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"Construction Stage Analysis of Cable - Stayed Bridges"
(Tuti Bahari Bridge)

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Abstract
The erection procedure of the cable-stayed bridge depends on its structural system. Methods of erecting of cable-stayed bridges are as varied and numerous as the ingenuity and number of ere10ctor contractors. The erection method not only affects the stresses in the structure during erection but may also have an effect on the final stresses of the complete structure. This paper deals with the analysis of cable-stayed bridges at different erection stages during construction, The backward construction process analysis is investigated. The stage by stage construction of TUTI BAHARI cable stayed bridge is performed using MIDAS Civil software. The required pre-tension forces in cable-stays and the corresponding structural configurations of the bridge at different erection stages have been examined and compared in details. The objective of the construction stage analysis simulation is to identify stresses and deformations of the concrete girder and towers, as well as the cable tension stress, to meet the design requirements. Because large deflections occur in the bridge during cantilever construction, it's necessary to perform construction stage analysis for the cable stayed bridge. The results obtained during the backward construction stage analysis are compared with the AASHTO 2010 requirements.

Keywords: Erection procedure, Backward construction, Construction stage, Pre-tension.

1. Introduction
The erection procedure depends on the structure system of the bridge, the site conditions, dimensions of the shop-fabricated bridge units, equipment and other characteristic of the particular bridge (2).

The methods of the erection for cable-stayed bridges are broadly described by three different construction methods. These are: the staging method, the push-out method and the cantilever method. The staging erection method is most often used where there is a low clearance requirement to the underside of the structure and temporary bents will not interfere with any traffic below the bridge. Its advantage is its accuracy in maintaining required geometry and grade and its relatively low cost for low clearance. The push-out technique has been used successfully on a number of occasions in Europe but is relatively new to American construction. This method is commonly used in Europe where care must be taken not to interfere with traffic below the bridge and where cantilever construction is impractical. In this method, large sections of bridge deck are pushed out over the piers on rollers or sliding Teflon bearings, the deck is pushed out from both abutments toward the center or in some instances, from one abutment all the way to the other abutment. Assembling the components in an erection bay at one or both ends of the structure and progressively pushing the components out into the span as they are completed can simplify construction and reduce cost.(3).

The cantilever erection method is very often employed in cable-stayed bridge construction where temporary supports are necessary. It may increase the steel requirements over that required for final positioning to accommodate the increased moments and shears during the erection process. The principal advantage is that it does not interfere with traffic below the bridge.

Erecting the stiffening girders and deck are either by the cantilever method or by using a few intermediate temporary supports. For this purpose, cranes are used moving on the already erected structure, or floating cranes which may erect whole prefabricated sections. During erection by the free cantilevering method, temporary guy ropes are sometimes introduced to restrict the excessive deflections caused when more panels are added.

The erection procedure for cable-stayed bridges with only a central main girder and cables in a single plane system is basically the same as that used with the two- plane cable system. Erection is carried out by cantilevering from the first span of each approach viaduct, so that the bridge grew from the abutments along each viaduct. Then each side span and, finally, each half of the main span is erected, until the two halves meet at the center of the river. The first few sections are lifted by specially designed gantry-type cranes onto false work to support the first span while the joints between sections are welded up.

If the tower is connected to the plate girders, whole sections are erected behind the abutments on the earth embankment and subsequently moved towards the final position. Often particular care must be taken not to interfere with the existing traffic. In such cases, the whole superstructure is assembled on the side and jacked forward on movable bearings. Assembling the bridge is done unit by unit from the rear end and continually moving forward as construction proceeds, so that with the last shove the entire bridge is moved into its final position. It should be noted that the sliding movement is not performed with the aid of rollers, but on Teflon sliding pads (2).

Fabrication and erection costs add significantly to project cost estimates, and, as a result, present trends are to fabricate components as large as possible for simplified erection. In this manner larger components of the bridge are assembled in the shop in contrast to assembling many smaller units in dangerously elevated, exposed position on the project site. The vagaries of inclement weather are avoided to a certain extent because fewer components must be erected. The techniques and methods of erecting cable stayed bridges are as varied and numerous as the ingenuity and number of erector contractors(3).

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The purpose of this paper is to model TUTI BAHARI cable-stayed bridge as per its geometry and find the initial pre-tension force in cables using unknown load factor method. Then, the construction stage analysis is done using finite element Software MIDAS Civil, in which backward construction stage analysis is carried out. In backward construction stage analysis there is activation and deactivation of various structural groups, boundary groups and load groups to stimulate action of actual construction. The results obtained during the backward construction stage analysis are checked to be in agreement with the AASHTO 2010 requirements.

2. Research Problem Statement

•The non-linear structural behavior of cable stayed bridges is not yet established .Structural stability of the whole bridge under gravity and wind loads presents increasingly important problems both in design and construction. These problems result from the high compressive force in the towers and deck as well as the large forces on the flexible bridge.

•The cable and the pre-tension required are still under investigation .Most of the methods proposed in literature are either inadequate or prone to have drawn backs.

3. Objectives of the Research

The objectives of this study are:.

•To analyze the cable-stayed bridge using non-linear finite element package programs. MIDAS civil

• Analysis the model of cable – stayed bridge during Construction stage..

•To determine the optimum pre-tensioning cable forces, displacement and stress during construction stage.

•To check the results obtained from analysis the model with AASHTO 2010,

4. Literature review

Alessio Pipinato, Carlo Pellegrino and Claudio Modena, 2012, (4) studied the analysis of cable-stayed bridges at various erection stages during construction. The forward construction process and the backward construction process analysis were investigated by using MIDAS 2000. They also compared the use of either the linear computation procedure (linear theory) or the nonlinear computation procedure (nonlinear theory).

