Construction Stage Analysis of Cable Stayed Bridge

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Abstract— **Cable stayed Bridges are gaining considerable recognition as a solution for functional, structural and aesthetic requirements of bridges. Many such bridges have been constructed around the world and bridge designers look towards this bridge as the future of bridge construction. Cable stayed bridges can span up to 1000m or more and so they are also looked upon as a solution for long span bridge construction. While the design of such a bridge has its own range of challenges, the construction is an even bigger challenge. Due to this, at the design stage, the construction stage analysis has to be done to ensure that the structure can be constructed taking into account all the loads which come onto the structure during construction of the various stages. During construction, there are many activities which result in the application of load on the previously constructed structural member or members. These loads are called erection loads or construction stage loads and they get applied due to application of succeeding members, placement of machinery, lever arm reaction of machinery, pre-tensioning of the cables besides other activities. The positioning of such loads and machinery result in direct or eccentric loads which cause deflections and moments during the various stages of construction which vary as the construction goes along. There are two types of analysis, the forward constructions stage analysis and the backward construction stage analysis. In this paper parameters are compared for construction stage analysis and final stage analysis of a bridge under dead load. Parameters such as bending moments in the deck, displacements and axial forces will be compared. The deformed shape is compared as well. MIDAS Civil software is used to do the construction stage analysis.**

Keywords—cable stayed bridges, construction stage analysis, cables, MIDAS Civil, concrete bridges, steel bridges.

I. Introduction

The construction stage analysis of the cable stayed bridge has to take into account all types of loads that may come onto the structure while the construction is in progress. If the sequence of construction is considered, bridges can be broadly divided into its substructure and its superstructure. The substructure is laid as per the design and then the work of the superstructure begins. The pylons rise from the foundations, and this is the first stage of the construction sequence of the superstructure. It is only after the completion of the pylons that the deck and the cables can be installed. All this while, the pylon has to behave as a vertical cantilever and the stresses must be checked to make sure that the vertical cantilever is capable of enduring stresses which may come onto it due to winds etc. In the balanced cantilever approach each segment of the deck is lifted and the cables are anchored to the deck and the pylon starting at the face of the pylon. At this stage the forces in the cables have to be adjusted. This is the process of pre-tensioning of the cables. When this is done the axial stresses in the cables, the axial stresses in the deck, the moment in the deck will all be for that particular stage. The loads of the machinery, equipment as well as time dependent parameters such as creep and shrinkage are considered. At the next stage, when the second segment is attached, in the same way, there will be an effect on the stresses on the previous stage, which has already been completed while the current stage experiences its own stresses. Hence the axial stresses in the cables, the axial stresses in the deck, the moment in the deck will all change at each stage of construction. When the construction is over it is necessary the stresses match the stresses in the final stage analysis. MIDAS Civil is a software which can be used to analyse the bridge for the finals stage analysis as well as the construction stage analysis. In this paper the results have been extracted from the MIDAS civil software after doing the modelling using MIDAS Civil software.

II. Literature Review

The literature survey points out to various methods and analysis to find out stresses in the cables, deck and pylon during the various construction stages and it becomes evident that the construction stage analysis is the heart of cable stay bridge design and construction.

Wang et al. (2004) performed the analysis of cable stayed bridges during construction and highlighted that the shape of the bridge at the different stages of construction with the help of a finite element computation procedure. The harp arrangement of cable stayed bridge was used to do the analysis. The cable sag effect and the column-beam effect was taken into account. Shape finding analysis are then done for the cable stayed bridge and for the cable stage bridge under construction. The erection by cantilever method is considered. A "forward process analysis (FPA)" and a "backward process analysis (BPA)" is done and the results are tabulated. It was concluded that FPA provides a more real time approach while BPA does not. However, BPA has advantages of providing "accurate configuration and member pre-forces of the bridge structure at different erection stages" [1].

Svensson (2012) detailed out the requirements of construction stage analysis. The structure in the computer model must be dismantled backwards in a manner to represent each clear construction stage in the backward order. By doing this all the forces which would come into the picture when the 'highly indeterminate' final stage design is broken up into the smaller systems, each system at each stage having its own self weight loads and additional loads for construction equipment and all moments, forces etc are calculated so that, if necessary, all props, temporary supports, auxiliary cables may be added to the construction sequence forward. Svensson gives a detailed and stepwise "dismantling of bridge" sequence to calculate all the forces during the construction stages. Svensson also makes a case for the aerodynamic stability in the construction stage. During the construction all heavy winds and forces are to be considered and adequate bracing and stiffening should be provided to resist these forces [2].

