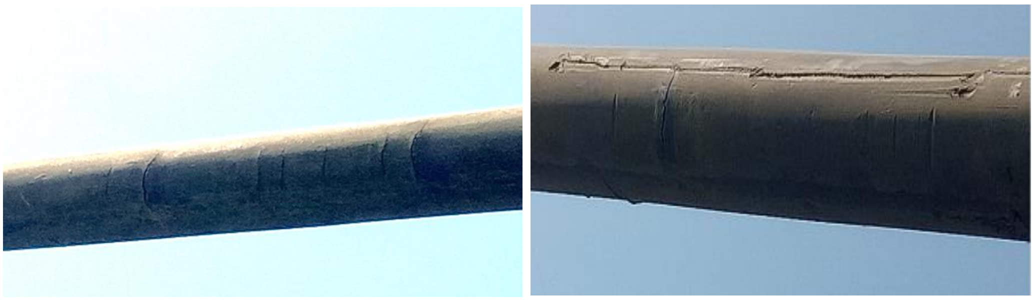

Figure 8. Cracks and damage in sheathing of cable3 D/S in August 2019

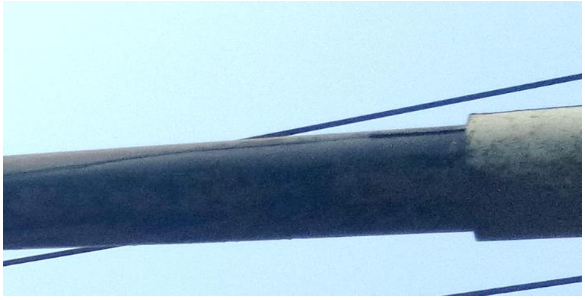

Figure 9. Cracks in sheathing of cable30 D/S in August 2019

Figure 10. Water stains on lower portion and cracks in sheathing of cable33 D/S

Visual inspections on the cables sheathing and cable anchorage portions were done in December 2018 and August 2019 and the accurate pictures of the cable condition were captured. In December of 2018, cables in damp anchorages and poor drainage condition due to insufficient slope and lighting pole footing on main span were found, and small damage and only one crack in the cable sheathing were also detected in cable3D/S as shown in figure7. In August 2019, the inspection showed new small scale cracks in the cable sheathing at the cable3D/S as shown in figure 8. Radial cracks were observed in cable sheathing of cable30D/S as shown in figure 9, that may allow the moisture and initiate corrosive attack of the cable strands. Due to the large quantity of entrained water in the cables, water stains were found on the lower portion of the cable33D/S as shown in Figure 10.

The visual inspections of the cables in June 2015 and December 2018 found damp conditions in the cable anchorages (cable 12 to cable 33) on the main span because of the poor drainage condition and lighting pole footings. The inspections of the cable's free length observe degradation of the protective sheathing of cable 3, cable 30 and cable 33 at downstream side.

4.2. Cable Force Measurements

The data of cable forces measured over years (2000 to 2018) is collected from MOC. Based on six years of data on the cable forces (2000, 2006, 2008, 2009, 2016 and 2018) investigated from the real cable stayed bridge, the evaluation of the cable condition is made. Tension forces obtained from inspection over years using vibration-based measurements method are compared with the measured intact cable forces. Relative error in each cable is computed over year to reflect the condition of cable forces. To easily determine the changes in cable forces, corresponding relative error (%) is calculated by the following Equation 5 [9].

$$\text{Relative Error (\%)} = ((F'-F)/F) \times 100 \qquad (5)$$

Where F' is Cable force measured from inspection and F is Cable force measured after complete construction. Figure 11 and 12 present diagrams of corresponding relative error in all cables on U/S and D/S over three years monitoring period (2006, 2008, 2009) between the period 2000 to 2009, respectively.

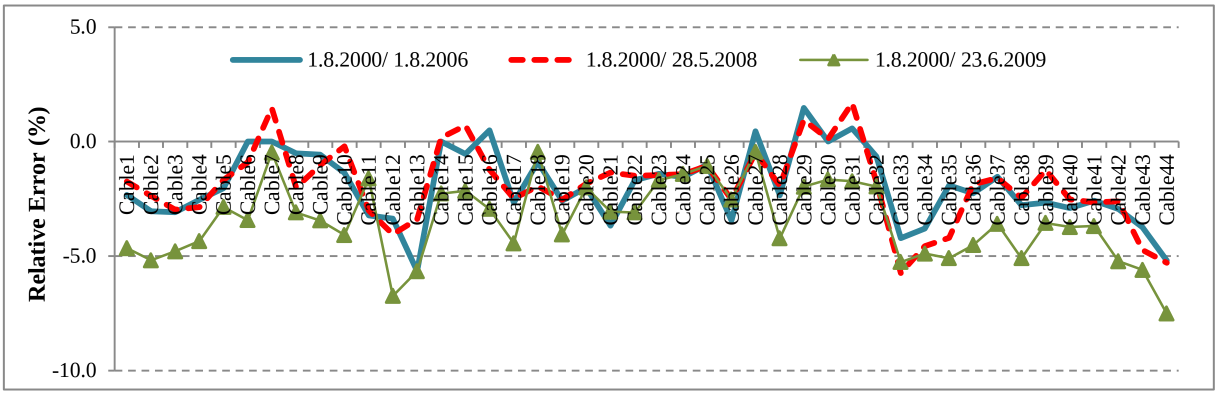

Figure 11. Corresponding relative error in cables on U/S over years (2000, 2006, 2008 and 2009)

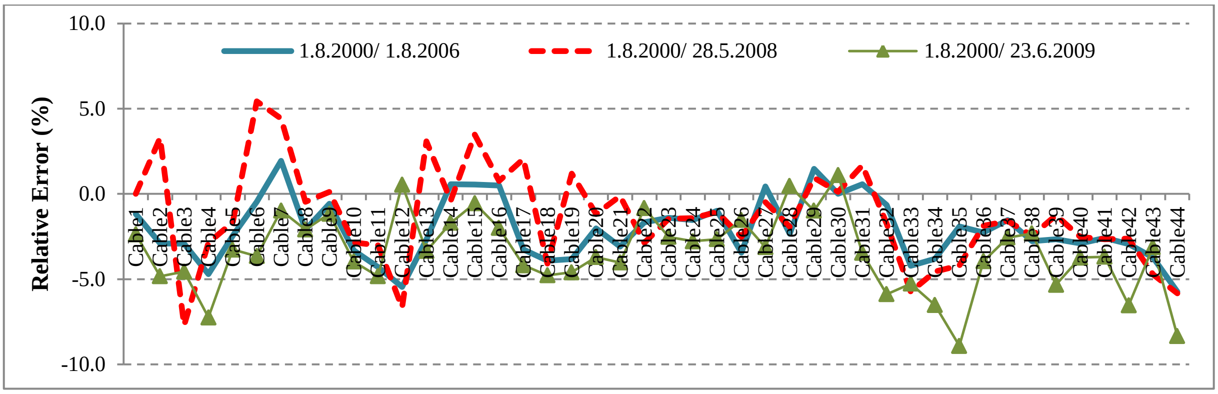

Figure 12. Corresponding relative error in cables on D/S over years (2000, 2006, 2008 and 2009)

Between the period of 2000 to 2009, it is indicated that there was 5% to -9% variation of the relative errors in all cables over the three years monitoring period. The corresponding relative error in all cables on U/S and D/S over three years monitoring period (2000, 2016, 2018) are shown in Figures 13 to 14, respectively.

