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Analysis and Design of Cable Stayed Bridge

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Abstract – *Cable Stayed Bridges are one of the most fascinating icons in the field of Engineering and are commonly used bridge typologies for spans between 200m and 1100mm due to their structural efficiency, cost and aesthetics. The basic structural form of a cable-stayed bridge is a series of overlapping triangles comprising the pylon, the cables, and the girder. All these members are under predominantly axial forces, with the cables under tension and both the pylon and the girder under compression. Axially loaded members are generally more efficient than flexural members. This contributes to the economy of the bridge. In this project, we have made an attempt to analyse a three span Cable Stayed Bridge using the MIDAS Civil software based on the design parameters which includes the bending moment, shear force and displacement*

Key Words: Cable Stayed Bridges, Unknown Load Factor Optimization, Construction Stage Analysis, Influence Line Diagram (ILD)

1. INTRODUCTION

With this project, we aim to analyse a cable-stayed bridge. The bridge comprises a total length of 550m, with the central portion of 370m being the three span cable stayed bridge with prestressed deck having mainspan 190m and backspan 90m connected to two twin pylons using stay cables. Cable stayed bridge on either side is connected to prestressed T-Beam bridge of total length of 90m, divided into 6 spans of 15m each.

Paper is organized as follows. Section I contains the literature review for the referred journals. Section II covers the methodology followed to finalise the configuration of the cable stayed bridge and modelling steps in MIDAS CIVIL. Section III mainly deals with the analysis results in MIDAS CIVIL. Finally, Section IV presents a conclusion.

1.1 Literature Review

Umang A. Koyani, Kaushik C. Koradia[1] did a parametric study of a three span, two plane cable-stayed bridge with a box girder deck. The various parameters were considered for analysis of cable-stayed bridges; those are side span to main span ratio, upper strut height, cable system, number of cables per plane and cable diameter. The effect of above parameters on maximum girder moment, deflection, shear force, axial force in the girder is analysed in MIDAS CIVIL. It was found that with the increase in side to main span ratio maximum moment is decreased up to a certain limit and then increases. With increase in number of cables maximum moment in girder decreases. Marko Justus Grabow [2] has given a detailed methodology that is to be followed in MIDAS CIVIL for modeling and analysing the overall construction process of a cable-stayed bridge. An example of a construction stage analysis is provided in detail for the Second Jindo Bridge, Korea. Various analysis features on MIDAS CIVIL are also verified in the thesis. Gurajapu Naga Raju, J. Sudha Mani [3] analysed a 600m span single tower cable-stayed bridge for attaining the cable forces using Strain Energy Method with the help of C programming and STAAD Pro which gave comparable results. Girder moments and shear forces of the girder and the pylons were obtained from STAAD Pro and the results were verified manually. Holger Svensson [4] has covered all aspects of the design, construction planning and execution on site, dealing with principles that appear important to him based on his 40-year experience as a bridge engineer. His book includes the structural details of beams, towers and especially the stay cables which are a crucial component of cable-stayed bridges, the preliminary design of cable-stayed bridges which provides the best understanding of the flow of forces and permits initial sizing, and the erection of cable-stayed bridges, which is equally as important as their final stage.

1.2 Objectives

- To decide a suitable configuration for the deck, cables and pylon for a total length of 550m and height restriction of 44m
- To perform the detailed design and analysis of the superstructure.
- To understand the design procedure of a cable-stayed bridge on MIDAS CIVIL and acquire an in-depth knowledge of the software
- To perform construction stage analysis and post-construction analysis of cable-stayed bridge

2. METHODOLOGY

2.1 Configuration of Cable-Stayed Bridge

The total length of the bridge is 550m. The central Cable-Stayed portion of the bridge is a symmetrical three-span semi-fan type having two twin pylons with a total length of 370m. The rest of the bridge on either side is designed as a Tee Beam and Slab bridge simply supported on piers with an effective span of 15m. The deck of each cable-stayed cantilever section is supported by a total of 9 cables, with 9 cables arranged in each semi-fan configuration on each side of the pylon, in two planes, on either side of the bridge. Each reinforced concrete pylon comprises two towers and two crossbeams, the lower one supporting the deck. The longitudinal motion of the deck was restrained at the pylon bearing to resist temporary out-of-balance.