Lee et al. (2015) reported high compressive forces in the deck due to the heavy tension forces in the cables. This is quite significant at the construction stages. A comparison of different cable arrangements was done to study these effects. It was observed that the cables in the outer regions experience high tensile stresses during the construction stages. However, the inner cables experience diminishing values of tensile force as the loads increase with the construction stages to the extent that they finally vanish. This is also accompanied by the formation of several plastic hinges along the deck. The analytical models as well as physical models were used to test the construction stage loads and displacements [3].

Recupero et al. (2016) viewed each construction stage as a separate structure which is to be analysed. A general methodology of analysis for the cantilever method of construction was presented, which follows the actual construction sequence. It was reported that the variation of cable forces vary with the construction stage and it was observed that the deformed shapes under creep effects are time dependent [4].

Jadhav et al. (2017) used the software MIDAS Civil to model the Bhim Gowda bridge. The unknown load factor method is used to calculate the pretension forces. The final forces in the cables match the calculated forces. The changing configuration at every stage of construction has been highlighted by the authors [5].

Amin and Mohamed (2021) discussed the construction stage analysis of the Tuti Bahari Bridge. MIDAS Civil software was used to model the bridge. The backward construction stage method was used for analysis to compare it to AASHTO 2010 requirements, it was reported that the tensions in the cable changed during every construction stage and the outer cabled carried maximum tension [6].

III. Methodology

A. Bridge Model

The classical three span cable stayed bridge is used in most of the long span cable stayed bridges. The classical three span cable stayed bridge works out to be the most optimal of all cable stays arrangements if they are proportioned correctly. It is thus used even for smaller spans. It is quite clear that from data available that two cable planes are important when it comes to dynamic stiffness and also heavy loads. The economical range for concrete deck bridges is up to around 500m while steel bridges are economical for ranges above 800m. However, there are steel deck bridges which are constructed in almost all span ranges. The parallel strand cable is a preferred cable type due to its high fatigue range and ultimate strength. The bridge choses in an alternate classical three span cable stayed bridge across the river Mandovi, in Goa, India, comparing it to the existing 'series of cable stayed bridges' Atal Setu. The spans have been decided based upon this as shown in Fig. 1. Keeping the above in mind the following basic design parameters are used for this paper,

- Total span of bridge is 620m.
- The ratio of main span to back span is 0.4L, if main span is L. This works out to be 137.5m
- The height of the pylon is 0.2L if main span is L. This works out to be 345m.
- The spacing on the deck is maintained at 12.5m in general on the main span and back span.
- The cable spacing on the pylon are spaced at 1.5m while following an intermediate fan-harp system of cable arrangement
- Parallel strand cables will be considered.
- Anchors are not be dealt with in this paper.
- The pylon will consider of two inclined verticals on either side of the deck.
- Two cable planes are considered.

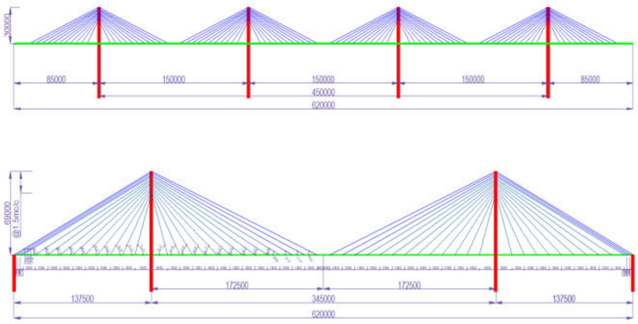

Fig. 1. Series of Cable Stayed Bridges At Atal Setu Span converted to classical three span cable stayed Bridge.

Fig 2. shows the enlarged view of one symmetrical part of the cable stayed bridge.

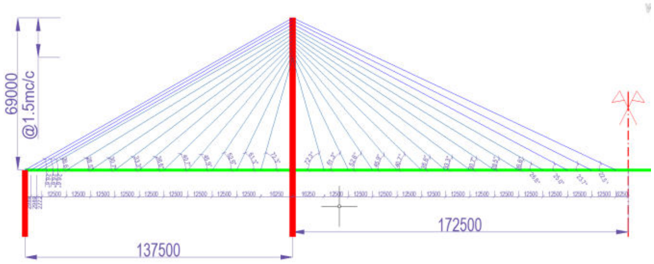

Fig. 2. One symmetrical span of classical three span cable stayed Bridge.