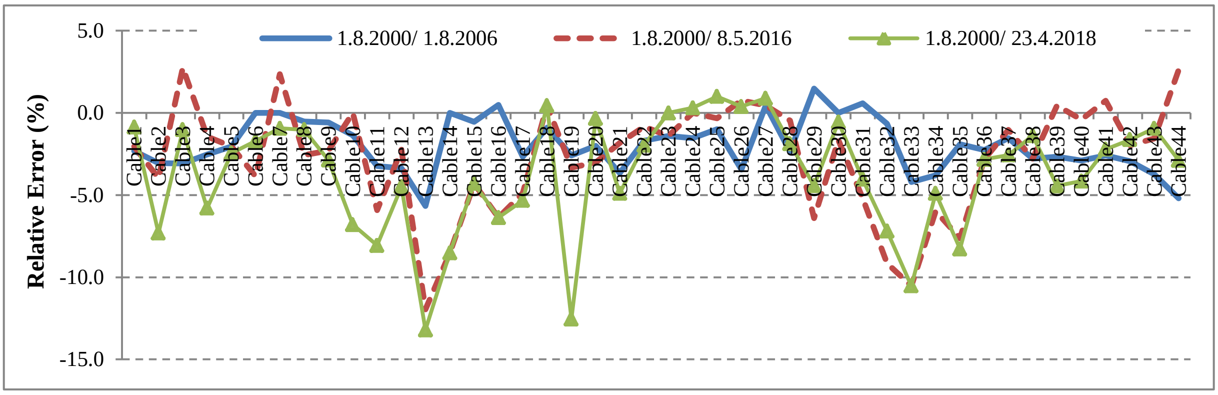

Figure 13. Corresponding relative error in cables on U/S over years (2000, 2006, 2016 and 2018)

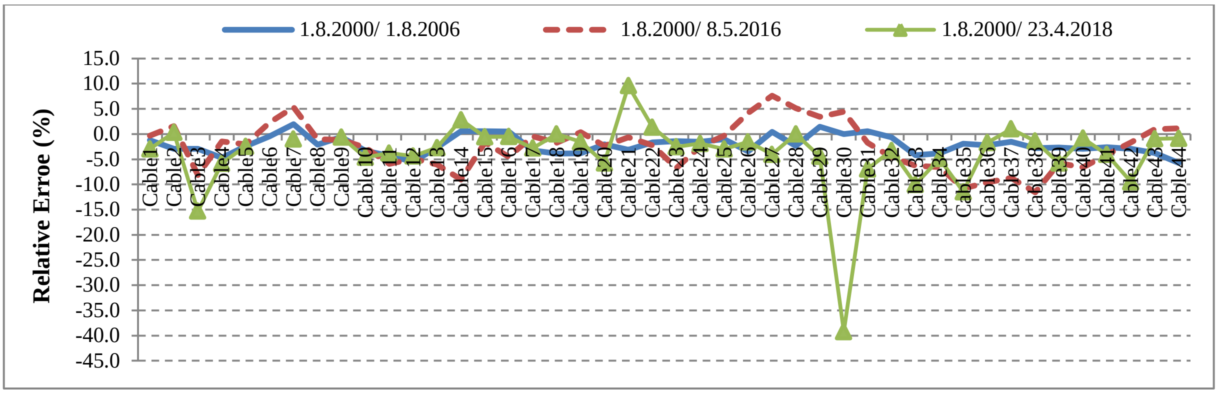

Figure 14. Corresponding relative error in cables on D/S over years (2000, 2006, 2016 and 2018)

From the above diagrams, it is noticeable that there are marked rise in the value of relative error of some cables. Among them, the peak change of relative error value of cable30 at D/S has been observed in 2018.

As a possible mistake of the measurements of the cable forces, assuming the relative error of the particular cable is considered not to exceed 10% for normal state in the study. From 2000 to 2009, the value of relative errors in all cables fluctuates between -10% and +10% during nine years. In previous year 2016, the relative error of cable13 and cable33U/S, and cable35D/S exceeded 10%. Relative error percentage of most cables are within -10% and +10% with the exception of a few cables; cable13, cable19, cable33U/S & cable3, cabe30, cable33, cable35D/S) which exceed 10% over 18 years. Among them, maximum cable force change is observed in Cable 30D/S and the value is 39.2%. The decreasing tension forces in these seven cables are obvious indications during 18years service. The cause of force drops in these cables should be studied in detail. O.A et al (2015) show that cable force reduction is directly proportional to cable areas lost. In this study, these above tension force decreasing cables are predicted to be deterioration condition without considering other phenomena according to the results of the data analysis (visual inspection & cable force measurement). These cables force changes effects are evaluated on the cable tension stress and deck deflection.

By applying the equation 1, the area loss rate of the seven cables are calculated. In the upstream side, three cables (cable 13, 19 and 33) are suffered up to area loss rate 13.2%, 12.55% and 10.5% respectively. In the downstream side, it is observed that the maximum cable force change (39.2%) occurs in cable 30 and other three cables (cable 3, 33 and 35) are 15.3%, 10% and 11.5% respectively. By the area loss rate equation, the area loss rate percentage is directly proportional to the values of cable force changes. According to linear regression model, the Figure 14 shows the area loss rate variation of a particular cable (Cable13, 19 and 33U/S and Cable3, 30, 33 and 35D/S) with increase in time.