2.2 Steps followed to finalize the configuration of Cable-Stayed Length

1. Determination of back span to main span ratio (Optimum range: 0.45 - 0.55)
2. Determination of cable spacing (Optimum range for concrete: 5m - 15m)
3. Determination of deck stiffness (Number of longitudinal girder, Girder depth, Stay layout: harp, fan or intermediate)
4. Determination of stay angle [optimum angle 45°, permissible range 25°-65°]
5. Finalize pylon height considering height restriction (Optimum ratio of pylon height to the main span: 0.2 - 0.25)

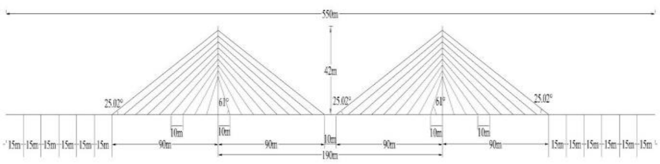
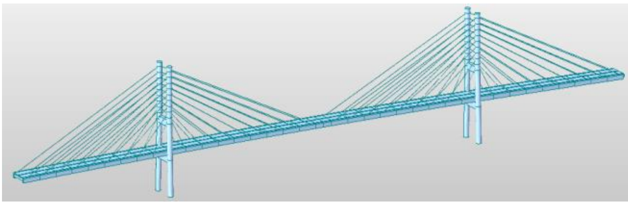


Fig -1: Longitudinal View of Bridge

2.3 Design Steps in MIDAS Civil

a. Defining material and section properties of each component of the bridge. M60 concrete is provided for the deck and pylons.
b. Cable Stayed Bridge Wizard function available in MIDAS is used to symmetrically model the 2D configuration of three span cable stayed bridge
c. It is then mirrored to obtain the 3D model of the bridge.
d. Cables are modeled as equivalent truss elements for linear analysis to obtain initial cable forces that will consider the decreased axial stiffness of cable due to sagging effect. It is then transformed to an elastic catenary element that considers the tangential stiffness during nonlinear analysis.
e. Pylon, longitudinal girder and cross beam are modeled as beam elements. Time dependent effects like creep and shrinkage are considered for non-linear analysis of concrete structures as per IRC 112: 2011.
f. Boundary input: The bases of pylons are fixed while the end supports of the cantilevered length on either side of pylons are simply supported.
g. Loading input as per IRC: 6-2014. Self-weight of components is auto-generated by the software. Thermal load, IRC live load, longitudinal forces, construction load and wind load are input as per IRC:6 specifications
h. Defining two lane traffic: The concerned Cable stayed bridge has a deck that can facilitate two lane traffic on it. The width of each lane is 3.5m. In order to define lane 1 the frame numbers are entered with lane width. And then the second lane is defined where the lane numbering is entered in reverse order so that the vehicles on that lane move in the opposite direction to that of the vehicles moving in lane 1.

Fig -2: 3D Isometric View of Bridge in MIDAS Civil



3. ANALYSIS RESULTS

3.1 Unknown Load Factor Optimization (ULF)

Unknown load factor optimization function in MIDAS calculates the load factors in order to satisfy specific constraints like displacement or bending moment defined for a system.

Table -1: Initial Pretension Forces in Each Cable per Pylon

Cable No.	Pretension Force (kN)	Cable No.	Pretension Force (kN)
1	5610.2	2	4226.528
3	3503.219	4	3482.771
5	3604.084	6	3369.743
7	2630.308	8	1155.452
9	74.1	10	401.65
11	1052.976	12	1734.661
13	2437.215	14	3123.742
15	3786.562	16	4298.765
17	4468.29	18	4078.875

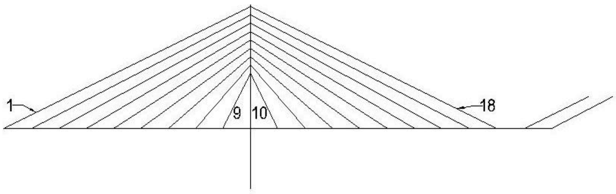


Fig -3: Cable Numbering

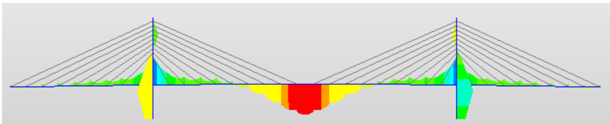


Fig -4a: Bending Moment Diagram before ULF Optimization

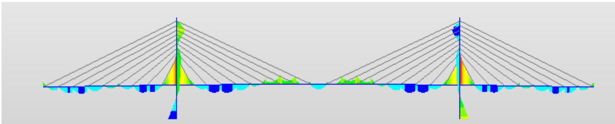


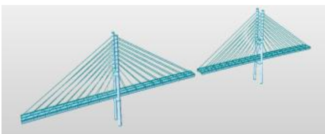
Fig -4b: Bending Moment Diagram after ULF Optimization

3.2 Construction Stage Analysis

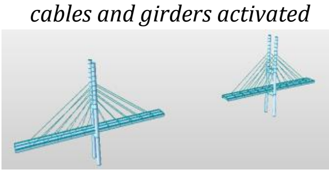
3.2.1 Backward Analysis

After the determination of the ideal cable forces, and applying the initial prestress, backward analysis of the bridge is performed. Backward construction stage analysis is performed from the state of the finally completed structure for which an initial equilibrium state is determined, and the elements and loads are eliminated in reverse sequence to the real construction sequence.