B. Analysis using MIDAS Civil

The Structure is analysed in MIDAS Civil which is a finite element based software. Material properties are assigned to the various members of the structural system as shown in Table I. The distinct components of a cable stayed bridge are clear to see in the two tables and each of these components are given the properties as required. Table I shows the girder with value of E and weight density as that of steel. Hence, the properties are for the steel deck girder. Table I shows the girder with value of E and weight density as that of steel.

TABLE I. MATERIAL PROPERTIES ASSIGNED TO BRIDGE IN MIDAS CIVIL FOR BRIDGE

ID	Name	Properties		
		Modulus of Elasticity (kN/m^2)	***Poisson's Ratio***	***Weight Density (kN/m^3)***
1	Cable	1.9613×10^3	0.3	77.09
2	Girder	1.9995×10^3	0.3	77.09

ID	Name	Properties		
		Modulus of Elasticity (kN/m²)	***Poisson's Ratio***	***Weight Density (kN/m³)***
3	Pylon	2.78×10^3	0.2	23.56
4	CBeam_Girder	1.9613×10^3	0.3	77.09
5	CBeam_Pylon	2.78×10^3	0.2	23.56

The bridge is modelled using the MIDAS Civil software. Initially the cables are modelled as truss elements. This is important to find out the pretension forces in the cables. The modelled structure is shown in Fig.4. At this final stage analysis, the dead loads are assigned to the deck which includes the self-weight and the additional loads which include parapet walls, crash barriers etc. The sections are the sections which are the final sizes and to be checked for the construction stage. The 'Unknown Load Factor' in MIDAS Civil is used to calculate the pretension load. Cable tuning is done and then the final pretension loads are applied to a model which is saved without any applied loads. The element and node names in Fig. 3 will be referred to in the results.

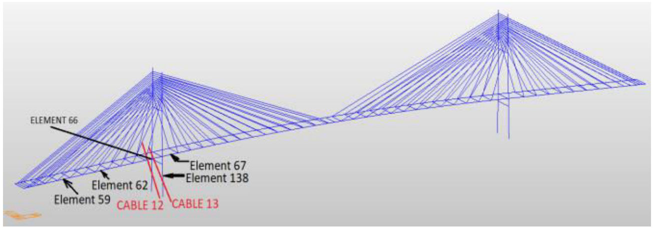

Fig. 3. 3D of model of Bridge in Midas Civil

IV. Results

From the literature that has been read it has become clear that construction stage analysis seems to be the heart of the design and construction of cable stayed bridges. Constructability is a major consideration while conceptualising a bridge and the construction stage analysis allows for the designer to look into this aspect. In the model which was considered for this paper the preliminary design and final stage design has been dealt with in the previous section. In this section the results of the construction stage analysis are shown. With the help of MIDAS Civil software, the backward stage analysis was conducted and the following results were found

A. Bridge Model

Fig. 4 shows the model with the deformed shape after the final stage. For this bridge there are 41 Construction stages and the various deformations and change in stresses are recorded for each of these stages and they are compared with the deformations of the final stage model.

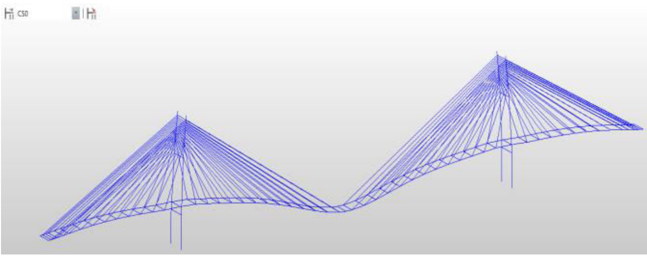

Fig. 4. Deformed shape at CS0

B. Bending Moment Variation

The variation of bending moment along the height of the pylon and across the deck of the bridge is as shown for the different construction stages. In this paper six construction stages are chosen to be highlighted where significant changes are noted in the moments. These are CS0, C10, CS24, CS26, CS35 & CS41.

Fig. 5 shows the CS0 (construction stage zero) case where all the elements are in the order of the final stage. The maximum bending moment is 73692.3 kN-m as noted in the figure.