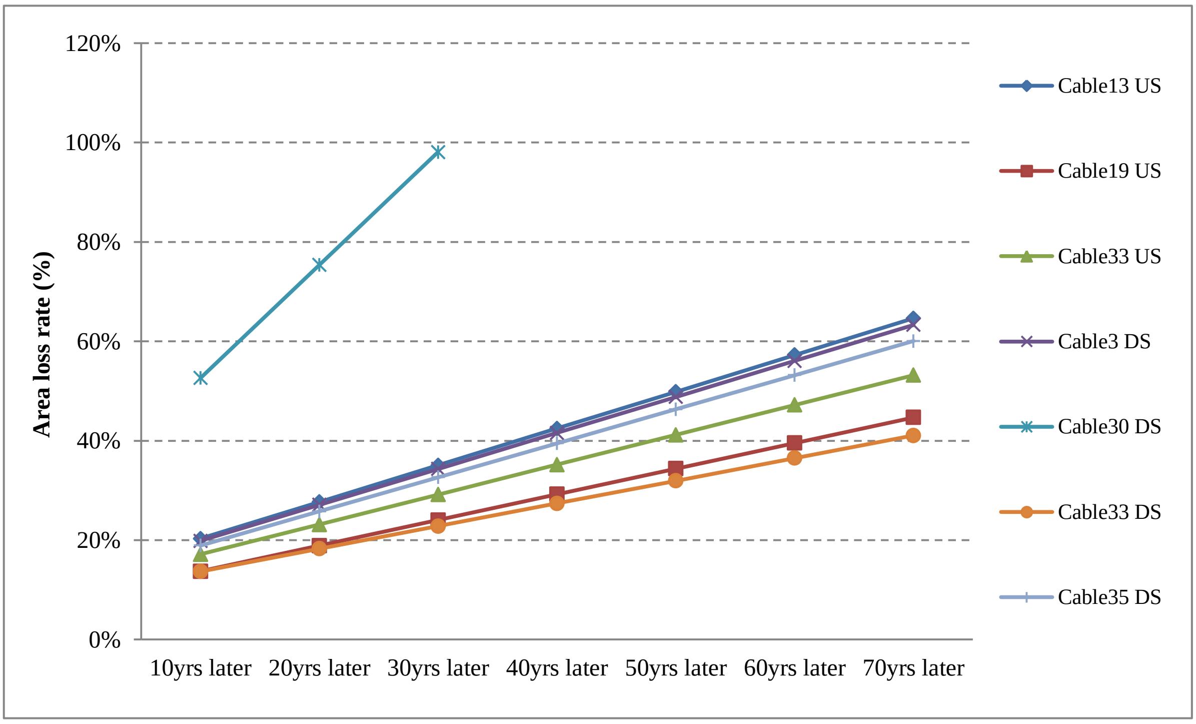

Figure 15. Area loss rate variation of cables

5. Results and Discussions

5.1. Cable Stress Assessment

In the study, the tension force decreasing cables are modeled by applying the reduction of cross-sectional area as a function of area loss rate according to O.A. et al (2015). The study investigates the behavior of the cables of the bridge with the affected cables. Comparison of cable stresses ratios taken by two conditions, i.e. the intact design condition and the current cables condition with the affected cables, is carried out to determine how cable stress change under cable force variation effects as shown in figure15 to 26. The cable stresses are checked at ULS and SLS with the 67% and 45% of ultimate limit strength of cable under current condition respectively as expressed in cable stress ratio (Stress limits are provided in Eurocode3) [17].

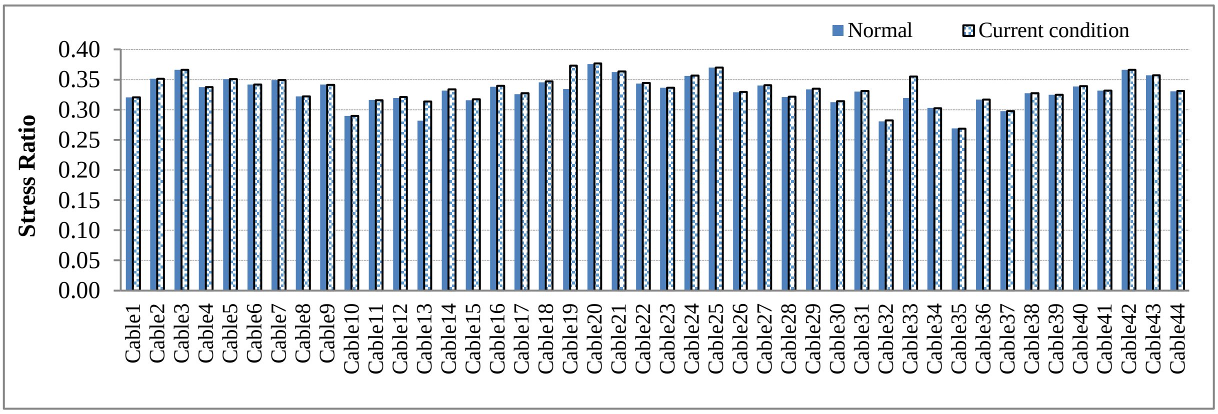

Figure 15. Comparison of cable stress ratio change on upstream side at SLS

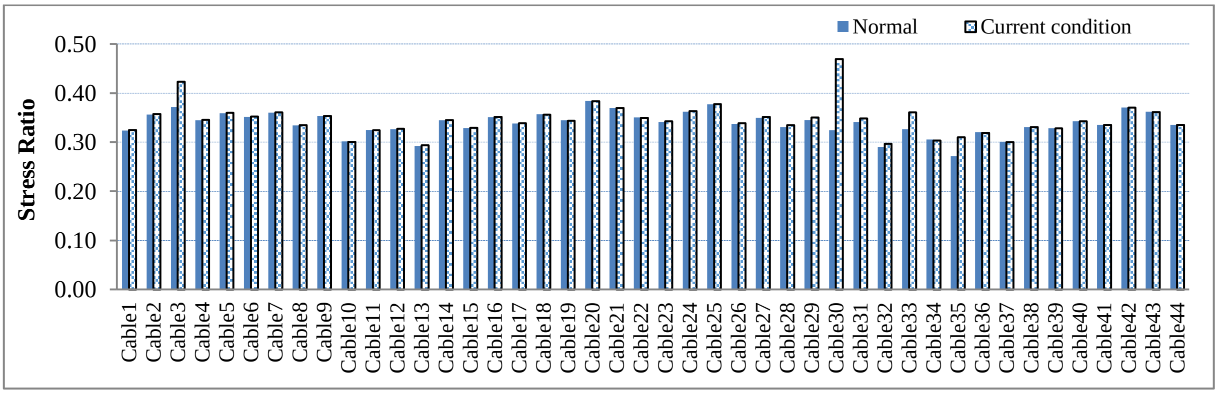

Figure 16. Comparison of Cable stress ratio change on downstream side at SLS

From the above case is observed that when the cables are affected by decreasing in tension force, the tension stresses increase in the affected cables and there are not too much stress changes in the surrounding affected cables, but the stress redistribution occurs. The highest stress ratio is discovered in the cable 30D/S and it is 0.47 because the cable that is most decreasing in tension force has the highest area loss rate.