CS0: Final Model. All loads, cables and girders activated



CS2: Key Segment removed



CS16: Sidespan 4th cable removed

CS38: All cables and girders removed

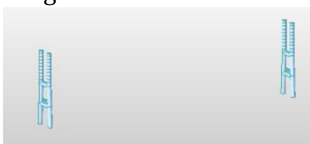
Fig -5: Construction Sequence in Backward Analysis

Table -2: Cable Axial forces just before deactivation

Cable No.	Cable Force (kN)	Cable No.	Cable Force (kN)
1	2446.18	2	2131.05
3	1872.78	4	1794.66
5	1665.94	6	1579.17
7	1435.12	8	980.57
9	199.8	10	274.22
11	881.74	12	1243.67
13	1505.59	14	1717.34
15	1897.27	16	2034.81
17	2113.98	18	2109.61

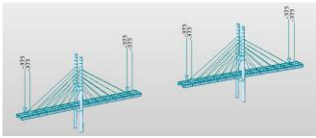
3.2.2 Forward Analysis

The forward analysis reflects the real construction sequence and using this analysis time dependent effects (creep, shrinkage) can be considered and implied in the design.



CS0: Pylons erected

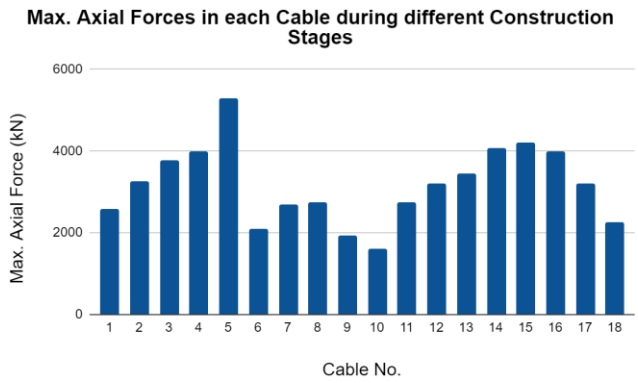
CS8: Pretension load and segment load activated



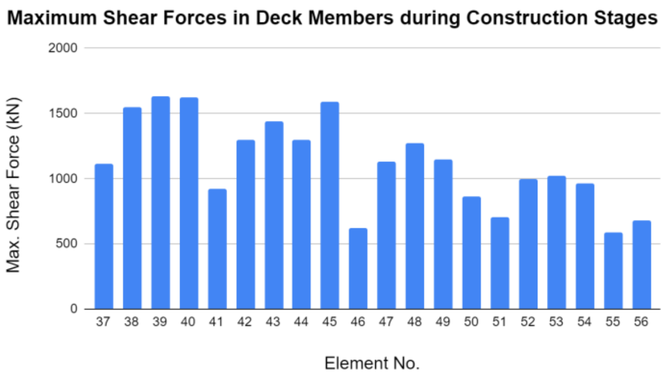
CS26: 7th Mainspan girder constructed

CS38: Key Segment added. All loads activated

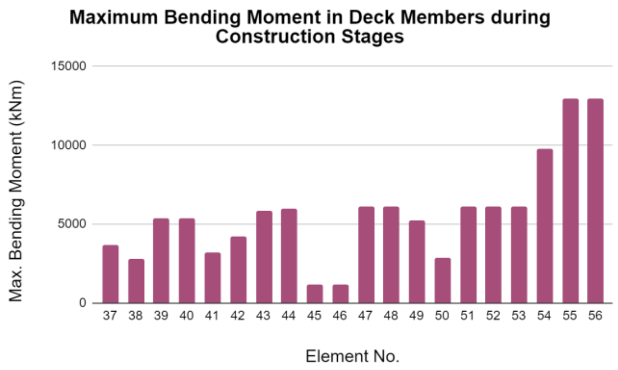
Fig -6: Construction Sequence in Forward Analysis



Graph -1: Axial Force variation in Cables during Forward Analysis



Graph -2: Shear Force variation in Deck during Forward Analysis



Graph -3: Bending Moment variation in Deck during Forward Analysis

3.3 Moving Load Analysis

The moving load analysis is performed as per Table 2 Live Load Combinations in IRC: 6-2014 for 2 lanes.