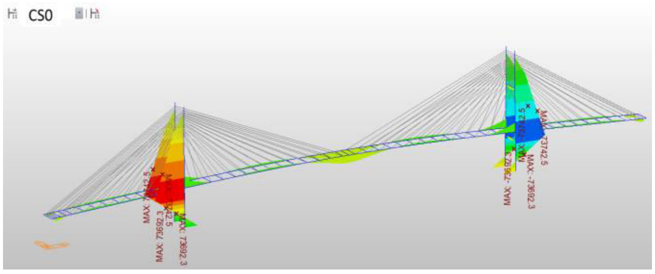

Fig. 5. Bending Moment at CS0

At CS10 i.e. construction stage 10, in Fig. 6, the maximum bending moment at the same section is 34061.1 kN-m in the pylon, in this backward analysis.

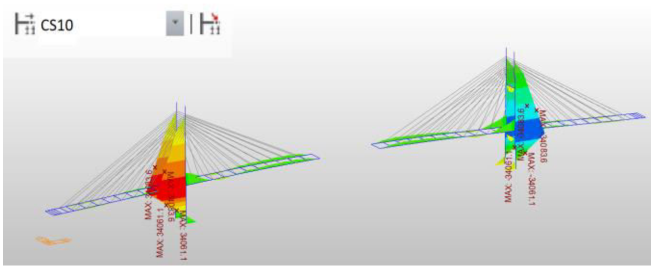

Fig. 6. Bending Moment at CS10

At CS24, (construction stage 24) in Fig. 7, the maximum bending moment at the same section is 10626.5 kN-m in the pylon. At this stage prominent bending moment variation in the side span deck is noted. This is in total contrast to the bending moments in the same section at CS0. The hogging moment of the deck at the pylon is also notable.

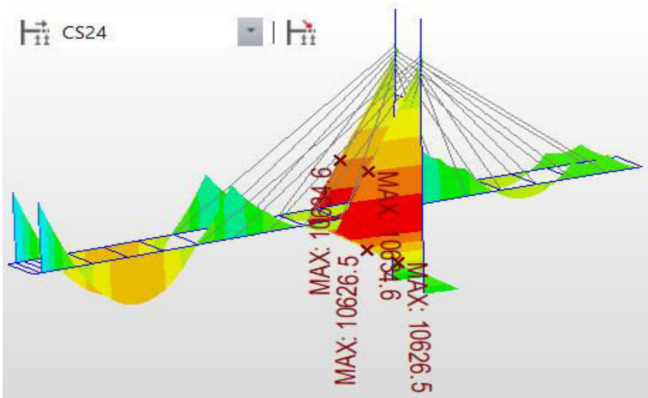

Fig. 7. Bending Moment at CS24

At CS26, (construction stage 26) in Fig. 8 the maximum bending moment is 9858.1 kN-m and, notably, is at the anchor head at the start of the side span.

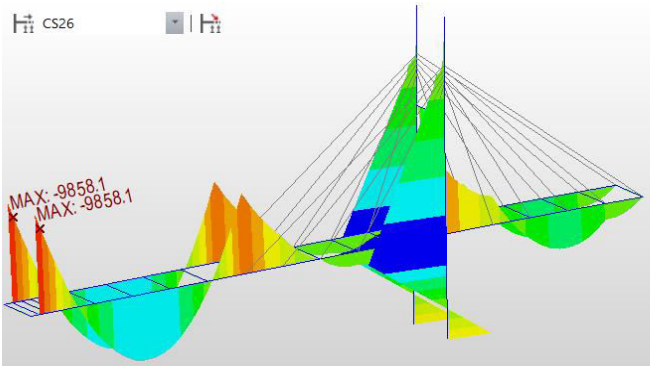

Fig. 8. Bending Moment at CS26

At CS35 i.e. construction stage 35, in Fig. 9, the maximum bending moment is 9461 kN-m and, notably, is at the centre of the side span and it is a negative moment due to the boundary condition. A temporary pier is modelled at this node due to which the negative moment is prominent. This moment is higher than the final stage moment at this section.

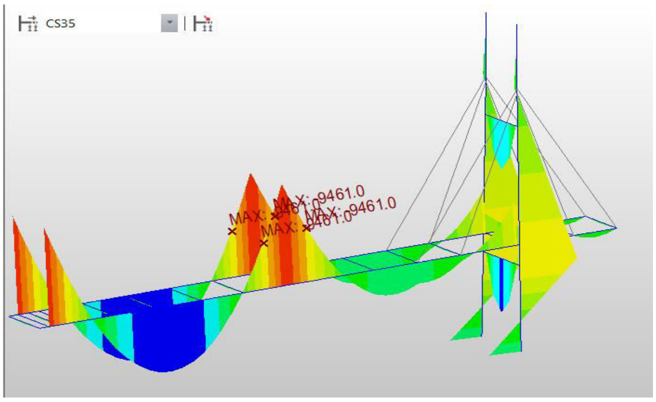

Fig. 9. Bending Moment at CS35

At CS41 i.e. construction stage 41, in Fig. 10, the maximum bending moment at the same section is observed to be 24826 kN-m in the pylon.