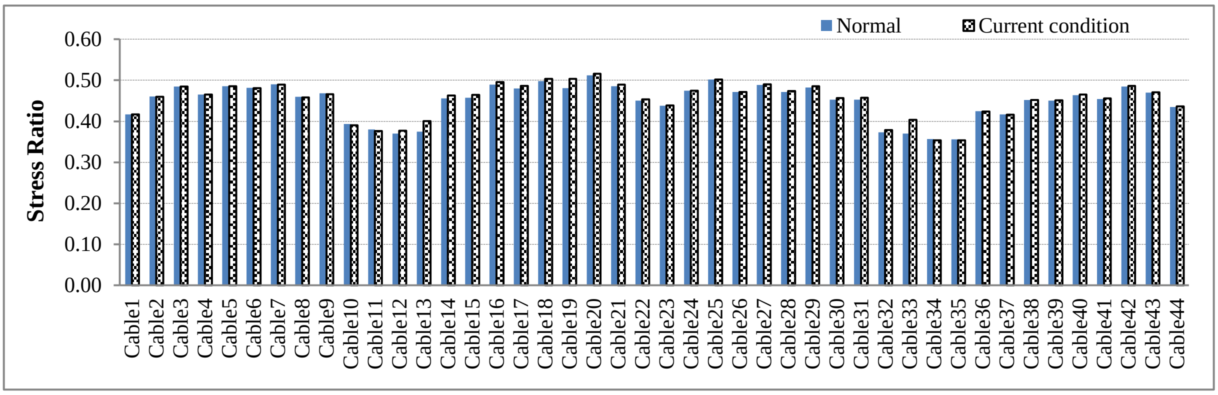

Figure 17. Comparison of cable stress ratio change on upstream side at ULS

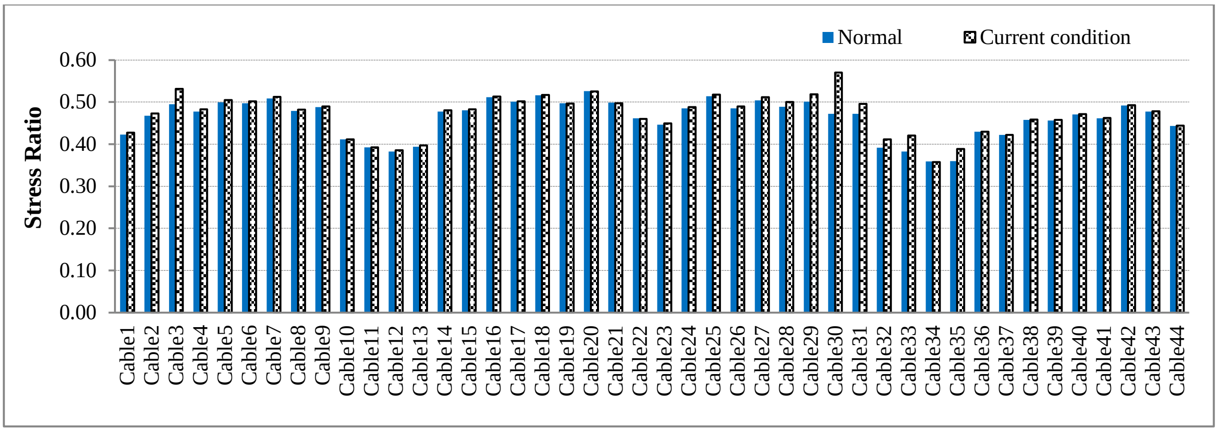

Figure 18. Comparison of cable stress ratio change on downstream side at ULS

At ULS, the most cables are however still well below the stress limit of 67% UTS, the stress in the cable30D/S increases to the stress limit of ULS as the largest force drop occurs 39.2% on the cable30D/S. In the current condition, it is observed that although the SLS stress in the cable30D/S exceeds the limit stress of 45% UTS, the stress meets the proposed limit state at ULS. Therefore, the cable30D/S is not safe for durable and fatigue stress develops on the cable. Then, the successive decreasing cable force is considered on these cables with time; 10 years later. The successive decreasing cable forces means the area loss rate of the cable with time. The cable stresses changes are also checked to determine their adequacy.

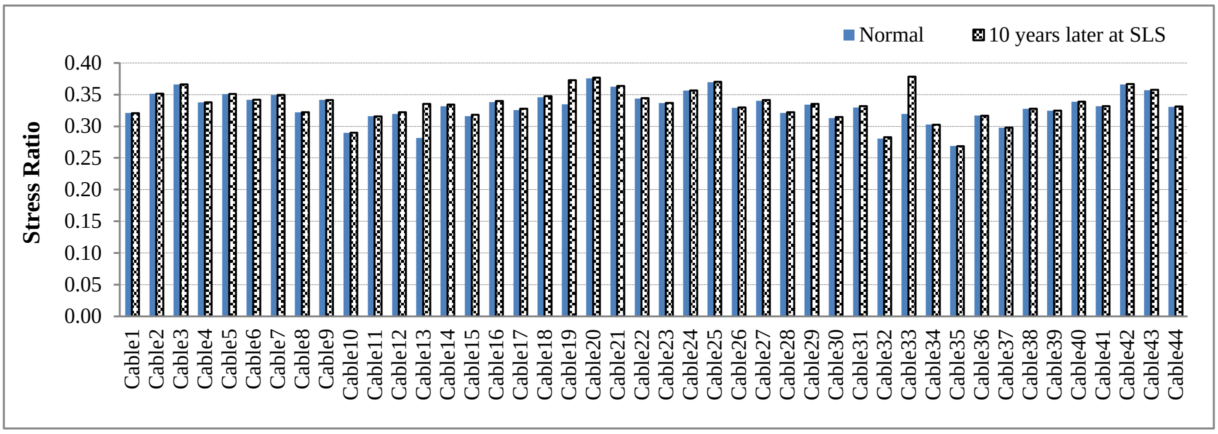

Figure 19. Comparison of cable stress ratio change on upstream side after 10 years later

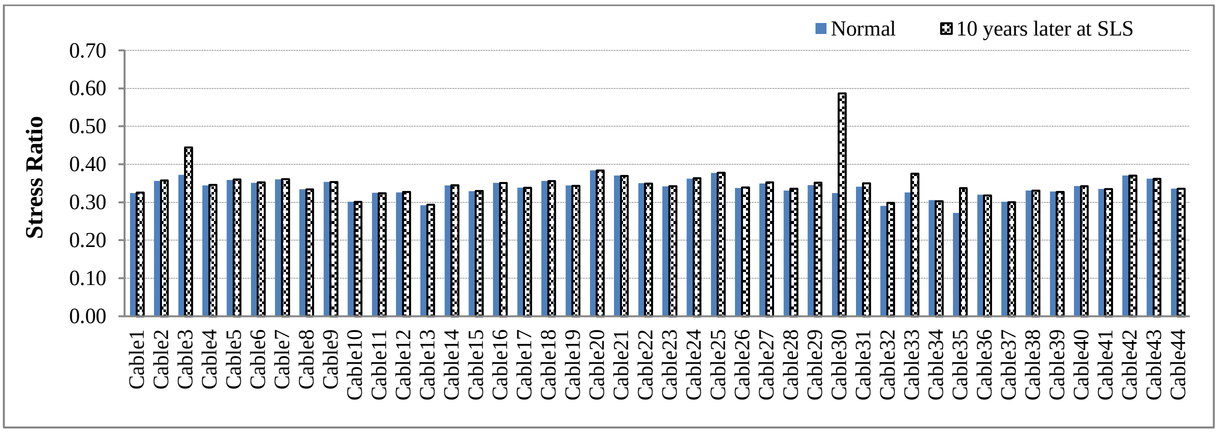

Figure 20. Comparison of cable stress ratio change on downstream side after 10 years later

For the case after 10 years later, the stress in the most cables are below the 45% of ultimate strength with the exception of the cable30D/S which has the 59% ultimate strength and the cable3D/S which reaches the stress limit of SLS.

