Dynamic Response of Radial, Fan and Harp Type of Cable Stayed Bridges Due to Moving Load and Earth Quake Load

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***Abstract*— The project focuses on the effects of earthquake and traffic loadings on the dynamic behavior of cable-stayed bridges. Quincy Bay View Bridge, located at Illinois, is considered as a numerical example in this study .Three different types of cable stayed bridges exists, Radial, Harp and Fan. The three different cable stayed bridges vary in their cable arrangement (connection pattern of the cables to their pylon) .The selected model Quincy bay view bridge is constructed using fan arrangement .The same is modelled and analyzed in SAP2000 in all the three arrangements by keeping all the bridge parameters constant (span, pylon height, frame sections dimensions, cable diameter) for all three and these three arrangements are compared. Effects on these three types of arrangements are analyzed when alterations are made in the bridge geometry. Bending moment decreases when cable number is increased , the same is found to increase when pylon height is decreased and when the mid span is increased. For the dynamic analysis of the 3D finite element model of the Bridge, earthquake and traffic loading applications are considered .Traffic loading is taken into account by considering the traffic loading as moving traffic load. Earth quake is applied by response spectrum method. A combined case considering the traffic and earthquake loadings together are also applied to the bridge model. The results show that the structural responses obtained for the Fan and Radial arrangement are almost same but a bit more advantage for the fan arrangement considering the girder bending moments at the supports, bending moments at the mid span is almost same for all the three arrangements .Results show that the support bending moments (20 % more compared to other two) and overall bridge deformation are comparatively high for harp arrangement. Overall comparison shows that fan arrangement stays ahead of the other two. Dynamic effects of earthquake are usually larger than the responses determined for the traffic loading case. Results show that the combined effect of the earthquake and traffic loadings should be considered for the realistic design of cable-stayed bridges.**

Keywords: Response Spectrum; Radial; Fan; Harp; Pylon

I. INTRODUCTION

Cable-stayed bridges have been developing rapidly in recent years, and become one of the most popular types of bridges for long spans length to 1000 m or even longer. The designers realized that cable stayed style requires less material for cables and deck and can be erected much easier than suspension bridges. Despite all the advantages, it has certain disadvantages. Cable- stayed bridges are normally sensitive to dynamic loadings such as earthquakes and moving load.

Cable stayed bridges have attractive appearance and so civil engineers are more interested in cable-stayed bridges and nowadays cable stayed bridges are preferred more than any other bridges for long span. The structural stability of these bridges under service loadings and environmental dynamic loadings are to be investigated. Three different cable stayed bridges are present namely radial, harp and fan. In this paper, three different connection systems including radial, harp and fan of the cable stayed bridges are studied. Three cable-stayed bridges with different cable connection patterns including radial, harp and fan are modeled by structural software SAP2000.

Due to the increasing traffic demand day by day and construction of cable-stayed bridges in earthquake zones, detailed analysis of dynamic behavior of these bridges under earthquake and traffic loads has become very important for realistic design. For the dynamic analysis of the 3D finite element model of the Bridge, earthquake and traffic loading applications are considered**.** Traffic loading is taken into account by considering the traffic loading as moving traffic load. Earth quake is applied by response spectrum method. A combined case considering the traffic and earthquake loadings together are also applied to the bridge model.

Studies conducted in the paper is

i) To analyze the effects of moving load and earth quake on the considered cable stayed bridge and to find the most severe effect

ii) Compare the 3 different types of cable stayed bridge namely Fan , Radial and harp

iii) Study the effect on these three types of bridge when the number of cables is increased, mid span of bridge is varied and when the pylon height is varied

II. CABLE STAYED BRIDGE AND PARTS

A typical cable stayed bridge is a deck with one or two pylons erected above the piers in the middle of the span. The cables are attached diagonally to the girder to provide additional supports or to reduce the depth of the girders used to support the deck slab. The pylons are the main load bearing element in the structure. Transfer pattern of the loads are, compression forces are transferred from the deck to the pylon through the cables and the pylon transfers the large amount of compression forces to the foundation

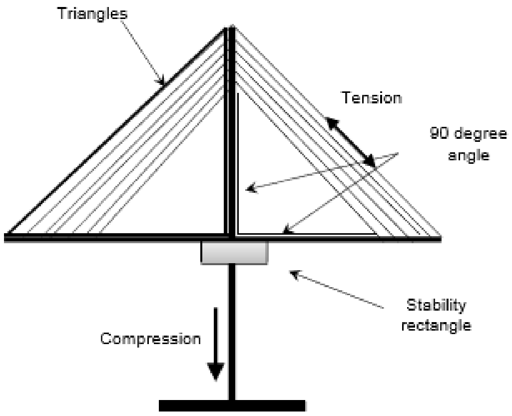

Figure 1: Load transfer of Cable Stayed Bridge

Cable stayed bridges provide outstanding architectural appearance due to their small diameter cables and unique overhead structure. Cable stayed bridges has 3 main components

A. Deck

The deck or road bed is the roadway surface of a cable-stayed bridge. The deck can be made of different materials such as steel, concrete or composite steel-concrete.

B. Pylon

Pylons of cable stayed bridges are aimed to support the weight and live load acting on the structure. There are several different shapes of pylons for cable stayed bridges such as Trapezoidal pylon, Twin pylon, A-frame pylon, and Single pylon. They are chosen based on the structure of the cable stayed bridge (for different cable arrangements), aesthetics, length, and other environmental parameters.