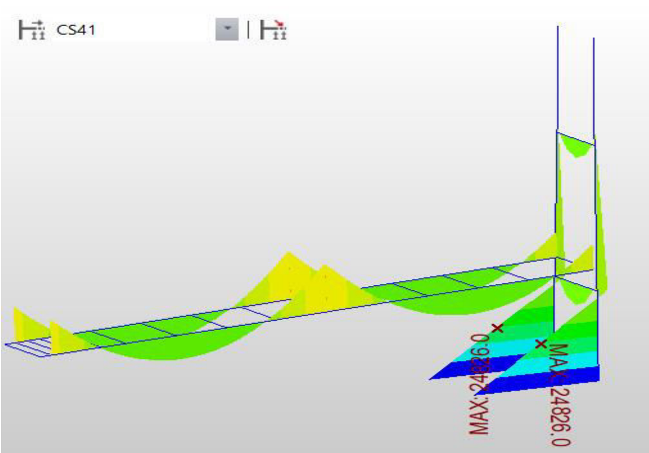

Fig. 10. Bending Moment at CS41

Fig. 11shows the variation of bending moment in pylon element 138 (refer Fig. 3) for all construction stages.

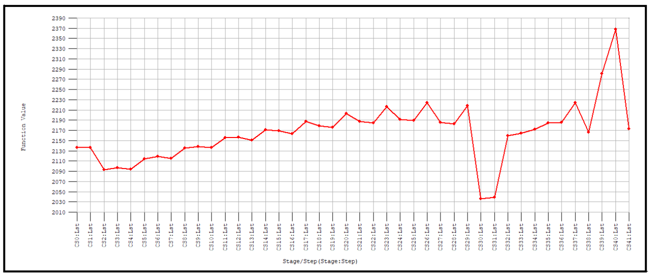

Fig. 11. Bending Moment Variation in Pylon element 138 for each construction stage

Fig. 12 shows the variation of bending moment in deck element 67 (refer Fig. 3) for all construction stages.

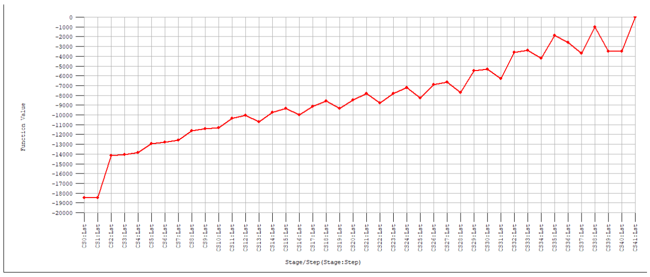

Fig. 12. Bending Moment Variation in Deck element 67 for each construction stage

Fig. 13 shows the variation of bending moment in deck element 59 and deck element 62 (refer Fig. 3.) for all construction stages. This variation in deck moment is highlighted in CS35 (Fig. 9.) This is a very important take away from the construction stage analysis as the variation of moments is very large across the construction stages.

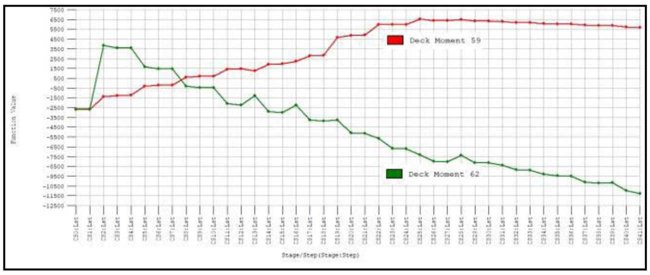

Fig. 13. Bending Moment Variation in Deck element 59 and Deck element 62 for each construction stage

C. Cable Force Variation

Cable forces at CS0, C10, CS24, CS26, CS35 and CS41 are as follows. The maximum force at each of the stages is recorded. Fig. 14 shows the CS0 i.e. construction stage zero case where all the elements are in the order of the final stage. The maximum force is recorded as 1123.5kN.