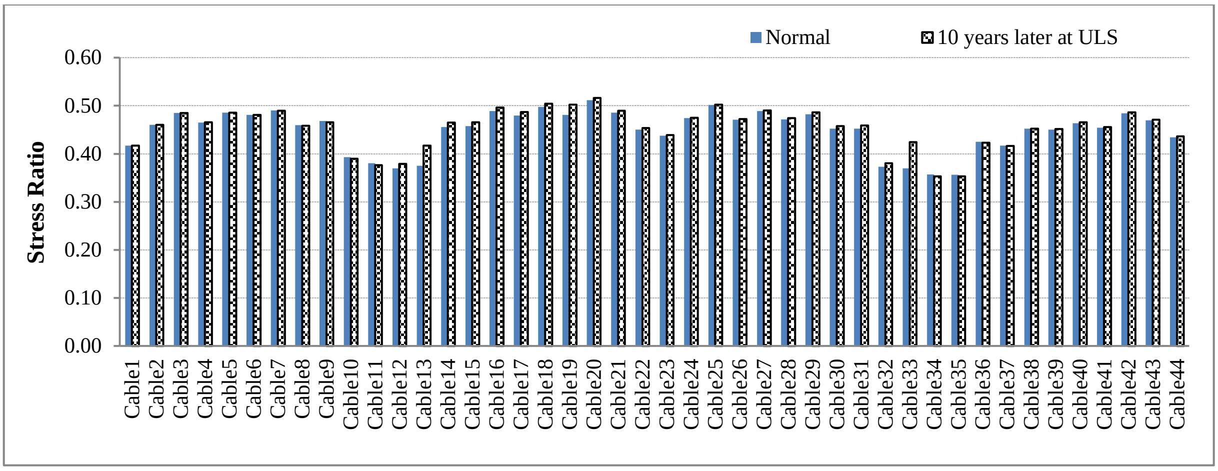

Figure 21. Comparison of cable stress ratio change on upstream side after 10 years later

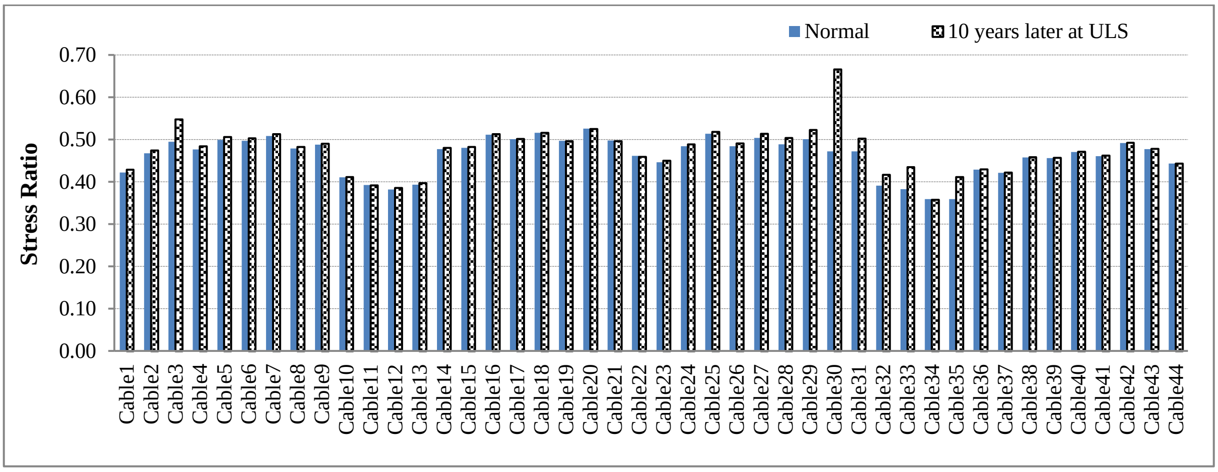

Figure 22. Comparison of cable stress ratio change on downstream side after 10 years later

At ULS, the cable3D/S is however still well below the stress limit of 67% UTS, the stress in the cable30D/S increases to the stress limit of ULS. The applied stress in the cable30D/S significantly exceeds the stress limit of ULS, it causes the critical condition to failure the cable. The analysis and result found that if the tension force in the cable30D/S continues to decline as excepted, the cable (cable30D/S) is critical than any other cables and no longer used, and a timely action is necessary. The cable is needed more attention during cable tension's inspection. It is required to check the sufficiency of the bridge with the other decreasing force cables under one cable loss condition. The cable loss effect on the structure with the other decreasing force cables is analyzed with the cable30D/S released and the stress ratio change comparisons for SLS and ULS are shown in Figure 23 to 26.