C. Cables

Cables are one of the main parts of a cable-stayed bridge. They transfer the dead weight of the deck to the pylons.

III. THREE DIFFERENT TYPES OF CABLE STAYED BRIDGE

Bridges are classified on the basis of the cable arrangement pattern:-

A. Fan

Several modern cable-stayed bridges have been built around the world using fan arrangement due to its efficiency. As shown in Fig. 1.3c, in this system, the cables are distributed over the upper part of the pylon, which are more steeply inclined close to the pylon (Bernard et al., 1988). The world largest cable-stayed bridge (Sutong Bridge in Jiangsu, China) was designed as a semi-fan arrangement using A-shape pylons. The semi-fan arrangement has better appearance in comparison to the fan arrangement.

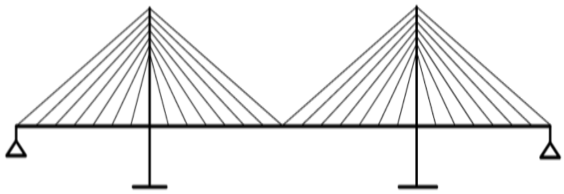

Figure 2: Fan connection

B. Harp

In a harp arrangement, the cables are made nearly parallel by attaching them to different points on the pylon as shown is in Fig. From economical point of view, this type cable stayed bridges is not efficient for long span bridges. This is because such an arrangement requires more steel for the cables, gives more compression in the deck, and produces bending moments in the pylon. However, in terms of aesthetics it is attractive in comparison to other types of cable stayed bridges. The parallel cables give a most pleasant appearance to the harp arrangement. The need for taller pylons is one of the disadvantages of this type of cable stayed bridges.

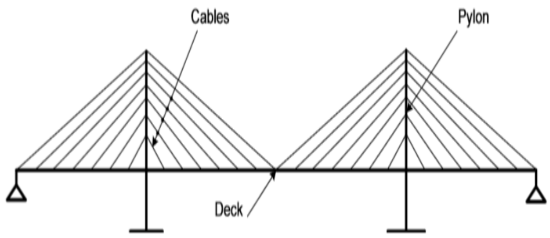

Figure 3: Harp connection

C. Radial

In this pattern, all the stay cables are attached to a single point at top of each pylon as shown in Fig. The relatively steep slope of the stay cables results in smaller cable cross section in comparison to the harp type. Moreover, the horizontal cable forces in the deck in this arrangement is less than the harp type However, by increasing the number of the stay cables, the weights of the anchorages increase and attaching the stay cables to anchorage becomes difficult. Therefore, the fan patterns are suitable only for moderate spans with a limited number of stay cables.

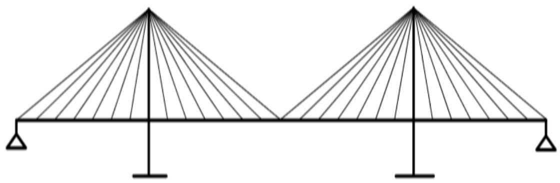

Figure 4: Radial connection

IV. DETAILS OF STRUCTURE SELECTED FOR STUDY

Figure 5: Quincy Bayview Bridge

In this study, the Quincy Bayview Bridge located in Illinois, USA as shown in Fig. is chosen as a typical cable-stayed bridge. The bridge is composed of 56 stay cables. The total length of the bridge L = 512.4 m with a main span length M = 256.2 m and two side spans l1 = l2 = 128.1 m as depicted in Fig. The deck superstructure is supported by stay cables with a semi-fan arrangement. The precast concrete deck has a thickness of 0.23 m and a width of 13.28 m. It also has two steel main girders that are located at the outer edge of the deck. These girders are internally attached by a set of equally spaced floor beams. The pylons have two steel legs as they are connected internally with a pair of struts. The pylon has a H-shape with two steel legs. The upper strut cross beam height is 45 m, and the lower strut cross beam supports the deck. The cross-section of the pylons is also given in Fig.