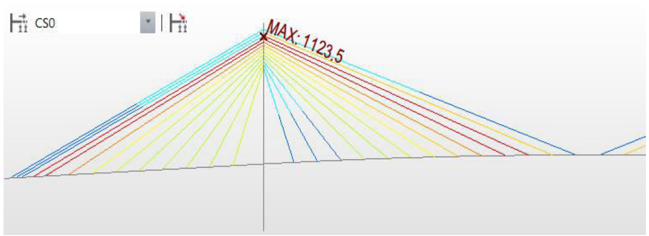

Fig. 14. Maximum Force in cable at CS0

Fig. 15 shows the CS10 i.e. construction stage 10 and the maximum force recorded as 1123.3kN.

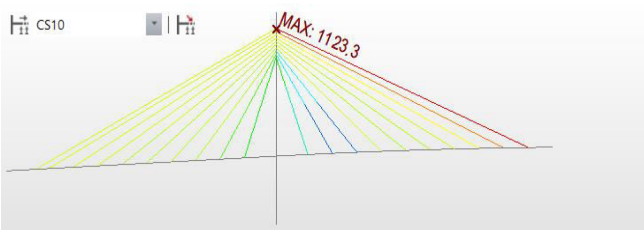

Fig. 15. Maximum Force in cable at CS10

Fig. 16 shows the CS24 i.e. construction stage 24 and the maximum force recorded as 892.6 kN.

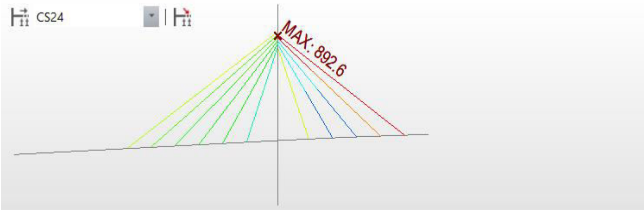

Fig. 16. Maximum Force in cable at CS24

Fig. 17 shows the CS35 i.e. construction stage 35 and the maximum force recorded as 311.2 kN.

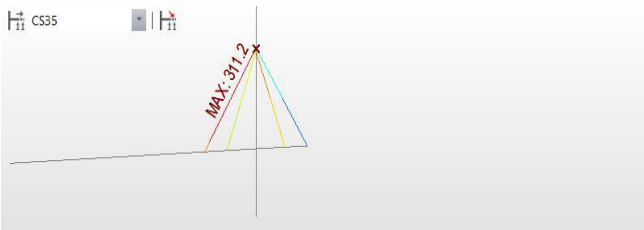

Fig. 17. Maximum Force in cable at CS17

Fig. 18 shows the CS41 i.e. the construction stage 41, there are no cables at this stage.

Fig. 18. CS41 with no cables.

Fig. 19 shows the variation of the forces in the cables 12 & 13 (refer Fig. 3) for all construction stages. There is a big variation at the last stage.

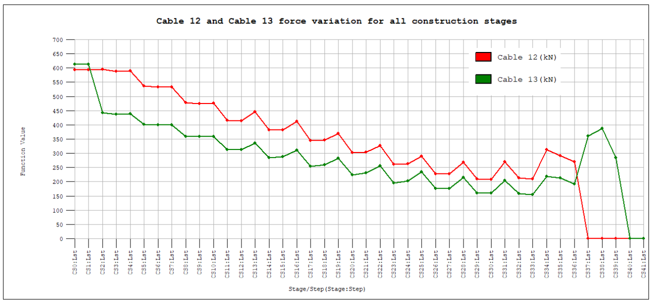

Fig. 19. Variation of Forces in cables 12 & 13 all each construction stages

D. Axial Forces in Pylon and Deck

The progression of the axial forces in the pylon and deck are of significance. This is especially important for the deck as second order effects are to be taken into account due to the slender deck and compressive force. The axial forces at the stages CS0, C10, CS24, CS26, CS35 and CS41 are shown.

Fig. 20 shows the axial compressive forces in the deck at CS0. The forces increase towards the pylon. The force in the pylon can also be noted.

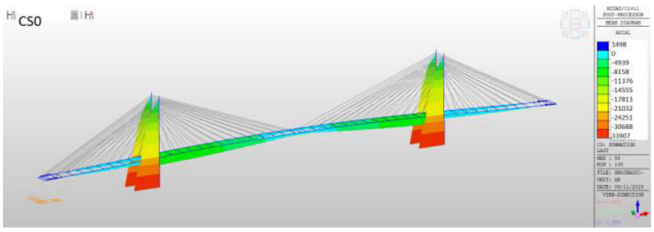

Fig. 20. Force in deck and pylon at CS0

Fig. 21 shows the axial compressive forces in the deck at CS10. The force increases towards the pylon. The force in the pylon can also be noted.