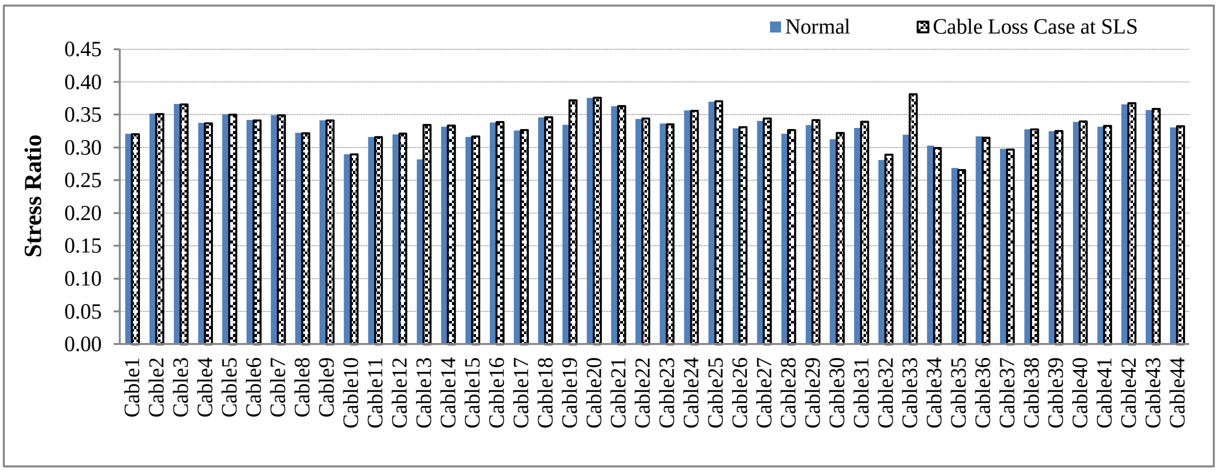

Figure 23. Comparison of cable stress ratio change on upstream side

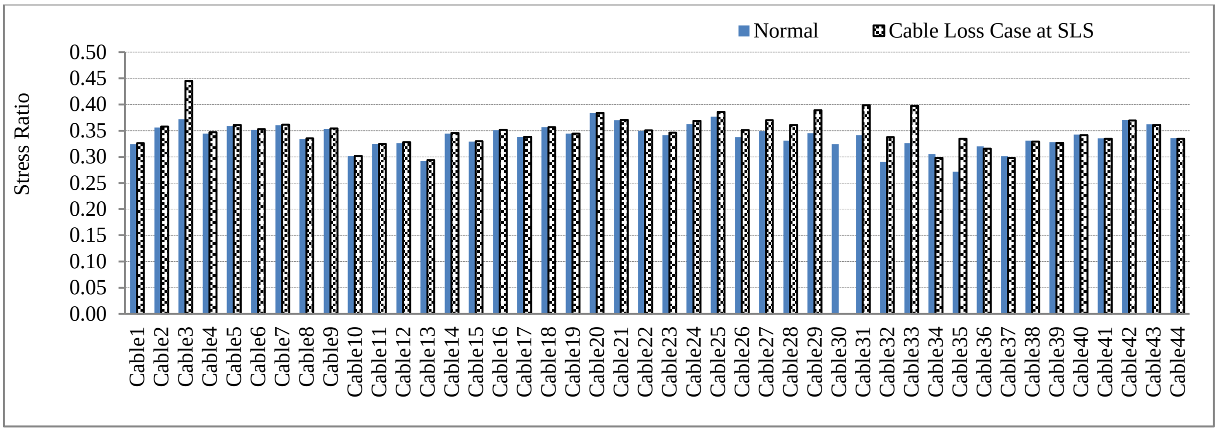

Figure 24. Comparison of cable stress ratio change on downstream side

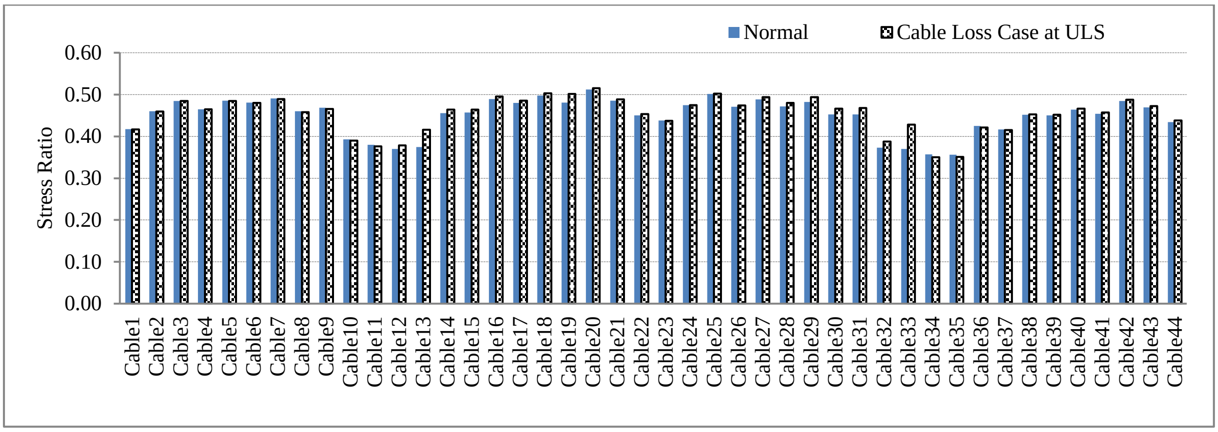

Figure 25. Comparison of cable stress ratio change on upstream side

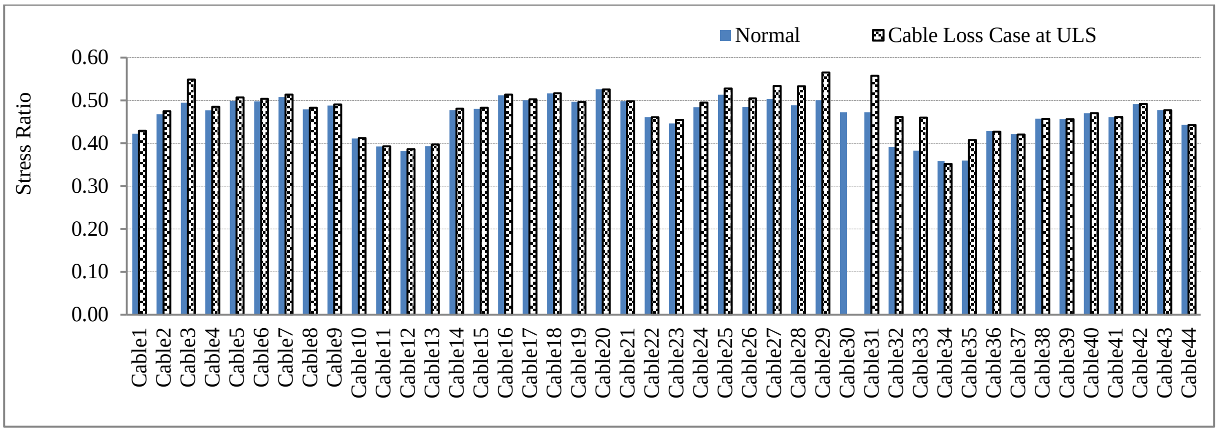

Figure 26. Comparison of cable stress ratio change on downstream side

The cable loss leads to the redistribution of load to adjacent cable. From the above mention figures 23 to 26, at SLS, all cables have the stresses below limit stress with the exception of the cable3D/S which reach to the stress limit. It is found that the increases in stresses are more obvious in the cables near the cables loss location.

At ULS, no cable exceeds the stress limit. Although cable3D/S reach the stress limit of SLS, the cable well remains below the stress limit of ULS. For one cable loss case, the cable3D/S is critical than the other cables. Moreover, the current visual inspection on the cable3D/S observes the slowing increasing rate of radial crack of the sheathing.

5.2. Cable Force Change Effect on Deck Response

The deflection of both side of the deck under the effect of the cable force changes (current condition), successive decreasing cable forces in the above expressed seven cables (after 10 years later) and one cable loss are analyzed and are expressed in the following Figures 27 to 32 to easily investigate the effect of cable force change on deck deflection change.