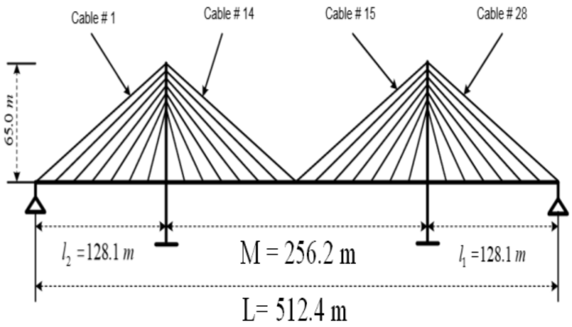

Figure 6: Bridge Span

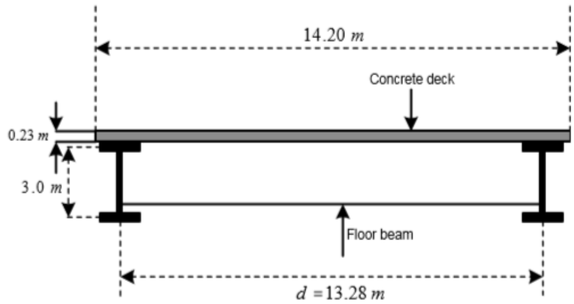

Figure 7: Bridge deck Span

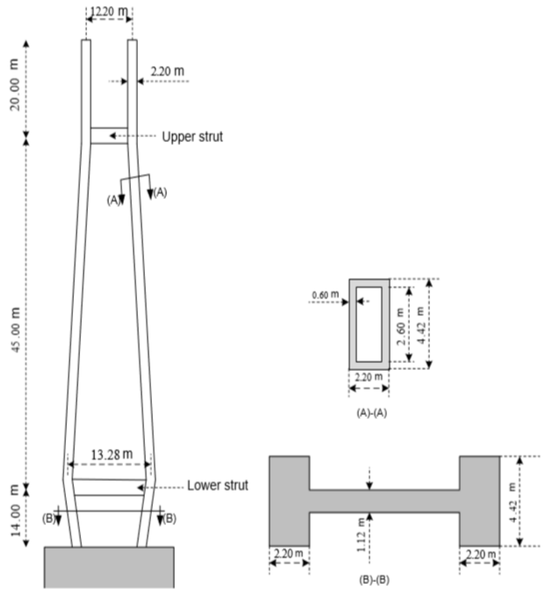

Figure 8: Bridge Geometric details

V. LOADS APPLIED TO THE STRUCTURE FOR ANALYSIS

Cable- stayed bridges are sensitive to dynamic loadings such as earthquakes, moving loads and wind .Cable-stayed bridges has very low inherent damping (usually less than 5% of critical) that may not be sufficient to overcome the ground motions caused by earth quake. In this paper the loads applied to the bridge for its analysis purpose are earth quake load and moving load.

A. *Earth Quake Load*

Earth quake load is applied to the model using response spectrum method. The code used for assigning earth quake is IS 1893 2002. The structure is assumed to be at zone V to get the maximum response of the structure due to earth quake. For earth quake resistant design, the entire time history of response may not be required. Instead, earthquake resistant design may be based on maximum (absolute) value of the response of a structure to a particular base motion. The response spectrum describes a plot showing the maximum response of a single degree of freedom system to a particular input motion as a function of natural frequency and damping. The response may be expressed in terms of acceleration, velocity or displacement.

B. *Moving Load*

While examining the dynamic behavior of Quincy Bayview Bridge under traffic loading, moving load model is considered by using the heavy truck HS20-44 defined in AASHTO. The vehicles enter into the bridge in predefined durations and travel along the selected traffic lanes until completing their predefined total durations.

Quincy Bayview Bridge has two lanes in each direction. In the application of moving traffic load pattern, two lanes in opposite direction are loaded mutually and when the loading duration is over, both the lanes of the bridge will be full of vehicles. Since various loading options in different intervals are possible, many critical situations are also analyzed. The design speed of the bridge is 80 km/h (22 m/s) .The duration of the analyses will be the time that begins when the vehicle enters into the bridge with a speed of 80 km/h and ends when it leaves the bridge and this duration is calculated as 24 s. Traffic loading application is given in Figure.

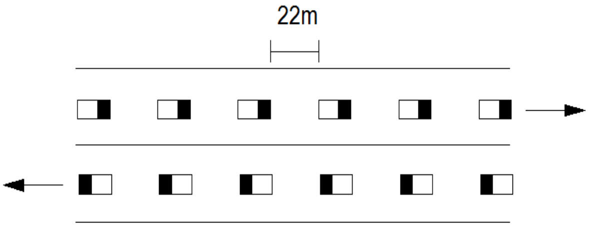

Figure 9: Moving load

The distance between the vehicles is an important factor while determining the magnitude of the load that will be applied to the bridge. The distance between vehicles is considered as 22 m. The length of a truck is considered as 9 m. So when the bridge is fully loaded 16 to 17 vehicles will be there in one lane.

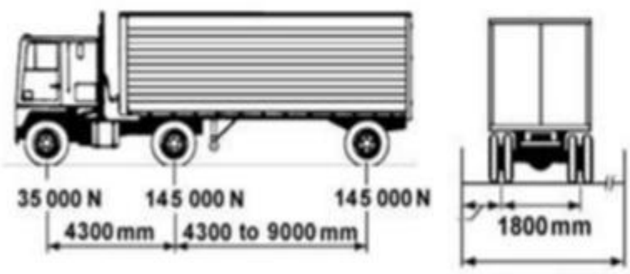

Figure 10: HS20-44 vehicle

VI. FINITE ELEMENT MODEL OF THE BRIDGE

3D finite element model of the Quincy Bayview Bridge is prepared with SAP 2000. The deck of the bridge and towers are defined as frame elements, the cables are defined as special type of cable elements that exist in SAP 2000 Software. Cable type chosen is cable undeformed length. Cable is modelled using straight frame objects. All together there are 33 models of the bridge modelled in SAP2000 for the detailed study of the cable stayed bridge.

Three bridges Fan , Harp , Radial bridges are modelled by keeping the span , cable diameter , girder dimensions etc constant (Same as that of Quincy Bay view bridge) , only the cable arrangement is altered namely radial , fan and harp.

Each of the three bridge models are modified by increasing the span of the bridge, changing the number of cables and changing the height of the pylon to study the effect of these factors on the cable stayed bridge. To study the effects 30 bridges are modelled by changing the above mentioned factors (While changing one factor all others are kept constant).

