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ANALYSIS OF CABLE STAYED BRIDGE UNDER CABLE LOSS

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ABSTRACT: In the recent years cable stayed bridges have received more attention than any other bridge. The Bandra-Worli Sea link, Vidyasagar Setu, Atal Setu are the best example of cable stayed bridge in India. In this paper, study of the cable stayed bridge under cable loss is done. The failure of cable may be one of the accidental or eventually event, which must be considered during cable stayed bridge design. The cables in a cable stayed bridge are exposed to corrosion, abrasion and fatigue processes which may cause a reduction in their section and a decrease in their resistance capacity. The cable stayed bridge is modelled with proper technique in SAP2000. The cable-stayed bridge is studied with the help of static, moving load (IRC: 6-2014) and earthquake analysis. The static and dynamic response of the cable stayed bridge under moving loads subjected to corrosion is studied and also considered cable loss due to excessive corrosion. The structural response to the sudden loss of cable is determined by considering the linear static analysis with dynamic amplification factor 2. Then a Parametric Study has been carried out by varying the cable layout of the bridge (Mixed type and Fan type) .The cable forces and nodal vertical displacements before and after the loss of cable is investigated and compared. The analysis results show that cable loss leads to the redistribution of load to adjacent cable. The effect is significant when the cable loss is in middle or far to pylon as compared to loss of the cable near to pylon.

KEYWORDS: Cable Force; Cable Loss; Cable Stayed Bridges; Corrosion; Dynamic Amplification Factor.

1 INTRODUCTION

Man has achieved a lot in the Structural Engineering as it is most evident in the World's largest bridge spans, tallest structures etc. In the recent years cable stayed bridges have received more attention than any other bridge mainly, because of their aesthetic appeal, ease of erection and effective as well as efficient utilization of construction material. Today the Atal Setu(2015) in Jammu and Kashmir is finest example for a revolution in cable stayed bridges due to the introduction of high strength cable and better construction techniques and analyzing tools readily available.

In cable-stayed bridges, damage or failure of primary structural components such a pylon, deck or cables, caused by accidental or eventually event can lead to the collapse of the entire bridge [16]. In cable stayed bridge the cables are inherently susceptible to corrosion damages [4]. The sudden loss of cables becomes unsafe. The D.A.F. smaller than 2.0 in cables near vicinity of ruptured cable [1] [10]. The reduction of the ultimate load increases with the Corrosion level [10]. The actual tensile strength doesn't decrease with the corrosion in galvanized wire [11].The loss of cables must be considered as a possible local failure since the cross sections of cables have usually a low resistance against accidental lateral loads stemming from vehicle impact or malicious actions. The loss of cables can lead to overloading and rupture of adjacent cables [6][12]. The cable connected to the mid span is found out to be the most critical cable [7].

The objective of the current study is to present the effect of corrosion on mixed and fan type cable stayed bridge and loss of cable due to increasing corrosion as well as sudden cable loss. By introducing Lemaitre's equivalent strain principle and geometrical damage theory, the corrosion mechanism of the cable is formulated. As per PTI guidelines the linear static analysis is performed considering D.A.F. 2.

2 CORROSION MECHANISM

"Indian economy suffers a loss of around Rs.375, 000 crore annually due to corrosion"- IANS, Chennai

There are two facts for studying corrosion is safety and economy. The bridge failure due to corrosion can result in life loss. Corrosion is degradation or destruction of metal. The term corrosion is defined as the conversion of metals by natural agencies into various compounds.

Consider mechanisms of cable corrosion deterioration result in the reduction in cable cross sectional area.

Effective area after corrosion $\bar{A} = A_0 - A^*$ (I)

Where A_0 = Cross sectional area of the stay cable in perfect state
A^* = Impaired area due to cable corrosion

The corresponding corrosion ratio $\overline{D} = \frac{A^*}{A_0} = \frac{A_0 - \overline{A}}{A_0}$ (II)

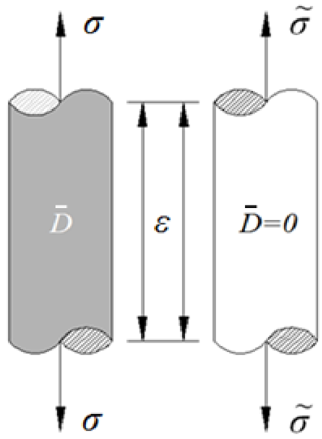

Figure 1. Equivalent Strain for corroded cable

As stay cable can only be loaded by tension, the normal stress of cable in perfect state and in corrosion state may be defined as:

$$T=\sigma A_0 = \sigma \bar{A} \tag{III}$$

Applying the Lemaitre's equivalent strain principle [8], it can be taken for granted that corrosion cable subjected to σ is equivalent to perfect cable subjected to effective stress *σ* on condition that the corresponding strains ε are the same.

$$\varepsilon = \frac{\sigma}{\bar{E}} = \frac{\sigma}{E} \tag{IV}$$

The effective modulus of elasticity Ē for corrosion cable can be arrived by:

$$\bar{E} = \frac{\bar{A}}{A_0} xE \tag{V}$$

The corrosion characteristic of stay cable has been taken into consideration by the modulus of elasticity, which has developed a convenient way in engineering to describe the actual cable state of existing cable structures [4].

3 SUDDEN CABLE LOSS

The collapse mechanism of the cable stayed bridge is called "zipper-type collapse", in which the first stay snapped due excessive accidental event or loading [14] [15]. Accordingly guideline, such as PTI (2005), recommends considering cable loss scenarios during design phase. Thus, in present study, the effect of sudden loss of critical cable is studied and analyzed statically and dynamically. The sudden loss of cable is required at a time given by the PTI (2005) recommendations. The cause of element failure is not considered in the current recommendations.