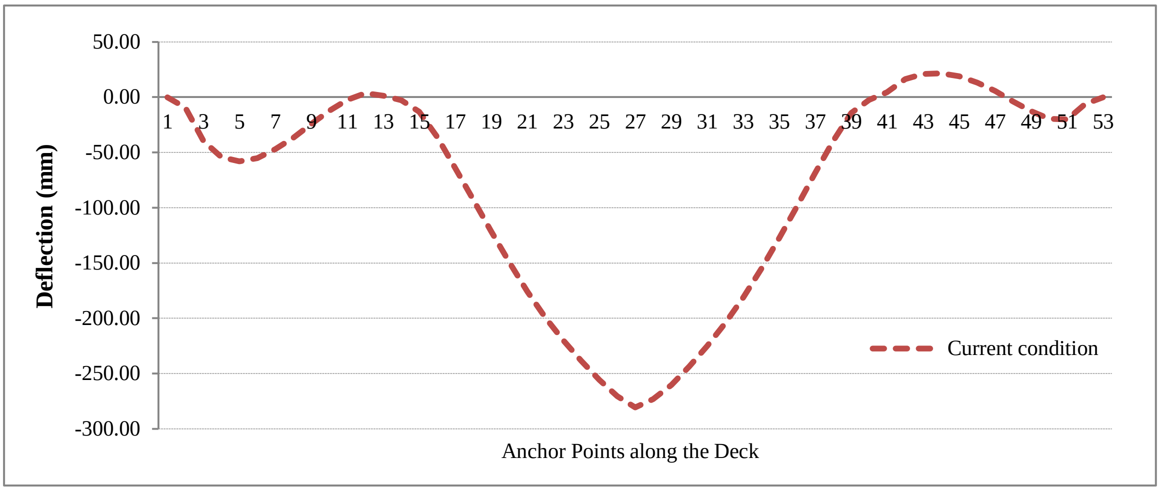

Figure 27. Deflection on upstream side along the deck

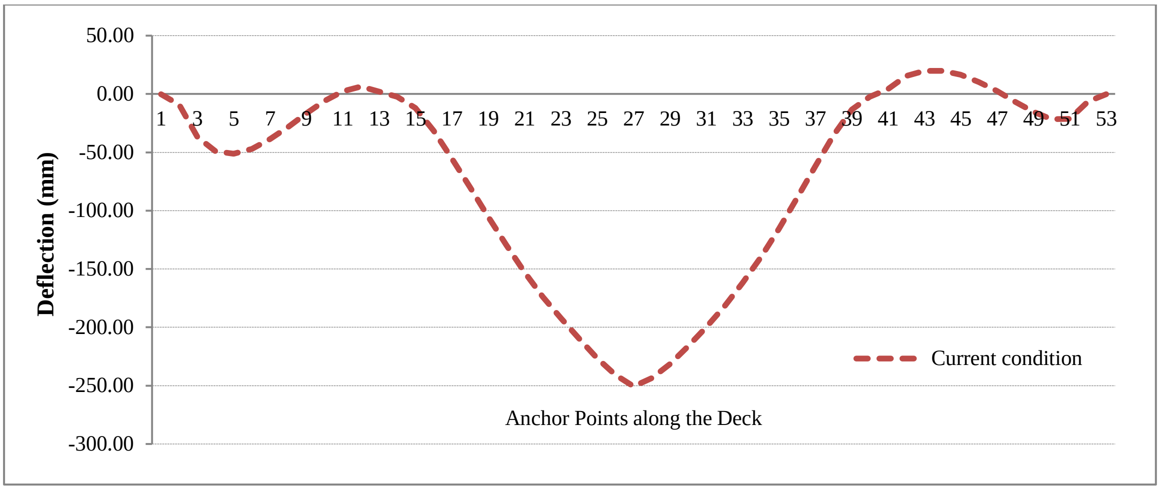

Figure 28. Deflection on downstream side along the deck

In the current condition, the deck deformed symmetrically in upstream side and downstream side, and the maximum deflection happened in the middle of the deck. In both U/S and D/S, there are no significant deflection changes on the anchorage points along the deck.