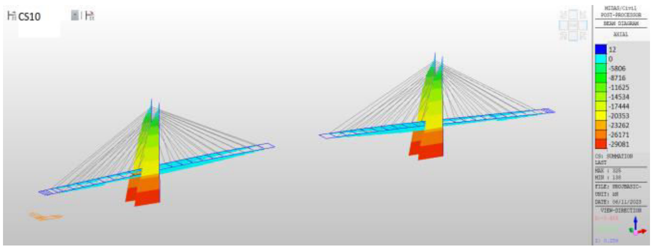

Fig. 21. Force in deck and pylon at CS10

Fig. 22 shows the axial compressive forces in the deck and pylon at CS24.

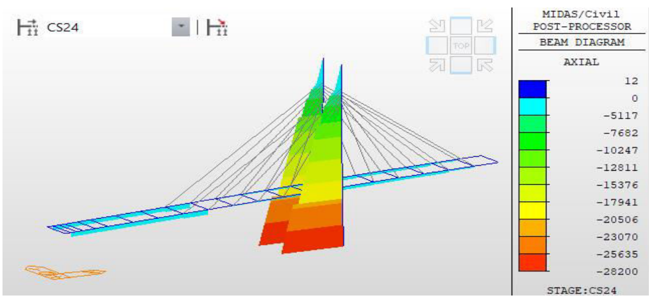

Fig. 22. Force in deck and pylon at 24

Fig. 23 shows the axial compressive forces in the deck and pylon at CS26.

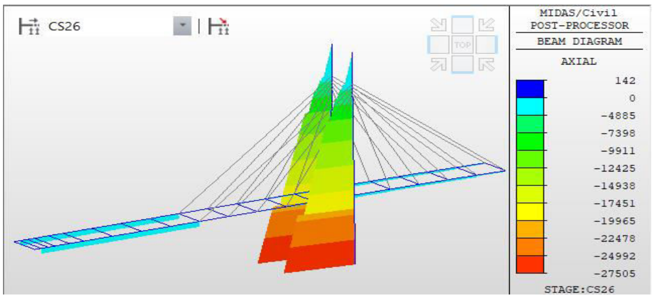

Fig. 23. Force in deck and pylon at CS26

Fig. 24 shows the axial compressive forces in the deck and pylon at CS35.

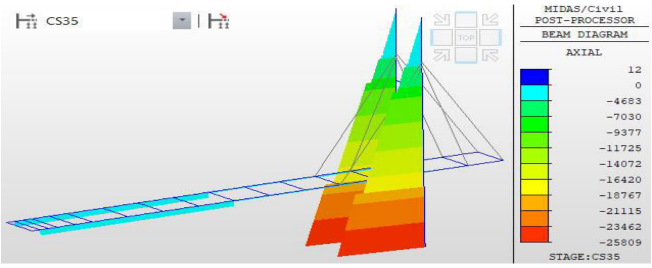

Fig. 24. Variation of Forces in cables 12 & 13 all each construction stages

Fig. 25 shows the axial compressive forces in the deck and pylon at CS22.

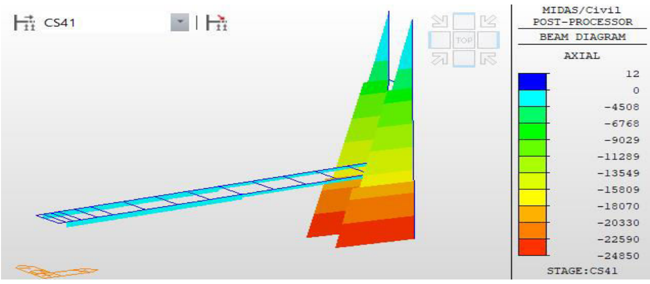

Fig. 25. Variation of Forces in cables 12 & 13 all each construction stages

Fig. 26 shows the axial compressive forces in the deck and in elements 66 & 67 which keep increasing with each construction stage. This increase is of great importance as the stiffness of the deck and the cables becomes a factor in the stability of the elements in each construction stage.