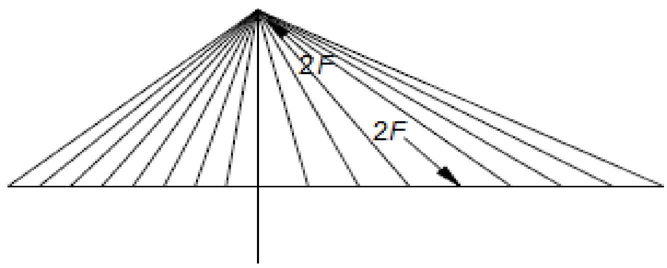

Figure 2. Load direction for analysis

For the analysis, the force from loss cable is applied to anchorage joints in the negative direction, as shown in Figure 2. Note that implicit to this assumption is an abrupt cable loss, then the results of the structure under dead and live loads could be superimposed with the load case of −2F.

4 DESCRIPTION OF STUDY

The cable stayed bridge is studied using the commercially available computer program SAP2000. The schematic diagram of cable stayed bridge is shown in Figure 3.

An 'H' shaped pylon is considered with two planes of mixed type as well as fan type cable layout. The central span is 220.0 m, with two side spans of 110.0 m. Therefore, the total length of the bridge is 440.0 m. The steel girder is supported by two planes of cables from 'H' shaped pylon in a mixed type and fan type arrangement, where total eighty cables support the whole bridge. The bridge has a width of 15.6m. Two main longitudinal steel girders are located at the outer edge of the deck. These girders are interconnected by a cross beam-girder. The pylons consist of two concrete legs, interconnected with a cross beam-pylon.

The cables are made of steel with the following cable property: Modulus of elasticity: 1.9 x 10^8 kN/m^2, Specific weight: 78.5kN/m^3, Area cable =0.003m^2, the ultimate tensile strength=1750N/mm^2.The pylon is made of concrete. The pylon property are assumed as: Modulus of elasticity=2.74 x 10^7kN/m^2, Specific weight: 25kN/m^3, Area =9.2m^2, Cross beam-Pylon: Area =7.2m^2.The girders are composed of steel with following Girder property: Modulus of elasticity=2.0 x 10^8kN/m^2, Specific weight: 78.5kN/m^3, Area =0.3092m^2, Cross beam-Girder: Area =0.049m^2.

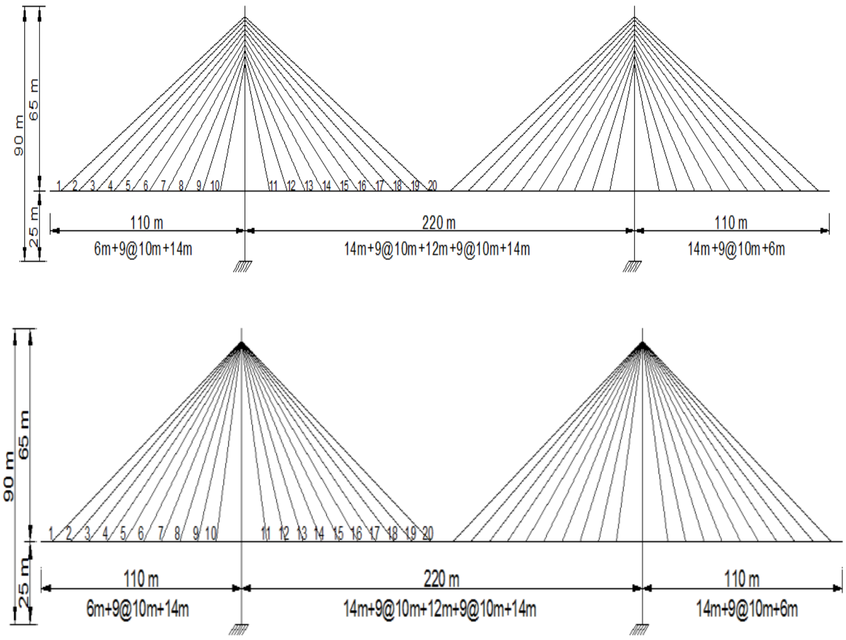

Figure 3. General layout of bridge

With modern commercial finite element programs it is possible to accurately predict both static and dynamic structural behavior of cable-stayed bridges .The finite element three dimensional model of the cable stayed bridge in the global coordinate system shown in Figure 4. The pylon and girders are modeled with frame element. The connection between girder and pylon is rigid, while the pylon base is fixed. Each cable consists of a tension only truss element, and is connected with pins at the pylon and the girder.
In this study, the cable stayed bridge is evaluated under the effect of Dead load (Self weight), Initial prestressing cable force, and Live load (Moving load).The following combination are used when evaluating cable loss.

- Load combination=1.0DL+1.0SDL+1.0PS+1.0LL
- Load combination=1.0DL+1.0SDL+1.0PS+0.75LL
- Load combination=1.1DL+1.1SDL+1.1PS+0.75LL+1.1CL(Sudden Loss)

During the study, moving loads on cable-stayed bridges are taken as per IRC-6:2014 guidelines. The deck is divided in four lanes according to IRC-6:2014 norms.