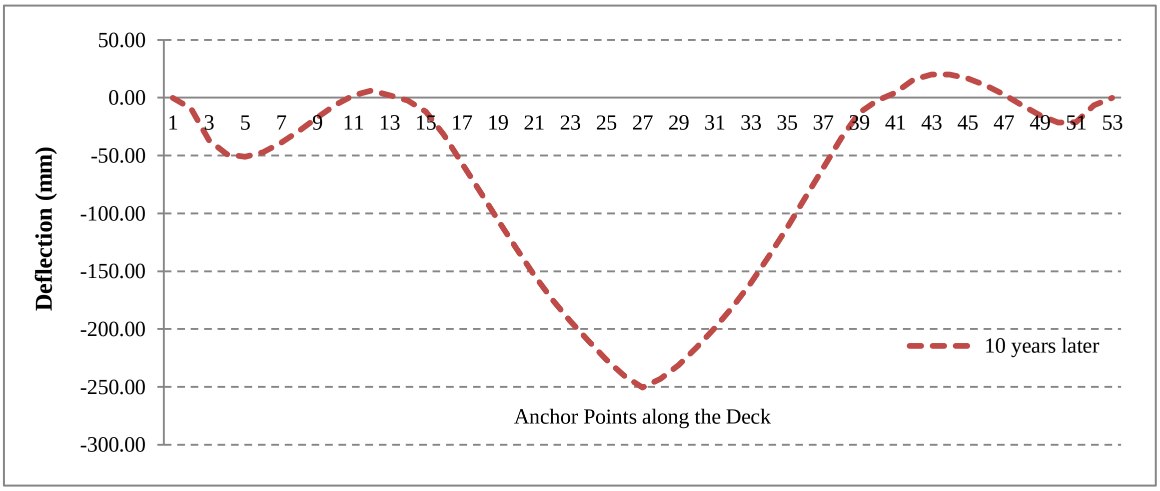

Figure 29. Deflection on upstream side along the deck

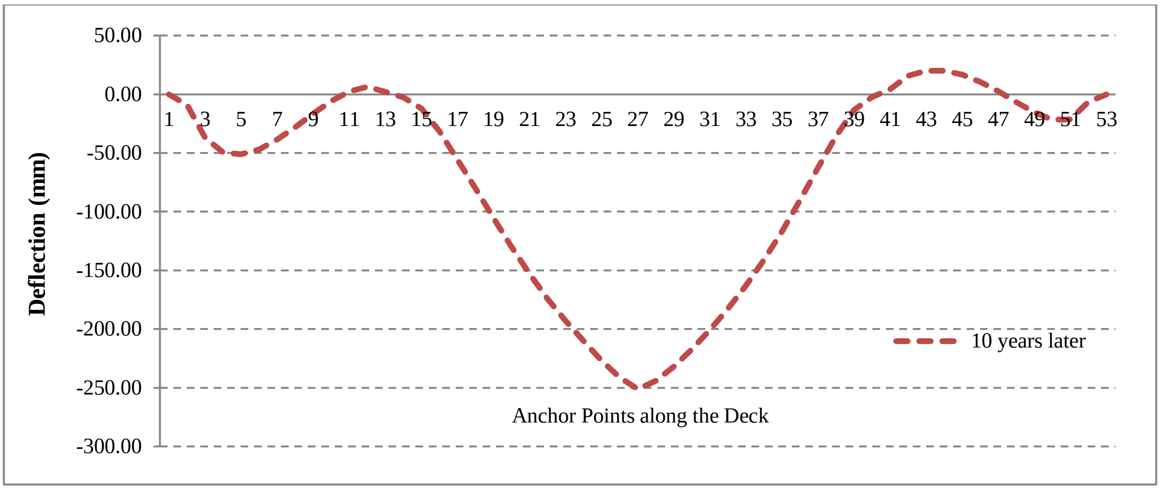

Figure 30. Deflection on downstream side along the deck

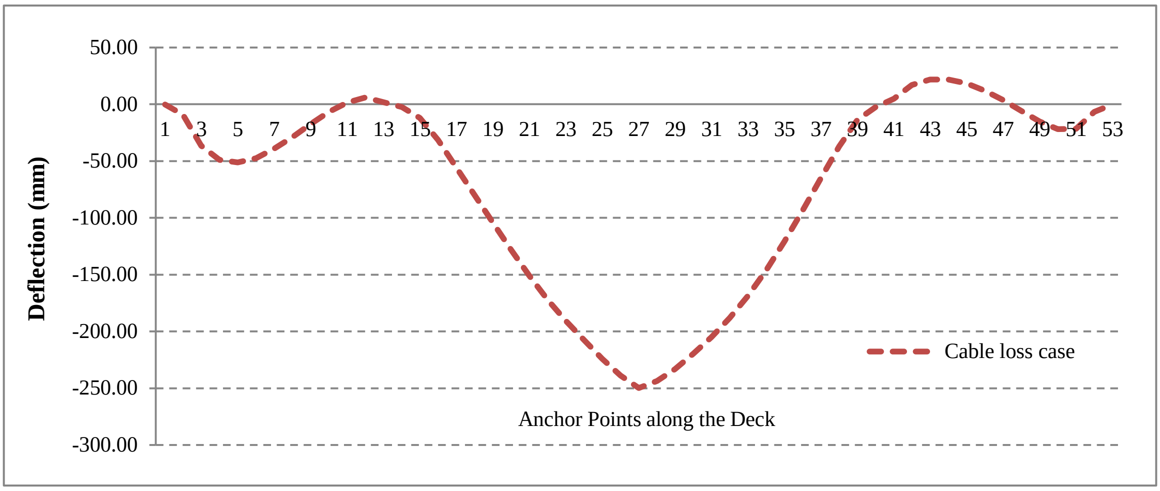

Figure 31. Deflection on upstream side along the deck

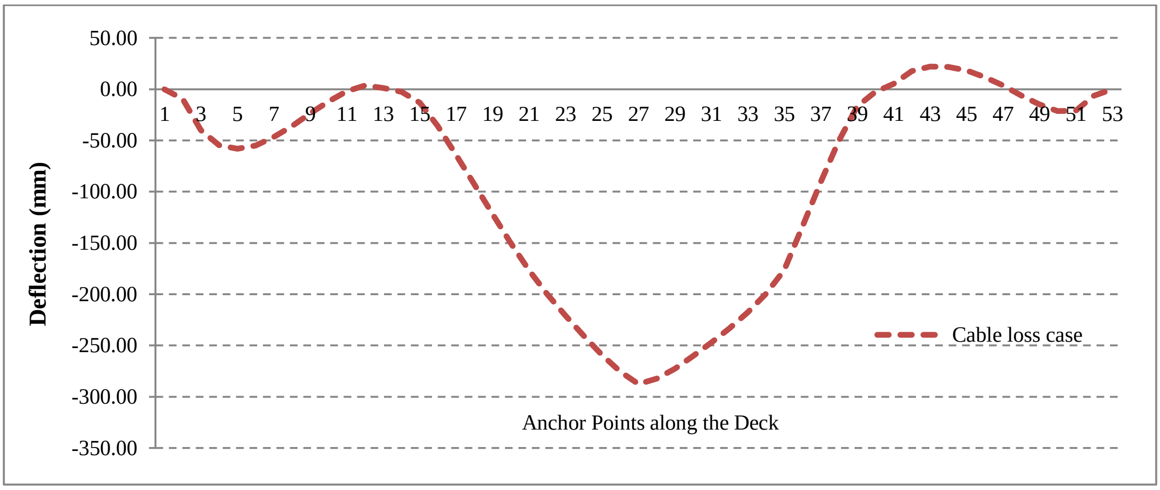

Figure 32. Deflection on downstream side along the deck

From the above figures, as for the cable loss case, in which one cable loss is located on the main span of downstream side, the deflection configuration on downstream side is slightly changed. The deformation of the deck in upstream side does not significantly change and is similar to the deflection shape under current condition. In the current condition, the significant deck deflection change is not encountered. In the case of 10 years later, the deck deflection changes are only occurred around the cable30 at downstream site. In the cable30D/S failure event, the deck responses are found to be still within the allowable limit although the deck deflection changes are significant at the anchorage point of failure cable.

6. Conclusion

The visual inspections observe that the radial cracks and longitudinal cracks are formed on the sheathing of the cables (cable3, cabe30, cable33D/S). These cracks still exist and more cracks increase with time. The cable tension's inspection results show that the 8% of all cables (cable13, cable19, cable33U/S & cable3, cabe30, cable33, cable35D/S) are abnormal cable force changes in the current condition. The relative error percentage of tension force in the seven cables exceeds 10% over 18 years. In order to focus on the successive decreasing cable force change effects, the pace of force change in the cables with time are determined by using regression analysis based on measured cable forces from 2000 to 2018. The study investigates the stress changes in the cables of the bridge due to abnormal cable force variations in the 8% of all cables. In the current condition, the stress ratios in the almost cables with the exception of Cable30D/S are within the allowable limit of SLS. However, the stress still meets the expressed limit state at ULS. It is needed to monitor annually on the tension force of the cable30D/S. Moreover, if it takes corresponding project adjustment and structure adjustment measures, the cable30D/S should pay more attention than other cables. In the case after 10 years later, the SLS stress in the most cables are below the 45% of ultimate strength with the exception of the cable30D/S which has the 59% ultimate strength and the cable3D/S which reaches the stress limit of SLS.

The analysis and result found that if the tension force in the cable30D/S continues to decline as excepted, the cable (cable30D/S) is critical than any other cables and no longer used, and a timely action is necessary. The cable is needed more attention during cable tension's inspection. As the result of loss of the cable30D/S, increases the adjacent cables by 20% of cable stress at ULS because the stress in the loss cable redistribute to the other remaining cables. It is also observed that the initiation of failure condition can start in the cable3D/S as the cable reaches to the stress limit of SLS. Under the effect of the cable force changes (current condition), successive decreasing cable force (after 10 years later) and one cable loss, deflection condition and shape for both deck are also analyzed and investigated. In the current condition, the significant deck deflection change is not encountered. In the case after 10 years later, the deck deflection changes are only occurred around the cable30 at downstream site. In the cable30D/S failure event, the deck responses are found to be still within the allowable limit although the deck deflection changes are significant at the anchorage point of failure cable. In this study, the abnormal cable force variations in 8% of all cables does not suffer the significant effect on the response of the bridge. In the one cable loss case, the cable3D/S is more critical than the other force variation cables. In all cases of study, as the deck deflections are still within the allowable limit, the adequacy of the bridge is still at sufficient level.

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8. Conflicts of Interest

The authors declare no conflict of interest.

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