Xue Chengfeng ,Liu Laijun,WuFangwen and Yang Caofang, 2015,(5) presented in their paper, a general methodology for construction processes to simulate a cable-stayed bridge. The construction stage of the Sutong Bridge was simulated with ANSYS program software package.

M .F. Granataa, P. Margiottaa, M. Aricia and A, Recuperob, 2012,(6) proposed a methodology for the evaluation of initial cable forces in composite bridges, based on simple partial elastic schemes of construction stages and presented reports for a comparison between different stay stressing sequences in order to evaluate the consequences of each one to the states of stress and to the final geometry of deck and pylon.

Prataprao Jadhav, Mohan Ganesh and Vinayagamoorthy M. ,2017,(7) carried out a study to determine the cable installation forces. Also, the initial equilibrium state for dead load at the final stage was determined. The unit load method was used to find the cable pretension loads. The Finite Element MIDAS Civil software was used to determine the cable forces.

Karthik .H. Purohit, A.A Bage ,2017, (8) carried out the static analysis on an actual three lane cable stayed bridge in Nagpur known as “Ram Jhulla”, which was under construction above the Nagpur Railway Station, with overall span of 200 m. Also, the construction stage analysis considering time dependent material properties like creep and shrinkage was carried out using finite element MIDAS Civil software. They, also checked various parameters like cable forces, deflection, axial force, bending moment during construction stages. The results obtained for deflections were compared with actual field measurements.

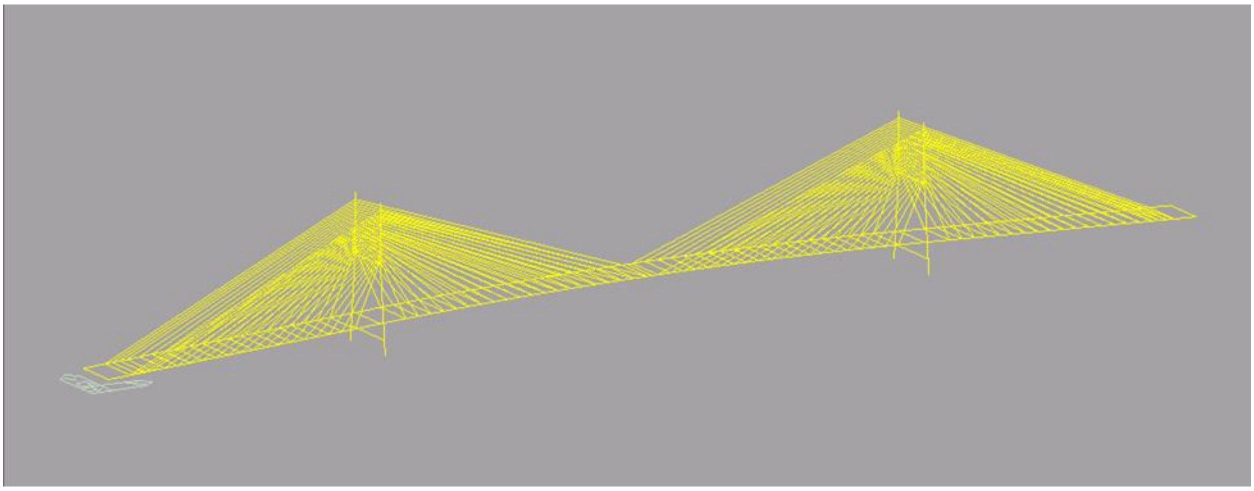

Fig. 1 TUTI BAHARI bridge elevation view

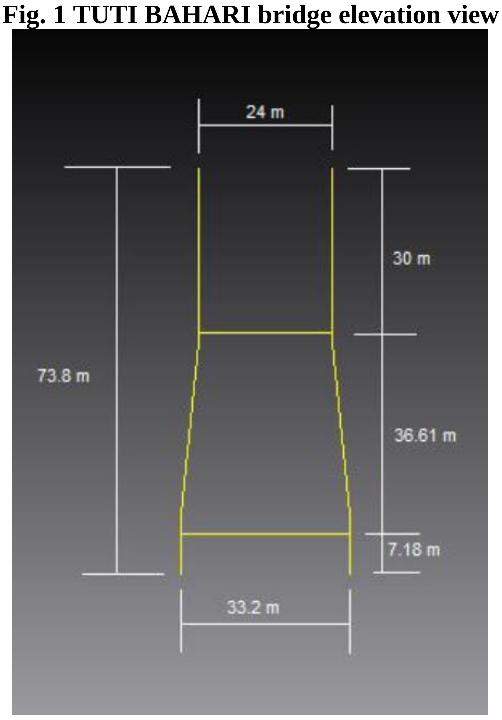

Fig. 2 Tower dimensions

5. Modeling and Simulation

5.1 Description of the Bridge

The data for TUTI BAHARI Bridge under consideration, which is the 3-span composite cable-stayed bridge, is described in Table 1

Table (1) description of the proposal bridge

Name	Description
Type of bridge	Cable - stayed bridge
Total length of bridge	600 m
Main span	300 m
Span arrangement	3 span arrangement
Width of bridge	24 m
Height of tower	73.8 m
depth of the deck slab	0.35 m
Number of pylons	2 towers
Type of pylon	H- shape
Cable arrangement	Semi- Fan type

5.2Properties of material

The material properties that are used in the proposed TUTI BAHARI bridge with H-shape tower model, are as follows:

- **For Stay Cable Steel:**
- Modulus of Elasticity = 197 GPa
- Tensile strength = 1860 MPa
- Poisson's ratio, v = 0.3
- Density γ = 78.5 kN/m^3
- Nominal diameter of strand =15.2 mm
- Thermal coefficient = 6.5010^{-6}/°F
- **For Concrete:**
- Modulus of Elasticity= 2.76*107kN/m^2
- Concrete Strength, f_{cu}= 24.5 kN/m^3
- Thermal coefficient = 5.0×10^{-6}/°F