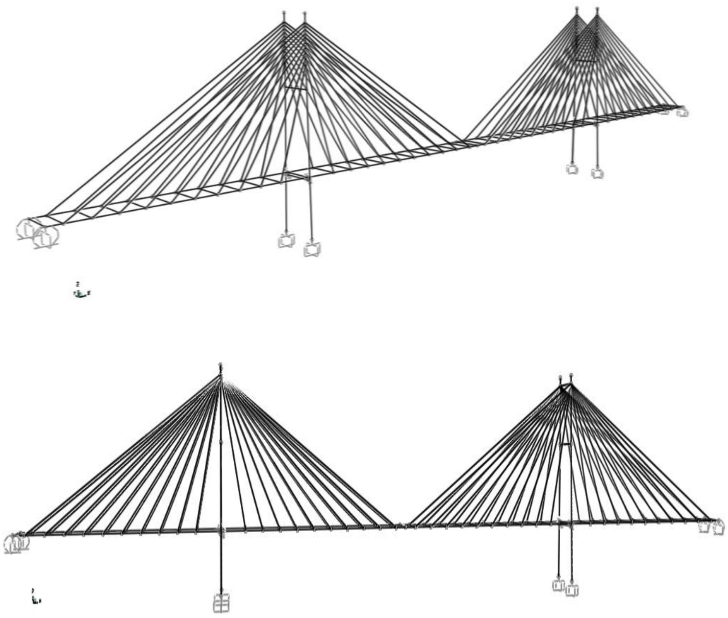

Figure 4. Three dimensional model of the cable stayed bridge in SAP2000

5 ANALYSIS RESULTS

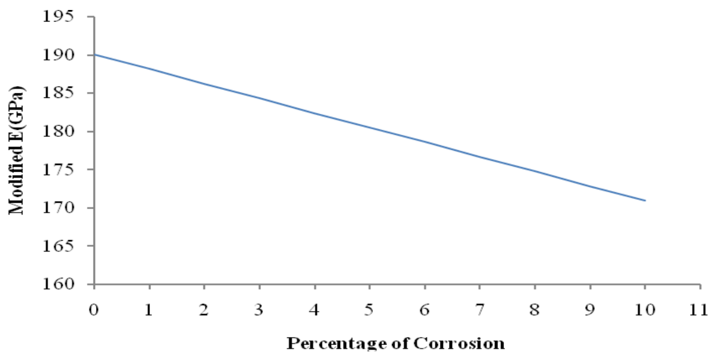

Figure 5. Graphical representation of modified modulus of elasticity

The modified modulus of elasticity calculated as per art.4.1. The Figure 5 shows the variation of the modified Young's Modulus with increase in percentage of corrosion. The Modified Young's Modulus decreases with increase in percentage of corrosion.

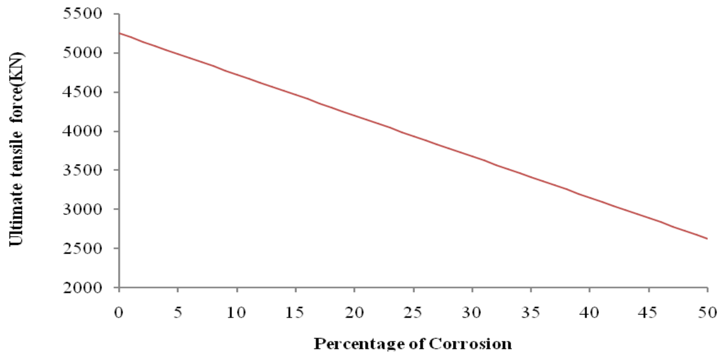

Figure 6. Graphical representation of ultimate tensile force

The variation in the ultimate tensile force of the cable for different percentage of corrosion is shown in Figure 6.The reduction in cross section area due to corrosion reduces the tensile strength of the cable. Hence the axial resisting force of cable reduces.

Analysis of cable stayed bridge has been done for mixed type and fan type arrangement and result in the form of axial force and displacement have been plotted.

In addition to that axial forces and displacement of anchorage point for cable loss condition due to excessive corrosion and sudden failure have been calculated for the same. In case of cable loss, cables on left side of pylon (i.e. cable 1, 2, 5, 9, 10) and cables on right side of pylon (i.e. cable 11, 12, 15, 19, 20) have been considered.

5.1 Case-1: Mixed type cable stayed bridge

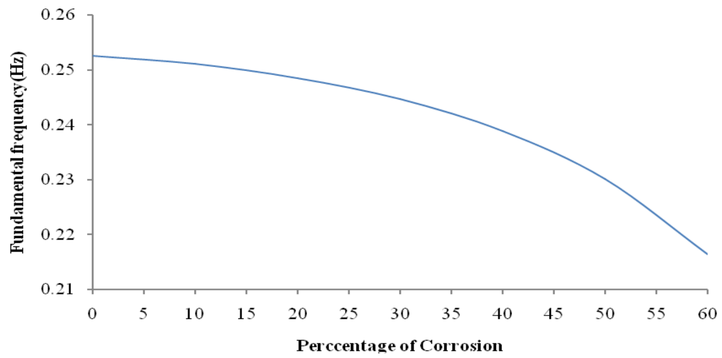

Figure 7. Graphical representation of fundamental frequency

The fundamental frequency is calculated for different percentage of corrosion.

The graphical representation of the results is shown in Figure 7.

There is a gradual decrease in frequency as the corrosion increases. The variation of the frequency is from 0.253 Hz to 0.216 Hz for 0% to 60% corrosion respectively.

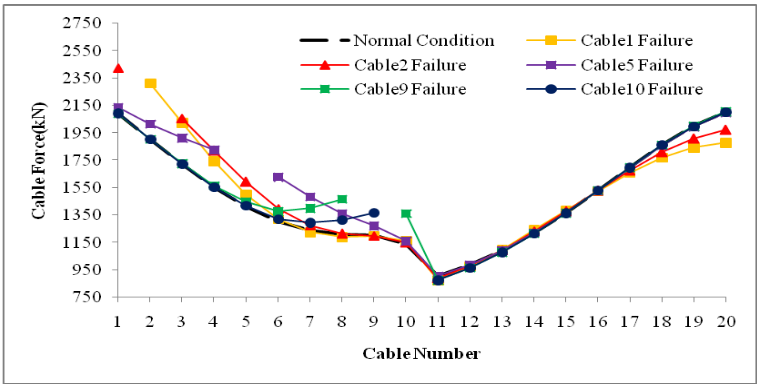

Figure 8. Axial force representation in mixed type cable stayed bridge considering cable failure due to excessive corrosion on LEFT side of pylon

Figure 8 shows that Cable1 and Cable2 which are on left side, away from pylon failed at 61% and 64% corrosion resulting in increase of axial force of adjacent cables by 22% and 19% respectively in mixed type cable stayed bridge.