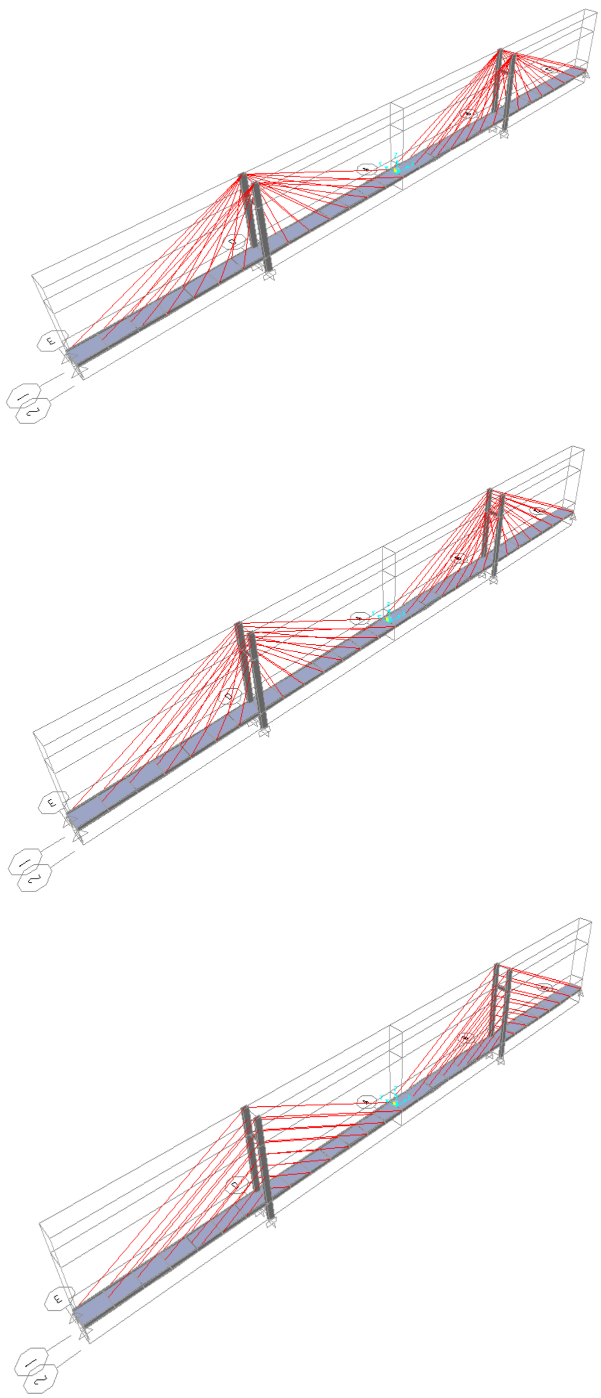

Figure 11: Radial, Fan and Harp models

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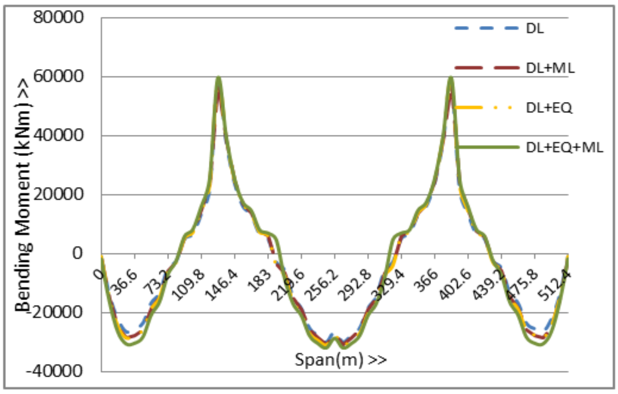
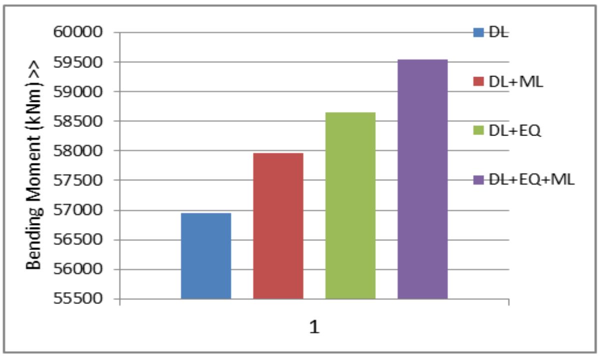
VII. RESULTS AND DISCUSSION

A. Effect of Applied loads on the original bridge (Fan type)



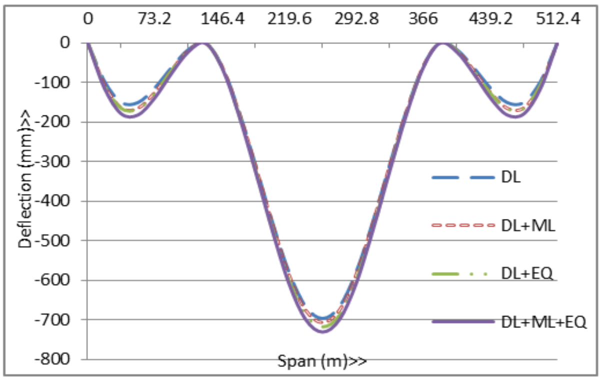
Graph 1: Bridge Span Vs Bending moment

The bending moment diagram of the bridge deck obtained for the traffic and earthquake loadings can be observed in the figure. In the graph it is clear that the effect of the moving load and the earth quake is almost similar. All the four cases considered here that is DL, DL+ML , DL+EQ , DL+EQ+ML the Bending moment plot throughout the bridge span almost coincides but the maximum effect is observed in the last combination which includes all the 3 that is (DL+ML+EQ) .Comparing the moving load and earth quake more effect is viewed for earth quake. The maximum bending moment is obtained at the top of the support for all the cases and so a bar chart showing the maximum moment due to all 4 cases is represented.