5.3Finite Element Method& Modeling

The 2D&3D finite element model of the TUTI BAHARI Bridge was developed and analyzed during construction stage using MIDAS Civil software. The unknown load factor method was used to find the optimum pre-tensioning cable force for bridge. The objective of the construction stage simulation is to identify stresses and deformations of the concrete girder and towers, as well as the cable tension stress. The cables were modeled as truss elements (160 elements). The pylons and the deck were modeled as straight frame elements (356 elements).The structure was modeled using the data presented in Tables 2, 3 and 4

5.4 Construction Stage Analysis

To check the stability during construction, construction stages should be defined in the design of a cable stayed bridge. The structure system could change significantly based on the erection method. The change of system during construction can result in a more critical condition for the structure compared to the state of the final stage. The cable pre-tensioning forces, which are introduced during the construction of a cable–stayed bridge, could be calculated by backward analysis from the final stage. To perform a construction stage analysis, construction stage should be defined to consider the effects of the activation and deactivation of main girder, cables cable anchorage, boundary condition, loads, etc. To review the changes during construction, each stage must be defined to represent a meaningful structural system. Fig 3 outlines the steps that are carried out to generate the construction stage analysis model.

5.4.1 Backward construction stage

The Construction stage analysis for a cable-stayed bridge can be classified into forward analysis and backward analysis, based on the analysis sequence. 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. The Structure Group SG0 to SG62 is defined by eliminating main girders and cables sequentially.

Construction stage **CS62** is the stage in which all the cable elements and main girders in the center span are eliminated, and the temporary bents in the side spans are erected. Actually, this is the 1st stage in the cable-stayed bridge construction.

The analytical sequence of backward construction stage analysis for TUTI BAHARI model is as shown in fig 4 to fig 8.

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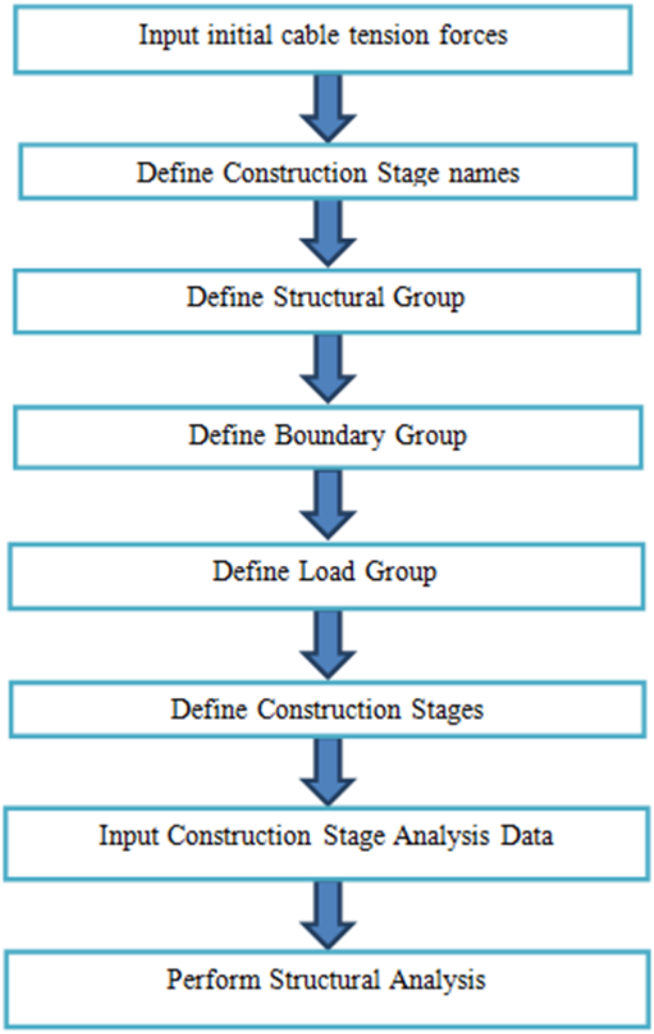

Fig. 3 Flowchart for Construction Stage Analysis

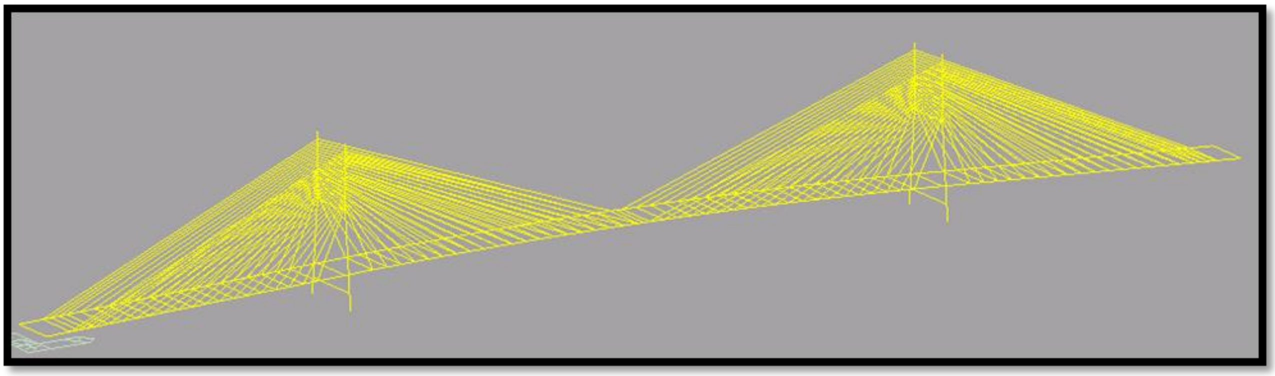

Fig 4 Definition of structure group (SG0)