The Cable5 in middle location on left side of pylon lost its strength at 74% corrosion resulting in increase of axial force of adjacent cables by 25%.

In case of the Cable9 and Cable10 which are on left side, nearer to pylon failed at 78% and 79% corrosion resulting in increase of axial force of adjacent cables by 21% and 14% respectively in mixed type cable stayed bridge.

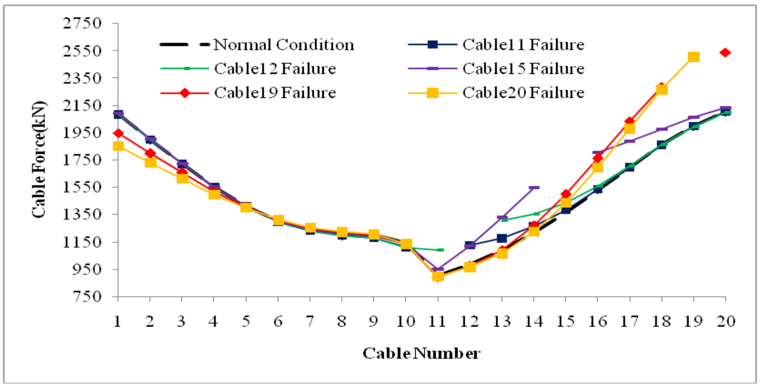

Figure 9. Axial force representation in mixed type cable stayed bridge considering cable failure due to excessive corrosion on RIGHT side of pylon

In case of the Cable11 and Cable12 which are on right side, nearer to pylon failed at 83% and 82% corrosion resulting in increase of axial force of adjacent cables by 14% and 21% respectively in mixed type cable stayed bridge.

The Cable15 in middle location on right side of pylon lost its strength at 74% corrosion resulting in increase of axial force of adjacent cables by 27%.The Cable19 and Cable20 which are on right side, away from pylon failed at 62% and 60% corrosion resulting in increase of axial force of adjacent cables by 23% and 25% respectively in mixed type cable stayed bridge.

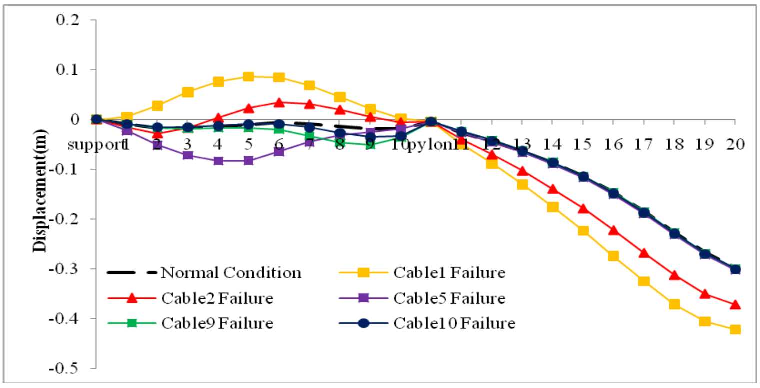

Figure 10. Displacement representation in mixed type cable stayed bridge considering cable failure due to excessive corrosion on LEFT side of pylon

The maximum displacement 422mm is found in mid span due to Cable1 which is on left side, away from pylon. The displacement is minor when the cables failed nearer to pylon.

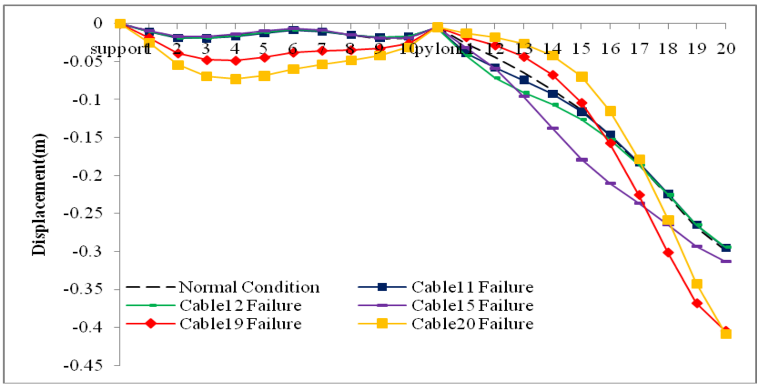

Figure 11. Displacement representation in mixed type cable stayed bridge considering cable failure due to excessive corrosion on RIGHT side of pylon

While the maximum displacement is 408mm at Cable20.The cables away from pylon having several effects.

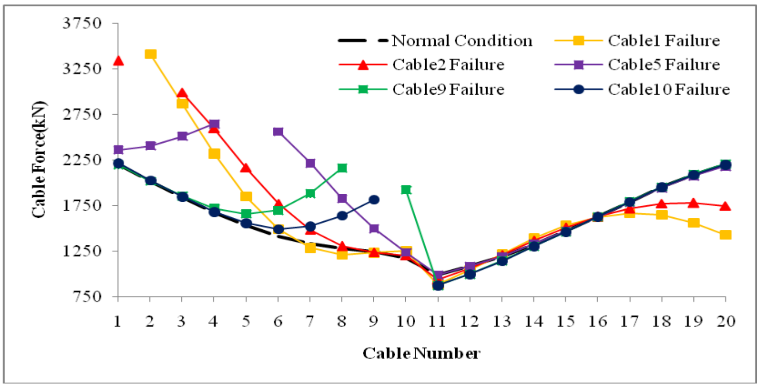

Figure 12. Axial force representation in mixed type cable stayed bridge considering sudden cable failure on LEFT side of pylon

From Figure 12, due to sudden loss of Cable1 and Cable2, the cable forces near the vicinity of rupture cable increase by 69% and 62% respectively. In case of sudden loss of Cable5 which is in middle location on left side of pylon, the axial forces of cables which are near to the cable loss increase drastically by 81%. While the sudden loss of Cable9 and Cable10 the cable forces increase by 69% and 46% respectively in mixed type cable stayed bridge.