Graph 2: Maximum Bending Moment

Approximately 2 % increment is obtained in the maximum bending moment in the case of moving load and 3 % increment is obtained for earth quake. The ultimate case is when both the loads act together; approximately 5% increment in maximum bending moment is obtained, therefore the ultimate case that is (DL+ML+EQ) effect is considered for further comparisons on the cable stayed bridge.



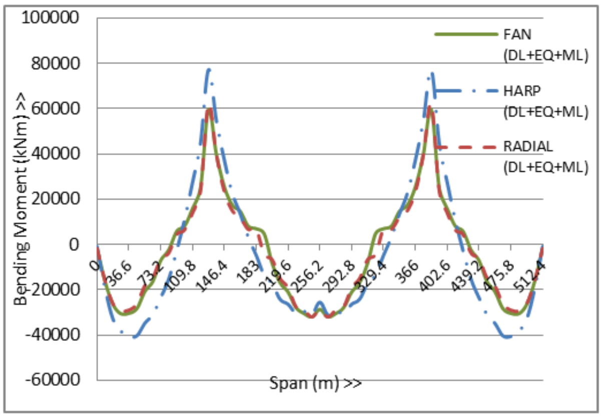
Graph 3: Bridge Span Vs Nodal displacement

Deflection graphs also shows that moving load increases the maximum deflection to 1.6%, 3.2% increment in maximum deflection is obtained when earth quake is applied and the maximum effect is obtained when moving load and earth quake acts together (5% increment in maximum deflection).

It is observed that the nodal displacements and bending moment obtained for the combined effect of the earthquake and traffic loading case are larger than the responses determined for the earthquake and traffic loading cases, separately. Furthermore, it is also observed that the structural responses obtained for the earthquake excitation case are usually larger than the responses determined for the traffic loading case. These results imply that the combined effect of the earthquake and traffic loadings should be considered for the realistic design of cable-stayed bridges.

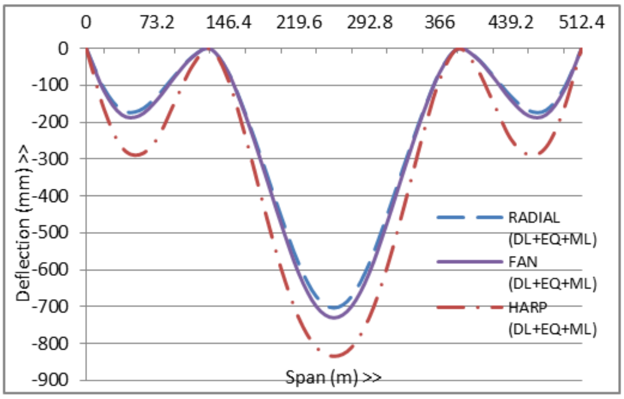
B. Comparison of three different types of bridge Radial , Fan and Harp

From the above graph maximum effect is obtained when earth quake and moving load is combined therefore the combined effect is used for further comparison between three types of cable stayed bridges Radial , Fan and harp



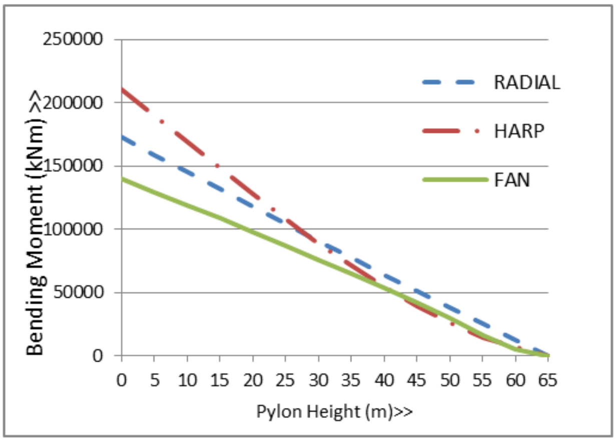
Graph 4: Bridge Span Vs Bending moment

Bending Moment diagram and deflection diagram throughout the full span of the bridge is plotted for three different cable connections (Radial, Fan and Harp). The bending moment diagram shows the maximum bending moment is obtained at the supports for all the 3 cable connections. Bending moment obtained at the mid span is almost constant for all the three connections. Maximum bending moment is obtained for harp connection and minimum for Fan connection.



Graph 5: Bridge Span Vs Nodal displacement

Deflection diagram shows maximum deflection for harp connection which is above 830mm and minimum deflection for radial connection which is close to 700mm. Deflection obtained for fan and radial connection is almost similar. No specific limit for the deflection is mentioned in any code, but for the bridge to be serviceable the deflection should be less than span/350. Fan and radial arrangement is under the limit, that is below 730mm but the deflection obtained for harp is above the limit.