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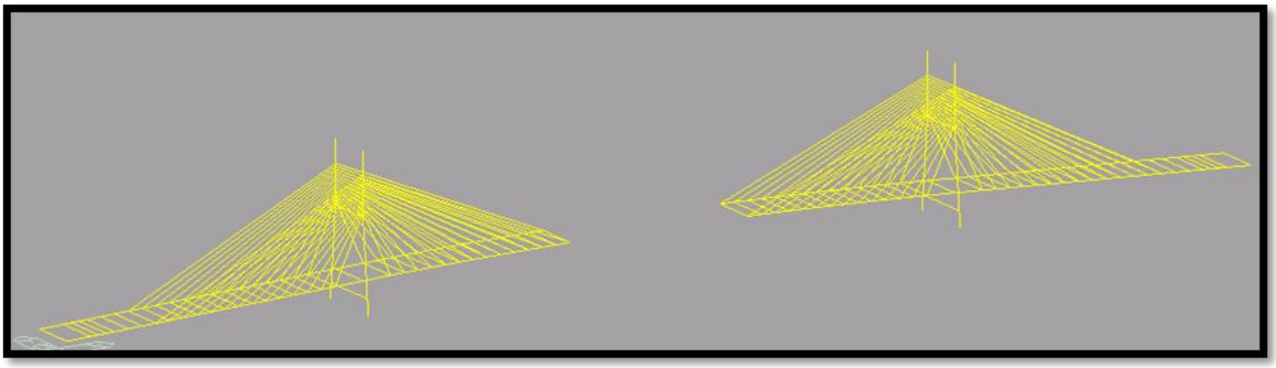

Fig 5 Definition structure group (SG20)

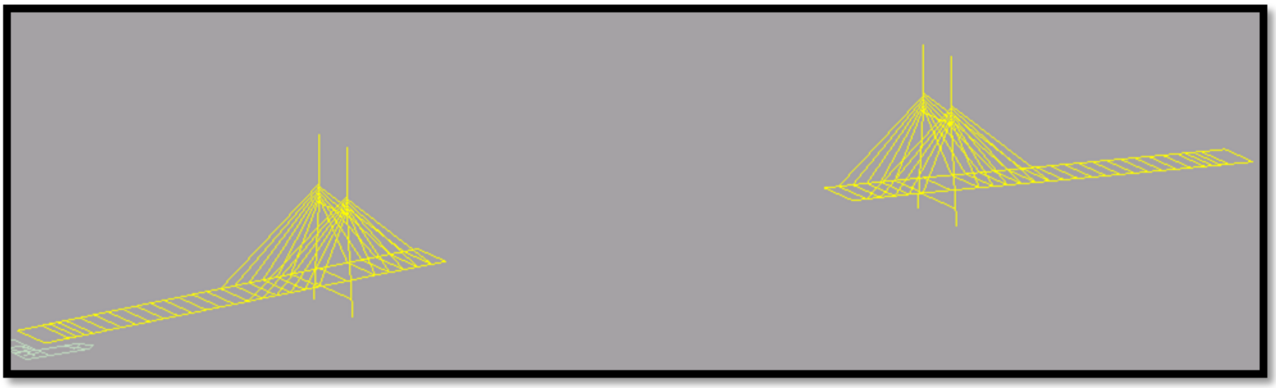

Fig 6 Define structure group (SG45)

Fig 7 Definition of structure group (SG55)

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Fig 8 Definition of structure group (SG62)

6. Results and Discussion

The result of the Construction Stage Analysis for each construction process requires detailed information on the existing partial structure to determine the actual structure state, investigate the deflection, and thus meet design guidelines. For the TUTI BAHARI cable-stayed bridge, some criteria in the construction stage were based on the design specification and construction scheme. Specifically, a zero allowable tension for the concrete tower was guaranteed in the construction stages analysis; each cable tension stress needed to be less than 0.45 times the cable design stress. These limitations played an important role in the construction stages to ensure that the erected structure was in a safe state. The check of backward Construction Stage Analysis Results is as follows:

6.1 Cable pre – tension

For each construction stage, axial forces for cables are reviewed as shown in Fig. 9 and Fig. 10. Also, the variation of cable pre-tension is reviewed by using the Step History Graph function. The variation of cable tension forces is checked for each construction stage for inner cables in the tower area from the final stage (CS0) to the last stage (CS62). In the construction stage analysis shown in Fig.11 and Fig. 12 the graphical variations contain the evolution of these pre-tension forces according to the stages considered in the analysis and is indicated the cable pre-tension (cable20),(cable60) outer cables, and (cable 20).(cable 21) inner cables, respectively for each CS. Notice that the value of pre –tension for cables 20,61 reached the maximum value 6970.77 kN ,5500 knN at(CS 59). Also, for cable 21 the maximum value is 2197.69kN at (CS57).