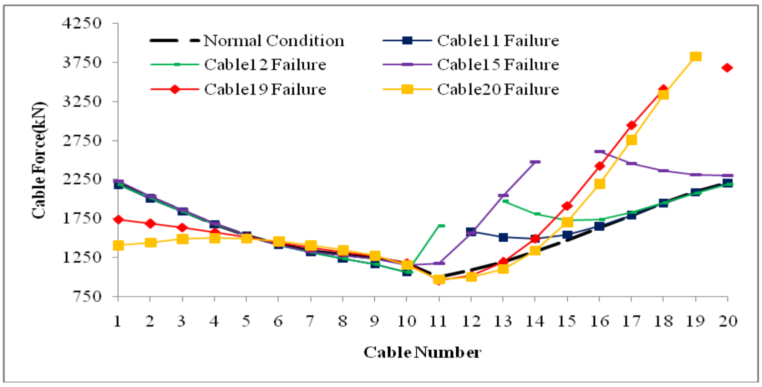

Figure 13. Axial force representation in mixed type cable stayed bridge considering sudden cable failure on RIGHT side of pylon

In Figure 13, the sudden loss of Cable11 and Cable12 the cable forces increase by 45% and 67% respectively in mixed type cable stayed bridge. In case of sudden loss of Cable15 which is in middle location on right side of pylon, the axial forces of cables which are near to the cable loss increase drastically by 86%.

While sudden loss of Cable19 and Cable20, the cable forces near the vicinity of rupture cable increase by 74% and 83% respectively.

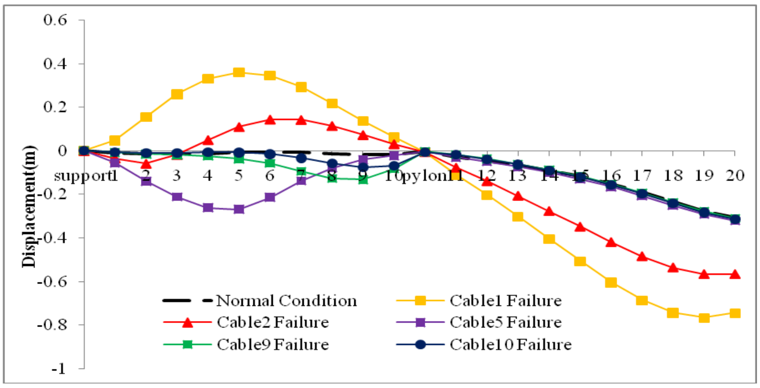

Figure 14. Displacement representation in mixed type cable stayed bridge considering sudden cable failure on LEFT side of pylon

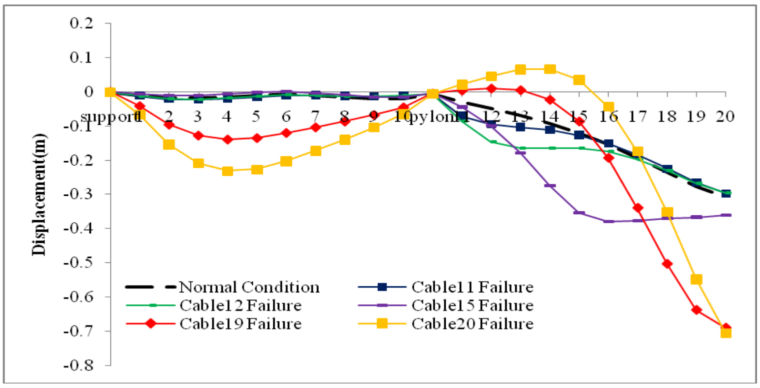

Figure 15. Displacement representation in mixed type cable stayed bridge considering sudden cable failure on LEFT side of pylon

The maximum displacement is as much as 766mm due to sudden cable loss in mixed type cable stayed bridge. Due to sudden cable loss, the adjacent anchorage points deform which increase the cable forces near the vicinity of rupture cable.

Here a linear dynamic time-history analysis is done. The spectrum compatible time history has been taken.

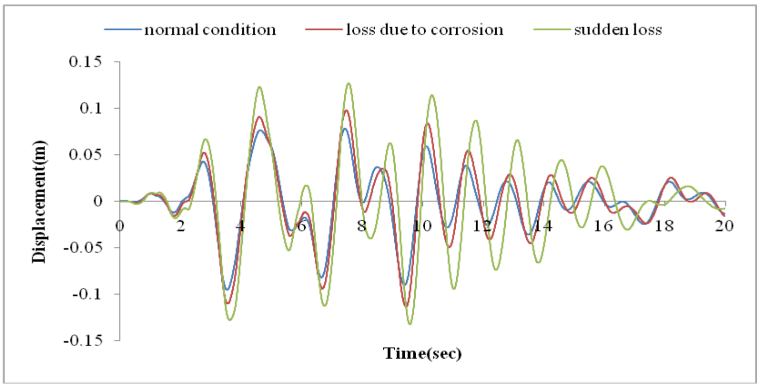

Figure 16. Displacement at Cable15 in mixed type arrangement using spectrum compatible time history

There is increase in maximum displacement due to loss of cable.