Graph 6: Bending Moment Vs Pylon Height

Bending moment obtained in the pylon is plotted .It is clear from the graph that maximum bending moment for all 3 types are obtained at the pylon position where the slab is resting. Bending moment decreases as the height increases and reaches to zero at the top most point of the pylon. The graph shows the maximum bending moment is obtained for harp connection and minimum for fan connection. Approximately 24% more moment is obtained for radial connection and 51 % more bending moment is obtained for harp connection compared to fan connection.

From the above study it is clear that out of the three cable connections (Fan, Radial and Harp) mentioned in this paper Fan arrangement is comparatively the best one.

C. Effect of alterations made in the bridge

1. Increase in the number of cables

Number of cables connected to one side of the pylon of the original fan type Quincy Bayview Bridge is 7 .Cable number is varied to study the effect on the number of cables on the bridge. All the 3 bridge types with different number of cables N=7, 8,9,10 are modelled for the study purpose. All other dimensions and specifications are kept constant other than the number of cables

From the bending moment graph of the whole span it is clear that the maximum bending moment occurs at the support section. Therefore a girder section at the support which has the maximum bending moment is selected for the study.

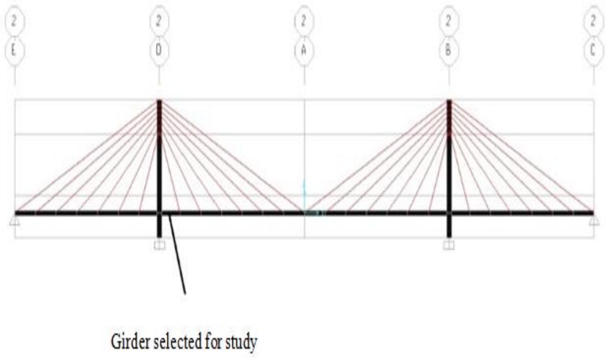
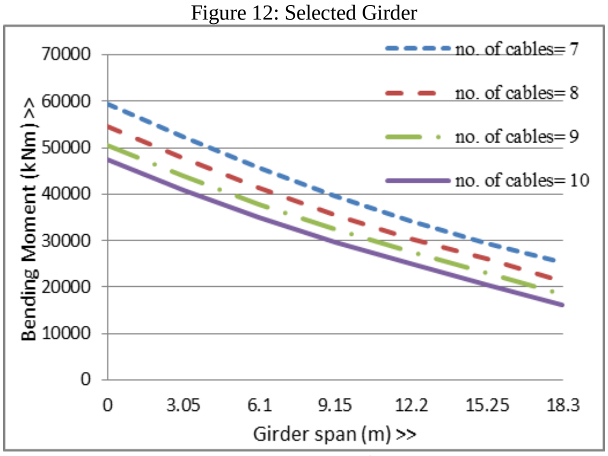
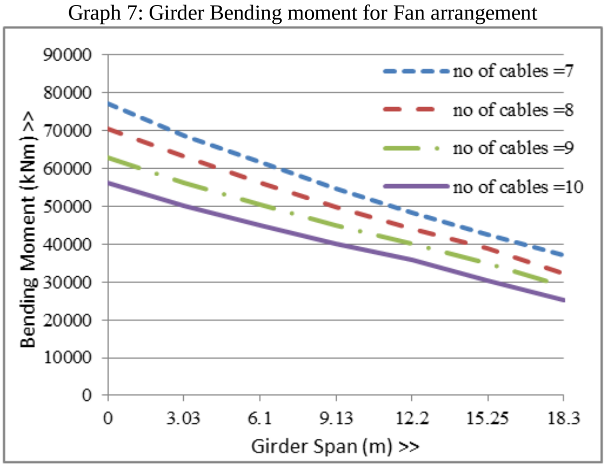


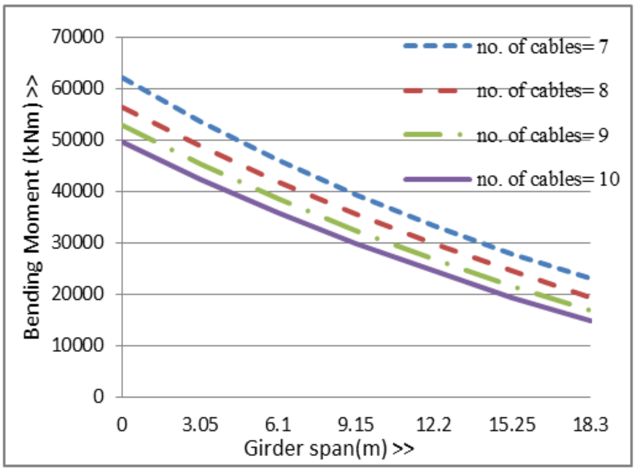
Figure 12: Selected Girder



Graph 7: Girder Bending moment for Fan arrangement



Graph 8: Girder Bending moment for Harp arrangement



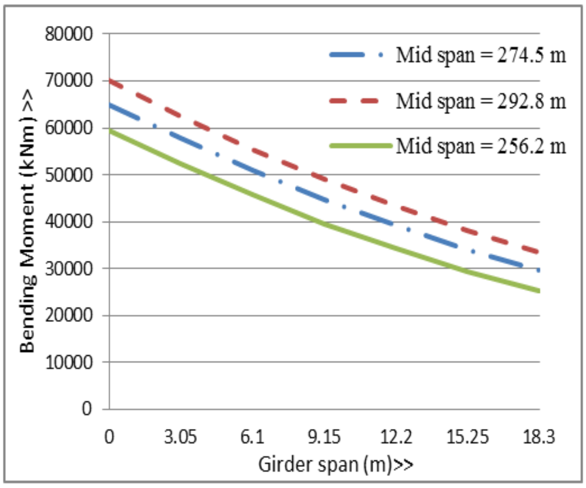
Graph 9: Girder Bending moment for Radial arrangement

For all the three cable arrangements the bending moment value reduces as the number of cables connecting the main girder to the pylon increases. As the number of cable increases the support to the main girder increases and so there are more number of cables for transferring the load on the deck to the pylon, hence the bending moment on the girder decreases.