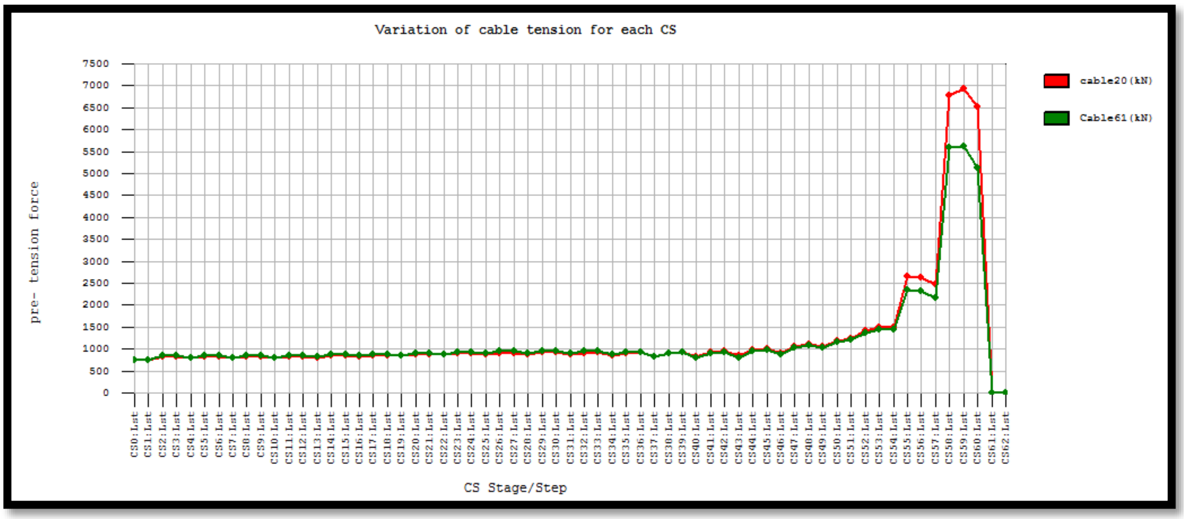

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Fig 11 variation of cable pretension for each CS

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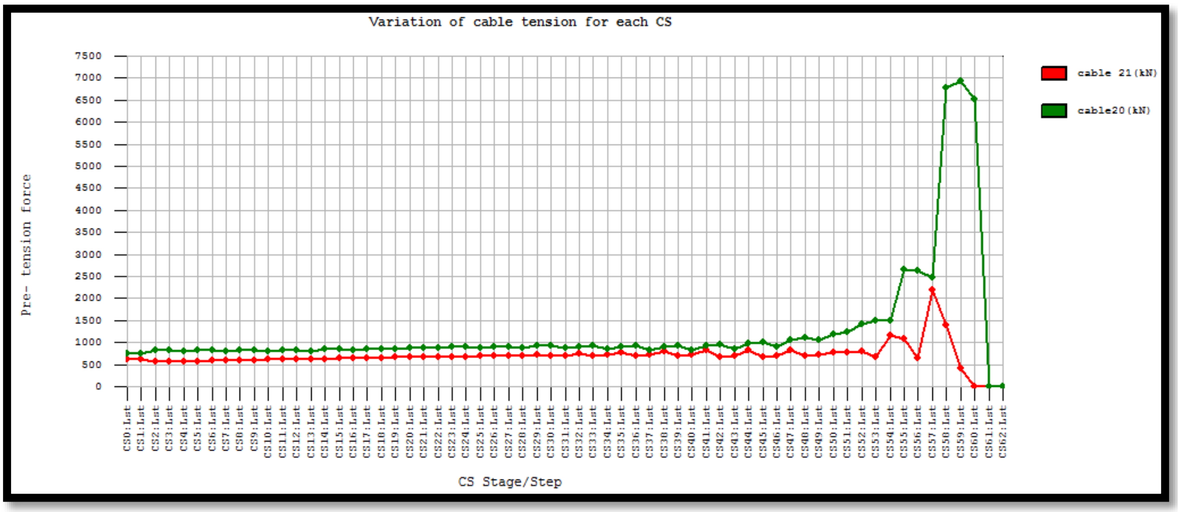

Fig 12 variation of cable pretension for each CS

6.2 Deformation

The changes of deformed shapes and section forces for each construction stage are reviewed by construction stage analysis as shown in Fig. 13 and Table 5. Also, the deformed shapes of the main girders and towers for each construction stage are reviewed using construction stage analysis graphs. For each construction stage, the horizontal displacements for the towers and vertical displacements for the main girders are checked at the ¼ point location of a side span. Fig 14 shows the graphic variation of horizontal and vertical displacement for each CS. The maximum vertical displacement is 0.039m at CS61. The minimum vertical displacement is -0.014m at CS31. Also, the maximum horizontal displacement is 0.043m at CS62 and the minimum horizontal displacement is -0.053m at CS 57.

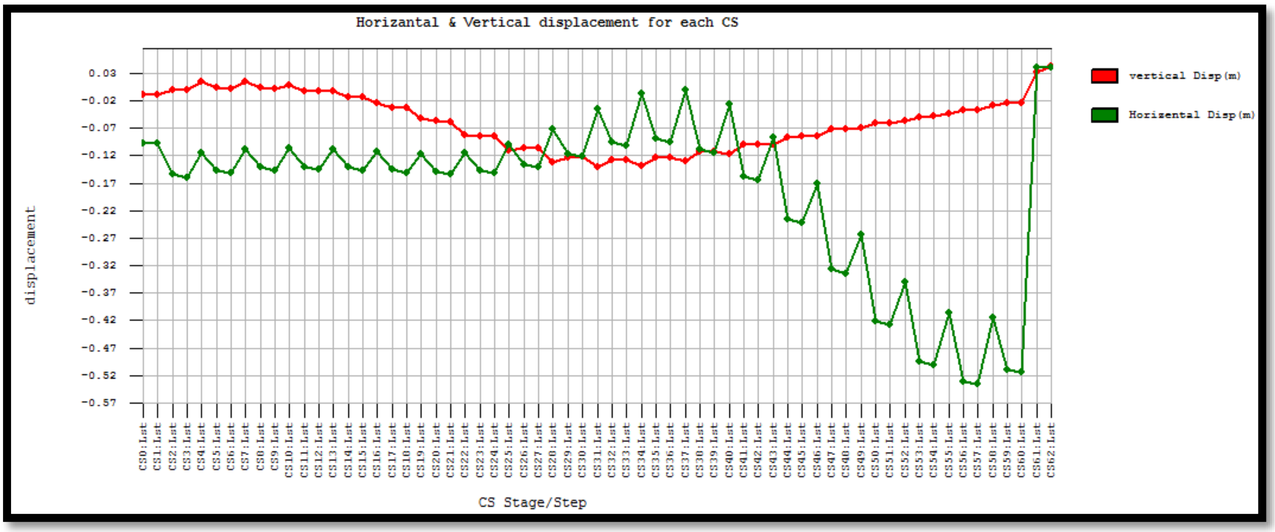

Fig 14 variation of horizontal and vertical displacement for each CS

6.3 cable stresses

For each construction stage, cables's stresses, main girder and tower stresses are reviewed as shown in Figures 15, 16 and 17. Also, the variation of cable stresses is reviewed by using the Step History Graph function from the final stage (CS0), as shown in Fg 18. The maximum value of cable stresses is 260 N/mm^{2}at cable (1).