5.2 Case-2: Fan type cable stayed bridge

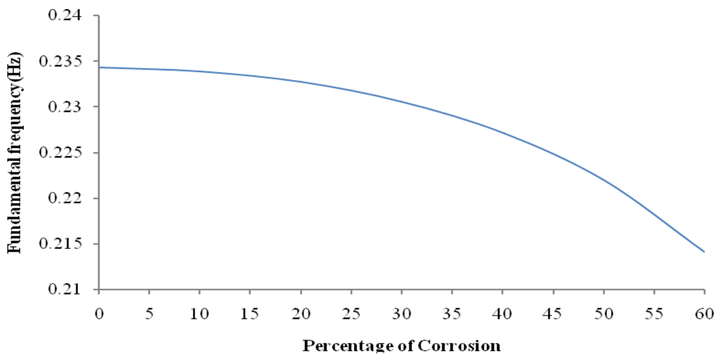

Figure 17. Graphical representation of fundamental frequency

The fundamental frequency is calculated for different percentage of corrosion. The graphical representation of the results is shown in Figure 17.

There is a gradual decrease in frequency as the corrosion increases. The variation of the frequency is from 0.234 Hz to 0.214 Hz for 0% to 60% corrosion respectively.

Figure 18 shows that Cable1 and Cable2 which are on left side, away from pylon failed at 61% and 65% corrosion resulting in increase of axial force of adjacent cables by 21% and 20% respectively in fan type cable stayed bridge.
The Cable5 in middle location on left side of pylon lost its strength at 75% corrosion resulting in increase of axial force of adjacent cables by 26%.

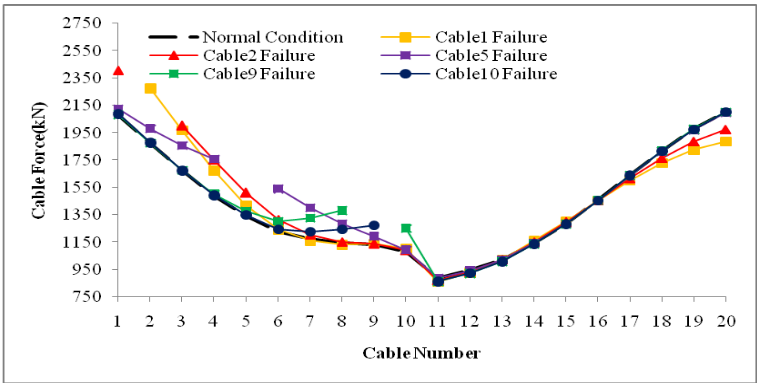

Figure 18. Axial force representation in fan type cable stayed bridge considering cable failure due to excessive corrosion on LEFT side of pylon

In case of the Cable9 and Cable10 which are on left side, nearer to pylon failed at 79% and 80% corrosion resulting in increase of axial force of adjacent cables by 21% and 12% respectively in fan type cable stayed bridge.

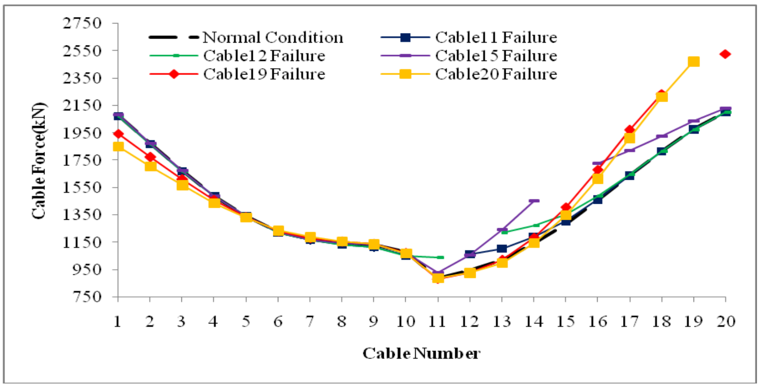

Figure 19. Axial force representation in fan type cable stayed bridge considering cable failure due to excessive corrosion on RIGHT side of pylon

In case of the Cable11 and Cable12 which are on right side, nearer to pylon failed at 84% and 83% corrosion resulting in increase of axial force of adjacent cables by 13% and 19% respectively in fan type cable stayed bridge.

The Cable15 in middle location on right side of pylon lost its strength at 76% corrosion resulting in increase of axial force of adjacent cables by 27%.The Cable19 and Cable20 which are on right side, away from pylon failed at 63% and 60% corrosion resulting in increase of axial force of adjacent cables by 23% and 25% respectively in fan type cable stayed bridge.

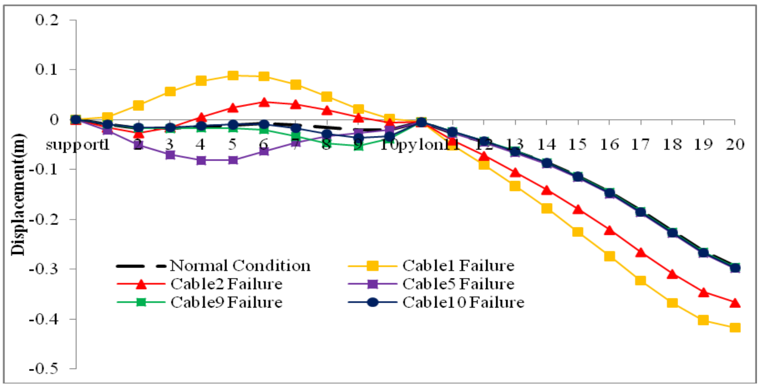

Figure 20. Displacement representation in fan type cable stayed bridge considering cable failure due to excessive corrosion on LEFT side of pylon

The maximum displacement 417mm is found in mid span due to Cable1 which is on left side, away from pylon. The displacement is minor when the cables failed nearer to pylon.