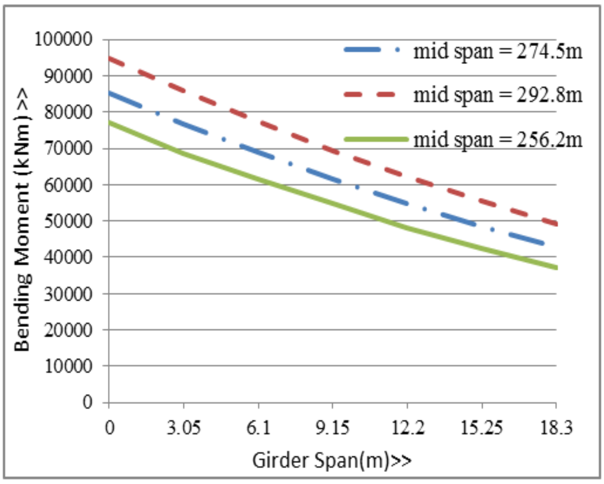
For Fan arrangement when the number of cables is increased from 7 to 8, 8.5 % decrease in maximum bending moment is obtained it reduces to 7.2 % and 6.3 % when the number of cables is changed from 8 to 9 and 9 to 10 respectively. For harp arrangement dip in maximum bending moment is obtained as 8.5%, 11 % and 11.04 % when the number of cables is varied from 7 to 8, 8 to 9 and 9 to 10 respectively. For radial arrangement the percentages obtained is 9.4 %, 6.5% and 6% for increment of number of cables from 7 to 10. Here we can find the bending moment reduction percentage decreases for radial and fan arrangement as the number of cables is increased one by one but for harp arrangement the bending moment reduction percentage increases as the number of cable is increased one by one.

2. *Increase in the mid span of the bridge*

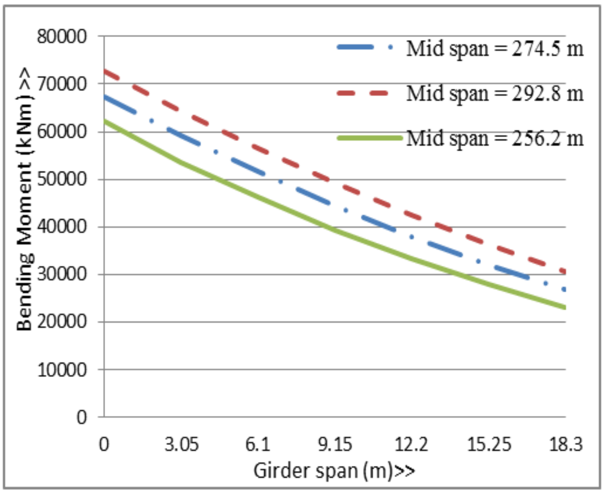
Mid span of the bridge is varied in the model to analyze the effect of change in mid span to the whole bridge. Mid span is varied for all three types of cable stayed bridge. While the mid span is varied for analysis purpose all other factors of bridge are kept constant. Bridges for 3 different mid span values are modelled (256.2m, 274.5m, 292.8m,). Secondary beam spacing of the original model is 18.3m and span of original bridge is 256.2m, so by keeping the secondary beam spacing constant span is varied to 274.5m and 292.8m



Graph 10: Girder Bending moment for Fan arrangement



Graph 11: Girder Bending moment for Harp arrangement



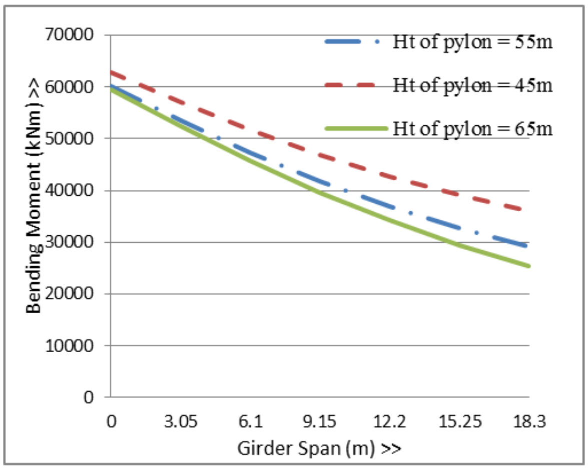
Graph 12: Girder Bending moment for Radial arrangement

Graph plotted above shows, when the mid span is increased the bending moment in the selected girder increases for all the 3 cable arrangements. As the span increases the dead weight of the bridge and number of vehicles also increases and so the span bending moment also increases. For radial and fan connection the bending moment increase percentage reduces as the span goes on increasing, for fan moment increase percentage is 9.31%