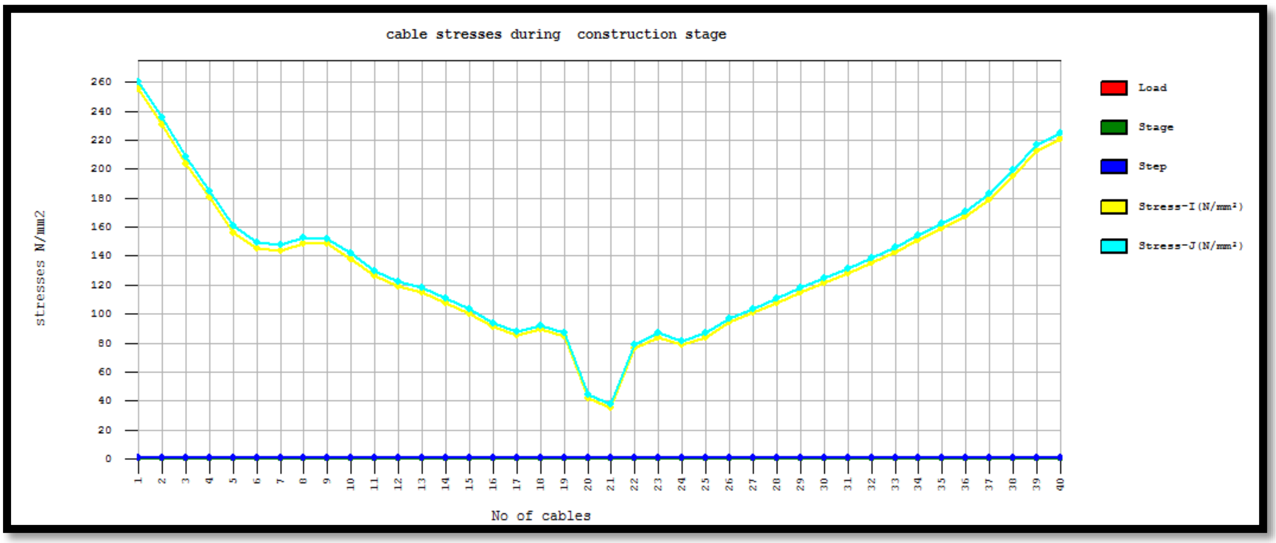

Fig 18 variation of cable stresses for each CS

7.Conclusions

A finite element methodology is presented for the construction simulation analysis of TUTI BAHARI cable-stayed bridge**.** The simulation analysis is used to determine the pre-tension force in the cable at each construction stage and identify the consequent deformation and stress of the structure. The finite element software MIDAS Civil has been applied in the simulation of the construction process.

- The results obtained during the backward construction stage analysis are compared with the AASHTO 2010 requirements.
- The minimum and the maximum deformation for all construction stages are controlled to be within the allowable range.
- During the construction stage the tensions in the cables were changing, because every cable was stressed initially in the installation stage.
- The maximum value of the cable stresses occurs at the outer cable, this value is within the allowable range.
- In conclusion, the cable-stayed bridge under this study during each of the construction stages is found to be stable, which is a reasonable result.

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Table (2): loading data of the model

Classification	Load type	Load
Dead load	Self- weight	Automatically calculated within the program
Additional dead load	Additional dead load (pavement, railing and parapets)	[99 kN/m]

:Table (3): Boundaries conditions

Boundaries	No
Support (fixed, pinned, roller)	20
Elastic link	4
Rigid link	8

Table (4) cable pre – tension forces

cable name	Optimized pretension load kN
Cable 1	6670.924041
Cable 2	6133.455631
Cable 3	5531.530848
Cable 4	4960.141608
Cable 5	4366.901929
Cable 6	4111.069787
Cable 7	4153.699496
Cable8	4344.880506
Cable 9	4378.645481
Cable 10	4106.029361
Cable 11	3781.592797
Cable 12	3576.922482
Cable 13	3457.736178
Cable 14	3238.497308
Cable 15	3034.995205
Cable 16	2759.147190
Cable 17	2596.184180
Cable 18	2662.053959
Cable 19	2430.958754
Cable 20	1073.910331
Cable 21	914.853003
Cable 22	2173.403144
Cable 23	2457.236897
Cable 24	2368.680407
Cable 25	2519.996643
Cable 26	2813.879131
Cable 27	3015.172401
Cable 28	3212.806949
Cable 29	3442.335628
Cable 30	3640.376023
Cable 31	3855.259550
Cable 32	4068.631079

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Cable 33	4268.056633
Cable 34	4476.635361
Cable 35	4678.992708
Cable 36	4836.211000
Cable 37	5061.540512
Cable 38	5356.495682
Cable 39	5623.689377
Cable 40	5611.981492