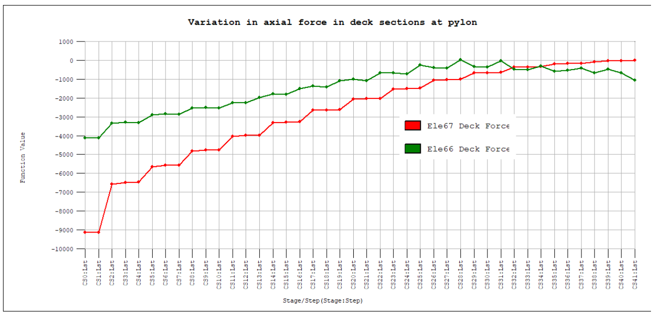

Fig. 26. Variation of Axial Compressive forces in deck elements 66 & 67 for every construction stage.

E. Displacements

Fig. 27 shows the vertical displacement of the node 35 & node 48 at CS29 and horizontal displacement of Node 1. The graph in Fig. 28 shows the varying vertical displacement of Node 48 for all construction stages. Fig. 29 shows the displacement variation of Node 1 in the pylon in the horizontal direction for all construction stages.

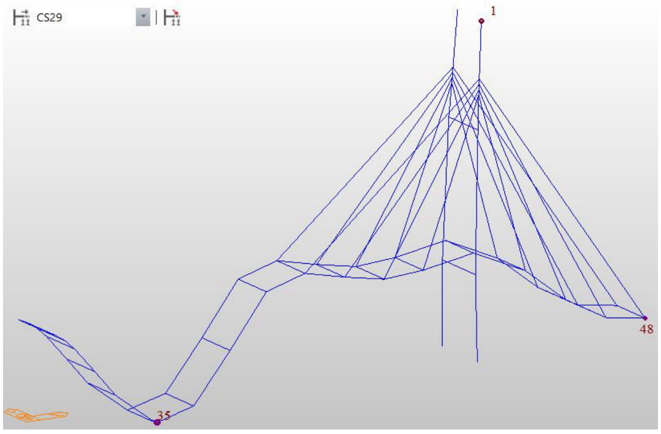

Fig. 27. Displacement of Node 35 & Node 48 at CS29

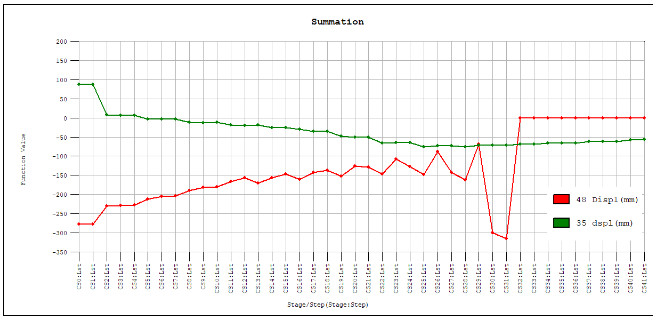

Fig. 28. Variation in Displacement of Node 35 & Node 48 for all construction stages

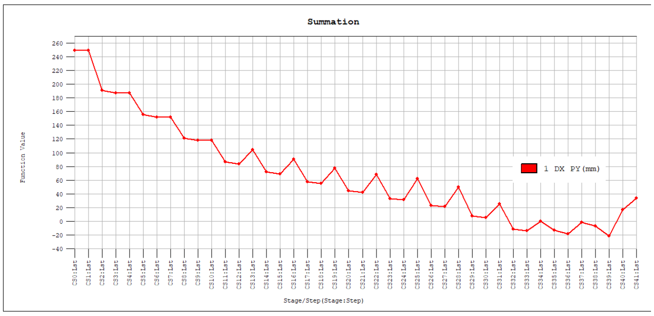

Fig. 29. Variation in Displacement of Node 1 for all construction stages

V. Conclusions

From the above analysis, following conclusions are drawn:

- The bending moment in the pylon varies with every construction stage. The variation of bending moment in the pylon is to be carefully noted. The reversal of stresses could involve the requirement of more reinforcement in certain areas which might not be the requirement for the final stage of design. The maximum bending moment for every stage must be checked with the finals stage design and adequate sectional and reinforcement requirements need to be incorporated.
- The bending moment across the deck varies with every construction stage. This must be checked with the final stage design and adequate

sectional requirements and reinforcement requirements must be provided based upon the construction stage variations.

- The axial force in the deck varies with every construction stage. This is a part of the final design. However, effects such as P-Delta effects and dynamic effects have to be carefully considered as the stiffness of the deck during the construction stage and final stage are very different.
- The stresses in the cables during the construction stage are a lot different than the stresses in the final stage model. In some cables the stresses are more than the final stage and the cables have to be designed for this.

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