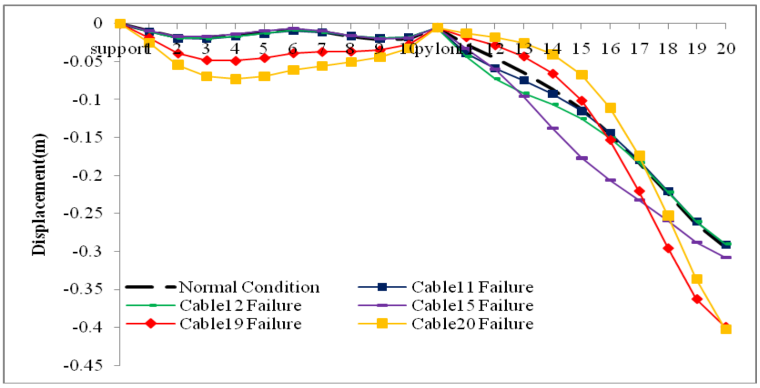

Figure 21. Displacement representation in fan type cable stayed bridge considering cable failure due to excessive corrosion on RIGHT side of pylon

While the maximum displacement is 402mm at Cable20.The cables away from pylon having several effects.

From Figure 22, due to sudden loss of Cable1 and Cable2, the cable forces near the vicinity of rupture cable increase by 69% and 63% respectively. In case of sudden loss of Cable5 which is in middle location on left side of pylon, the axial forces of cables which are near to the cable loss increase drastically by 84%.

While the sudden loss of Cable9 and Cable10 the cable forces increase by 67% and 41% respectively in fan type cable stayed bridge.

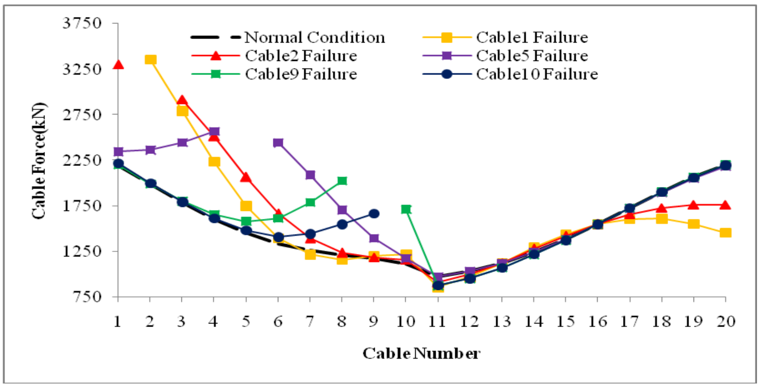

Figure 22. Axial force representation in fan type cable stayed bridge considering sudden cable failure on LEFT side of pylon

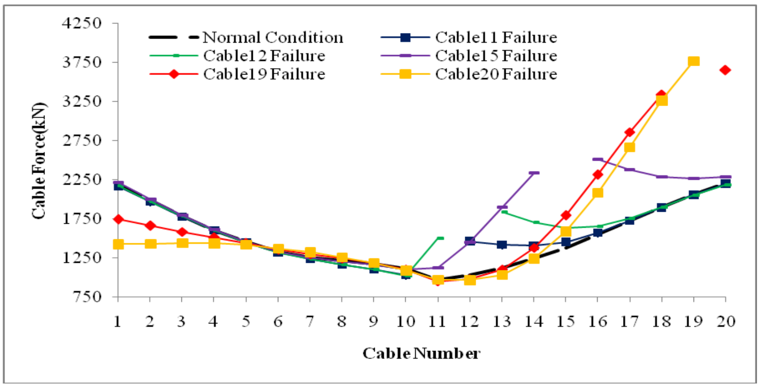

Figure 23. Axial force representation in fan type cable stayed bridge considering sudden cable failure on RIGHT side of pylon

In Figure 23, the sudden loss of Cable11 and Cable12 the cable forces increase by 41% and 64% respectively in fan type cable stayed bridge. In case of sudden loss of Cable15 which is in middle location on right side of pylon, the axial forces of cables which are near to the cable loss increase drastically by 88%. While sudden loss of Cable19 and Cable20, the cable forces near the vicinity of rupture cable increase by 75% and 83% respectively.

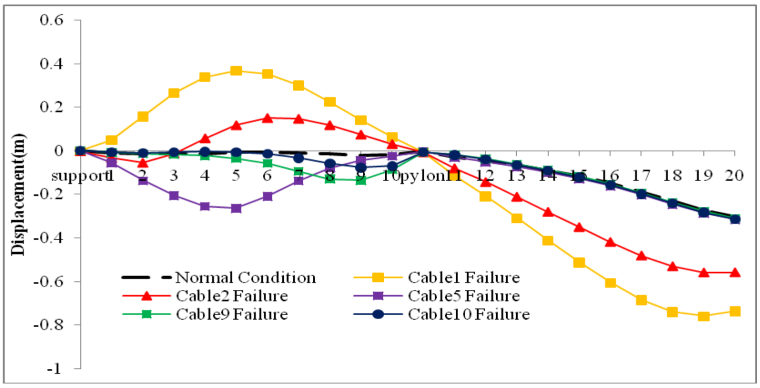

Figure 24. Displacement representation in fan type cable stayed bridge considering sudden cable failure on LEFT side of pylon

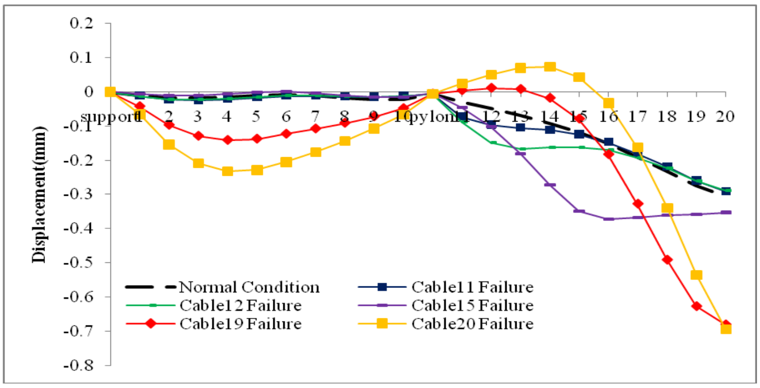

Figure 25. Displacement representation in fan type cable stayed bridge considering sudden cable failure on RIGHT side of pylon

The maximum displacement is as much as 758mm due to sudden cable loss in fan type cable stayed bridge. Due to sudden cable loss, the adjacent anchorage points deform which increase the cable forces near the vicinity of rupture cable

Here a linear dynamic time-history analysis is done. The spectrum compatible time history has been taken.