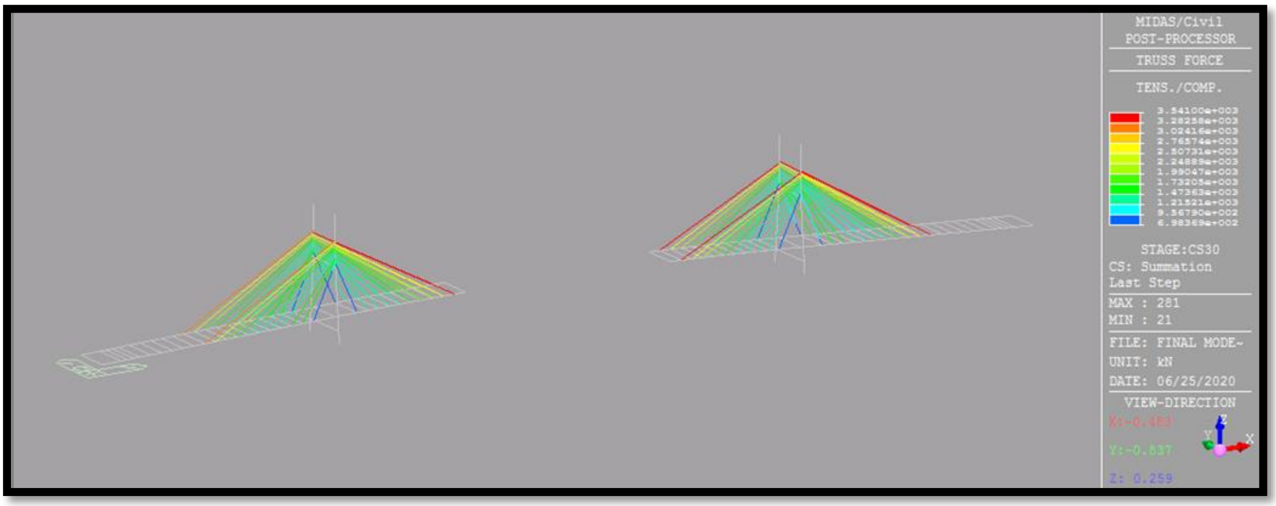

Fig. 9 Axial Forces for Each Construction Stage from Backward Analysis

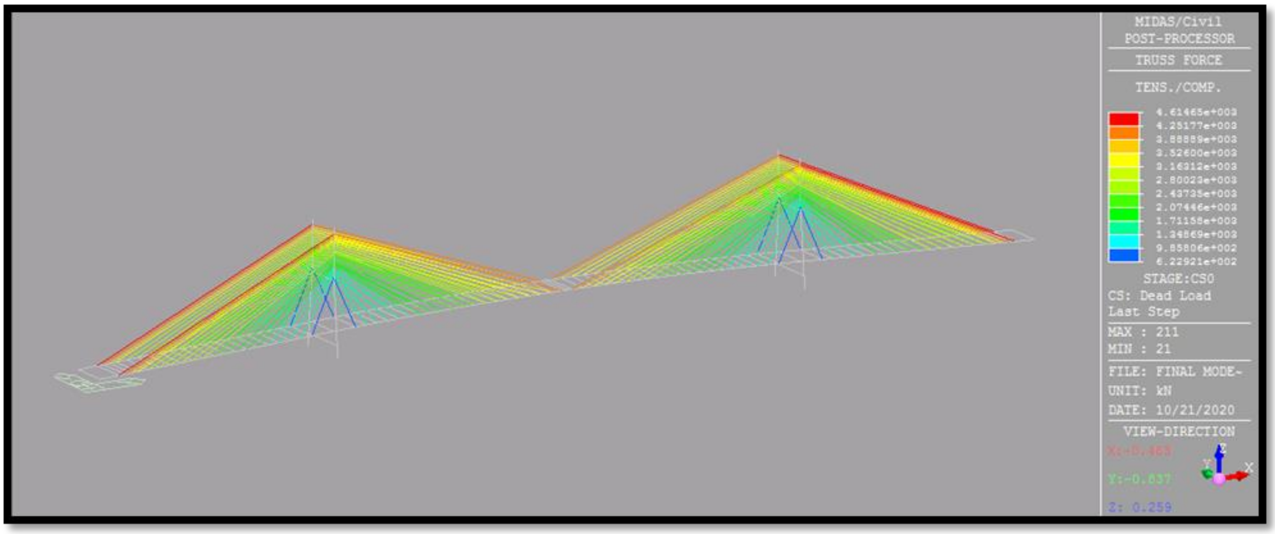

Fig. 10 Axial Forces for last Construction Stage from Backward Analysis

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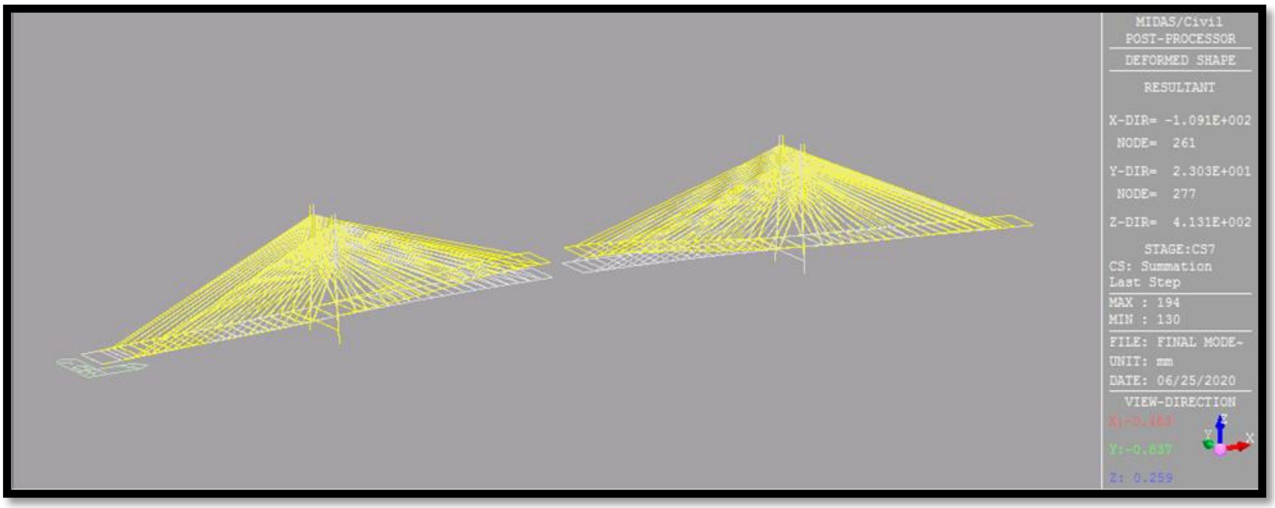