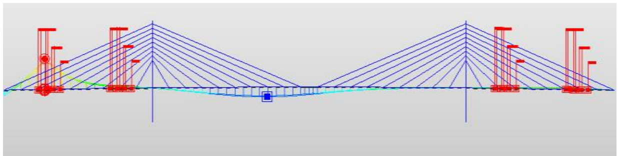


Fig -7: Position of Class 70R and ILD to get critical moment (16348kNm) in Deck at Backspan

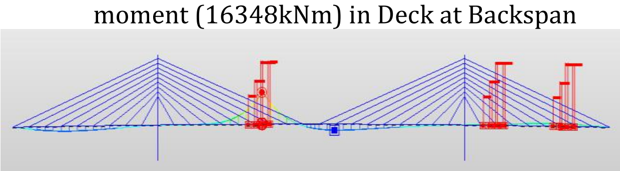
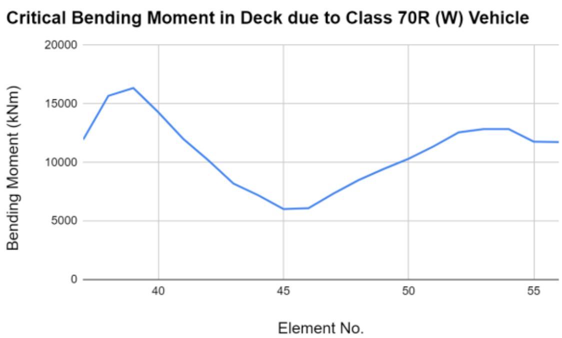


Fig -8: Position of Class 70R and ILD to get critical moment (12562kNm) in Deck at Mainspan



Graph -4: Bending Moment Variation in Deck due to critical position of Class 70R[W] Vehicles

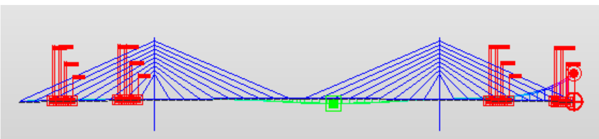


Fig -9: Position of Class 70R and ILD to get critical shear force 1540.9kN at support

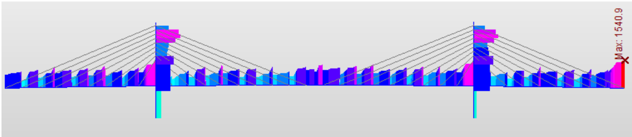


Fig -10: Critical Shear Force Diagram for deck due to different position of Class 70R Vehicles

Displacement due to Live Load:

Maximum displacement at centre of backspan = 60mm
Maximum displacement at centre of mainspan = 55mm

Check for Displacement due to Live Load:

Allowable deflection (δ_{max}) of cable-stayed bridge as per AASHTO = L/400

δ_{max} = 0.475m

Maximum displacement at backspan = 60m = 0.06m < 0.475m

Maximum displacement at mainspan = 55m = 0.055m < 0.475m

4. CONCLUSIONS

- Cable Stayed Bridges are very versatile structures whose behaviour is affected by a large number of design parameters like backspan to mainspan ratio, pylon height, number of stay cables, stay angle, pylon geometry, deck material and dimensions of various components.
- So first we conducted a study to obtain an optimum configuration for the proposed site. The backspan to mainspan ratio is 0.47 (between 0.45 - 0.55 for concrete bridges) and pylon height is 42m which had to be restricted.
- Concrete was chosen for both deck and pylon as both these materials are predominantly under compression.
- The H-shaped twin tower pylon was chosen for a two plane cable system with semi-fan pattern as it combines the advantages of harp (aesthetics) and fan (efficiency) patterns and eliminates their disadvantages.
- The cable angle was found to be between 25°-61° and the cable spacing is 10m which is optimum for concrete deck and cast-in situ balanced cantilever construction.
- In the Unknown Load factor optimization, it can be inferred that the maximum axial forces occur for the stay cables that are farther away from the pylon (5610.2kN) than the cables near to the pylon (74.1kN). This is because these cables are more effective in supporting the loads.
- In the backward construction stage analysis, the cable forces varied from 199.8kN near the pylon to 2446.18kN at the extreme end. The forces in cables

are maximum when the next cable gets deactivated creating a cantilevered deck and minimum when this cantilever deck segment gets deactivated.

- The pretension forces required for backspan cables (2600kN) are greater than mainspan cables (2500kN) as the loads from the mainspan are transferred to the pylon by the mainspan cables and finally it is carried by the back span stay cables at the end of forward construction stage analysis.
- Large deflection in deck and pylon occurs during construction stage analysis by balanced cantilever method thereby necessitating the need to carry out construction stage analysis to avoid unpredicted problems during actual construction and avoid huge economic losses.
- Live load combination provided is Class 70R for one lane and Class A in two lanes in opposite directions as per IRC:6-2014.
- Maximum bending moment (16348kNm) and shear force (1540.9kN) was found to be occurring in the back span for moving load analysis.
- The deflection in the deck due to live load was found to be within the limit as per relevant codes.
- Therefore, this study would give some knowledge of analysis of a three-span cable-stayed bridge with an H-shaped tower and how to use MIDAS software to perform the analysis of Cable Stayed Bridge.
- For the future scope of this project, the obtained bending moment and shear force data can be used to design the different components of the structure.

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