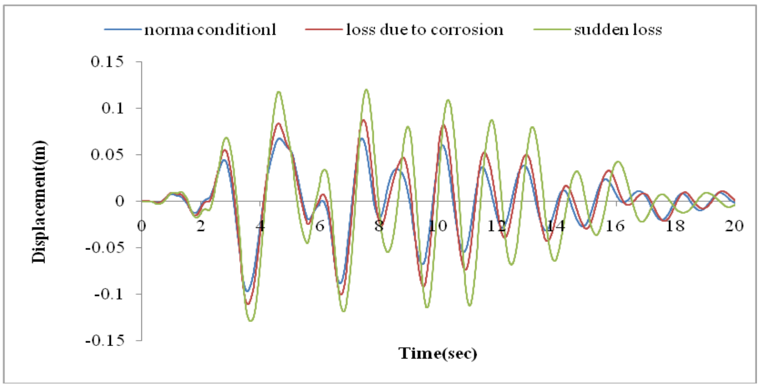

Figure 26. Displacement at Cable15 in fan type arrangement using spectrum compatible time history

There is increase in maximum displacement due to loss of cable.

6 CONCLUSIONS

[1] The cable axial strength decreases with increase in corrosion. Due to corrosion modulus of elasticity decreases, which resulting in reduction of structural stiffness.

[2] The cable forces near the vicinity of ruptured cable increases as much as 27% in case of cable loss due to excessive corrosion. The cable in middle and far away from pylon suffers from extreme effect of cable loss compared to cables nearer to pylon in excessive corrosion.

[3] While the axial forces drastically increase in the adjacent cable as much as 88% in sudden cable loss. When the middle cable abruptly fails, forces also increase significantly in the cables near the vicinity of the ruptured cable.

[4] The displacement of deck is found maximum in mid span as much as 422mm (mixed type) in case of excessive corrosion, while 766mm (mixed type) in sudden loss when the cable fails far away from pylon.

[5] The cables away from pylon are greatly affected by corrosion. Thus, the effective corrosion protection measures should be provided for cable. They should required special attention during design.

[6] Thus, cables in middle of span as well as away from pylon are more critical. The failure of bridge decreases as the location of lost cables near the pylon. The vertical displacement is increased due to cable loss when performing spectrum compatible time history.

REFERENCES

[1] Aoki, Y, Samali, B, Saleh, A and Valipour, H, "Assessment of key response quantities for design of a cable-stayed bridge subjected to sudden loss of cable(s)", Materials to Structures: Advancement through Innovation (Taylor and Francis), CRC Press, 387-392,2013.

[2] Guidelines for the Design of Cable-Stayed Bridges; ASCE, New York, USA, 1992.
[3] Hoang, Kiyomiya and Tongxiang, A, “Experimental study on Impact Force Factor during sudden cable loss in cable-stayed bridges”, Report of the Safety, Robustness and Condition Assessment of Structures (International Association for Bridge and Structural Engineering), Helsinki, 2015.
[4] Huang, J, Wang, R and Tang, L, “UL formulation for corrosion effect on cable state” ,Journal of Highway and Transportation Research and Development, Vol-4(1), 60-64,2009.
[5] IRC: 6, Standard Specifications and Code of Practice for Road Bridges-Section II- Loads and Stresses; Indian Roads Congress, New Delhi, 2014.
[6] Jian-guo, Yi-xiang, Li-ping, Jian and Jin, “Comparison of various procedures for progressive collapse analysis of cable-stayed bridges”,Journal of Zhejiang University-SCIENCE, 13(5), 323-334,2012.
[7] Kao, CS and Kou, CH, “The influence of broken cables on the structural behavior of long-span cable-stayed bridges”, Journal of Marine Science and Technology, Vol.18 (3), 395-404,2010.
[8] Lemaitre J, “Evaluation of dissipation and submitted damage in metals to dynamic loading”, *Proceeding of ICM-1*, Japan, 1971.
[9] Midas Civil 2010, Analysis for Civil Structures, Reference Manual, Japan.
[10] Mozos, CM and Aparicio, AC, “Parametric study on the dynamic response of cable stayed bridges to the sudden failure of a stay, Part II: Bending moment acting on the pylons and stress on the stays” Engineering Structure, 32, 3301-3312,2010.
[11] Nakamura, S and Suzumura, K, “Experimental study on fatigue strength of corroded bridge wires”, Journal of Bridge Engineering (ASCE), 18(3), 200-209,2013.
[12] Rajarshi, Das, Pandey, AD, Soumya, MJ, Saini, P and Anvesh, S, “Effect of dynamic unloading of cables in collapse progression through a cable stayed bridge”, Asian Journal Of Civil Engineering (BHRC), Vol-17(4), 397-416,2016.
[13] Recommendations for Stay Cable Design, Testing and Installation; 5th Edition; Post-Tensioning Institute, Phoenix, USA, 2007.
[14] Starossek, U, “Progressive Collapse of Bridges-Aspects of Analysis and Design”, *Proceedings of the International Symposium on Sea-Crossing Long-Span Bridges*, Mokpo, Korea, 2006.
[15] Wolff, M and Starossek, U, “Cable-loss analyses and collapse behavior of cable-stayed bridges”, *Proceeding of the International Conference on Bridge Maintenance, Safety and Management*, Philadelphia, USA, 2010.
[16] Zoli, TP and Steinhouse, J, “Some considerations in the design of long span bridges against progressive collapse”, 2007. http://www.pwri.go.jp/eng/ujnr/ tc/g/pdf/23/23-2-3zoli.pdf