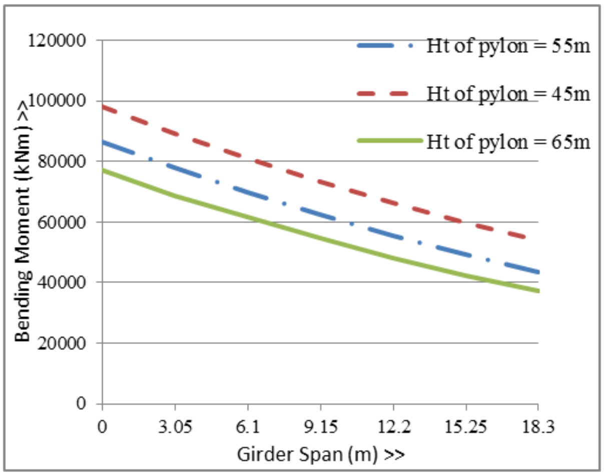
and 7.76% for rise of mid span from 256.2 m to 274.2 m and 274.5 m to 292.8 m respectively. For fan the percentages are 8.5% and 8% and for harp it is 10.7% and 10.9%, in harp the bending moment rise percentage increases or stays almost constant as the span increases.

3. Variation in the pylon height

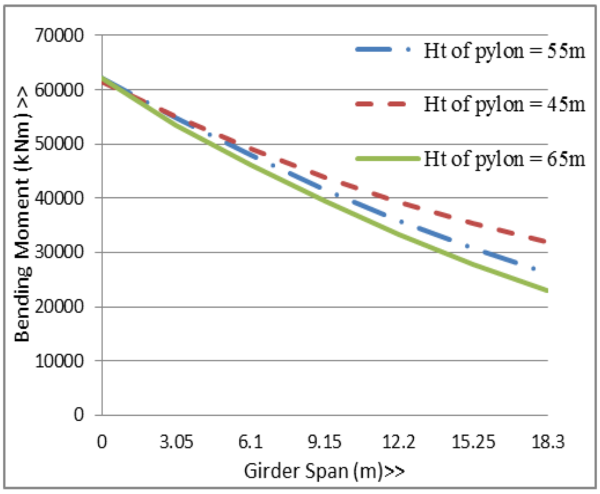
Finally the pylon height is varied in the model to analyze the effect of pylon height variation in the whole bridge. Pylon height of the original structure is 65m and this height is varied to 55m and 45m, the effect is analyzed and graph showing the bending moment variation of the selected girder is plotted.



Graph 13: Girder Bending moment for Fan arrangement



Graph 14: Girder Bending moment for Harp arrangement



Graph 15: Girder Bending moment for Radial arrangement

The graph plotted for harp arrangement shows the maximum moment occurs for the pylon height 45m than for pylon height = 55 m, 65m and bending moment slope for all the 3 pylon height is almost constant. For radial arrangement also the maximum moment is for the pylon height=45 m but only very less increment in moment is obtained at the supports than other two pylon heights, but in this case the slope of all the 3 pylon height is different, for pylon height = 45m the slope is less or the bending moment reduction throughout the span is less compared to other 2 pylon heights. Considering the radial arrangement it has almost equal bending moment at the supports for all the 3 pylon heights but the slope is least for pylon height= 45m and maximum for pylon height =65m.

VIII. CONCLUSION

The purpose of this study is to analyze the dynamic behavior of the cable stayed bridge under earth quake load and moving load. A combined effect of both the loads is also examined. It is observed that the nodal displacements and bending moment obtained for the combined effect of the earthquake recorded on medium soil condition in zone V specified in IS1893:2002 , and traffic loading case are larger than the responses determined for the earthquake and traffic loading cases, separately. Furthermore, it is also observed that the structural responses obtained for the earthquake excitation case are usually larger than the responses determined for the traffic loading case. These results imply that the combined effect of the earthquake and traffic loadings should be considered for the realistic design of cable-stayed bridges.

The second study conducted is to compare the three different types of cable stayed bridges namely Radial, Fan and Harp .The analysis result shows that the maximum bending moment at the girder support and the pylon at the support obtained for Fan cable arrangement is the least and so undoubtedly it can be concluded that fan arrangement is the best among the three and that is the reason why fan cable arrangement is most commonly used for long span bridges. The nodal displacements and bending moment obtained for harp arrangement is the maximum which makes it most unsuitable for long span bridges, only advantage of harp arrangement Bridge is its aesthetical appearance. Radial arrangement has a bit less bending moment values of that of fan type and it has less nodal displacement as that of fan, but what makes it unsuitable is the practical difficulties in connecting all the cables to one point at the top of pylon, makes it unsuitable for long span bridges.

Each type of cable stayed bridge is subjected to alteration like change in the number of cables, change in the mid span and change in the pylon height. It is found that, as the number of cables is increased the bending moment at the support decreases, maximum reduction is found for radial arrangement. When the mid span is increased it is found that the bending moment at support is increased and the maximum increment is found for harp arrangement. When the pylon height is varied the support moment has no much change for radial and fan arrangement but the overall bending moment throughout the span ,especially at the mid span is more when the pylon height is the least. For harp arrangement even at the support the bending moment is increased when the pylon height is reduced.

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