Fig. 13 Deformed Shape for Each Construction Stage from Backward Analysis

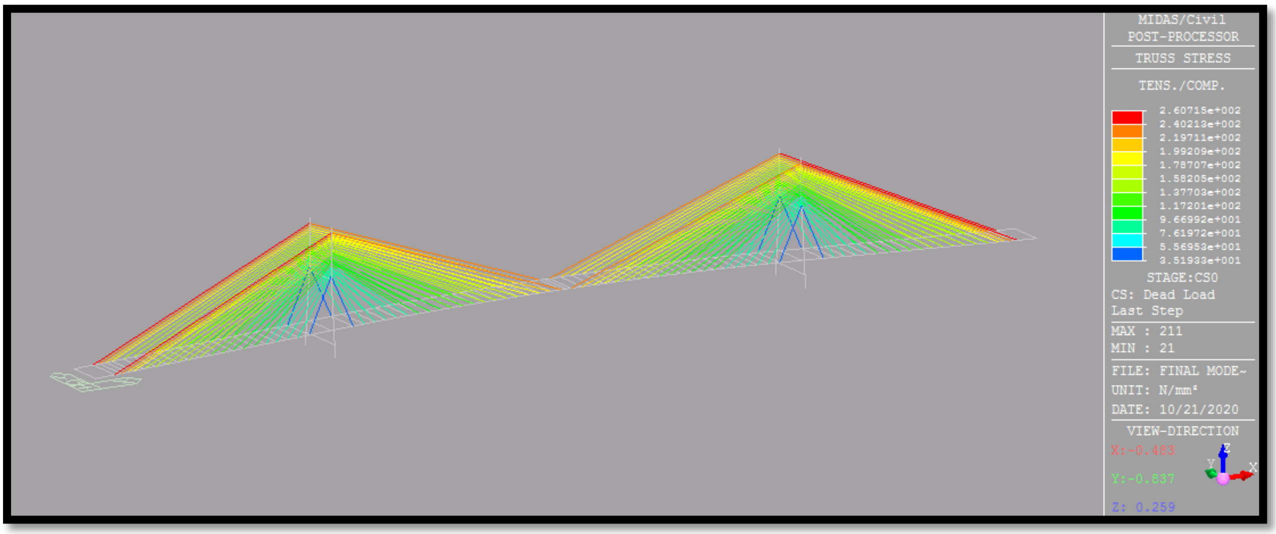

Fig. 15 Cable stresses for last Construction stage

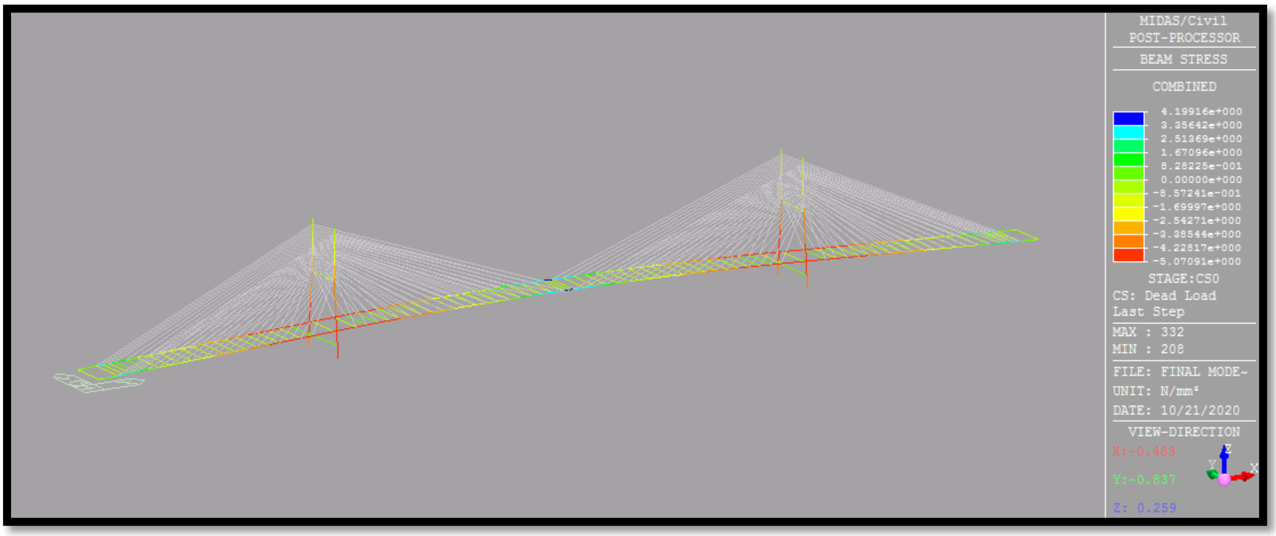

Fig. 16 Main girder and tower stresses for last Construction stage

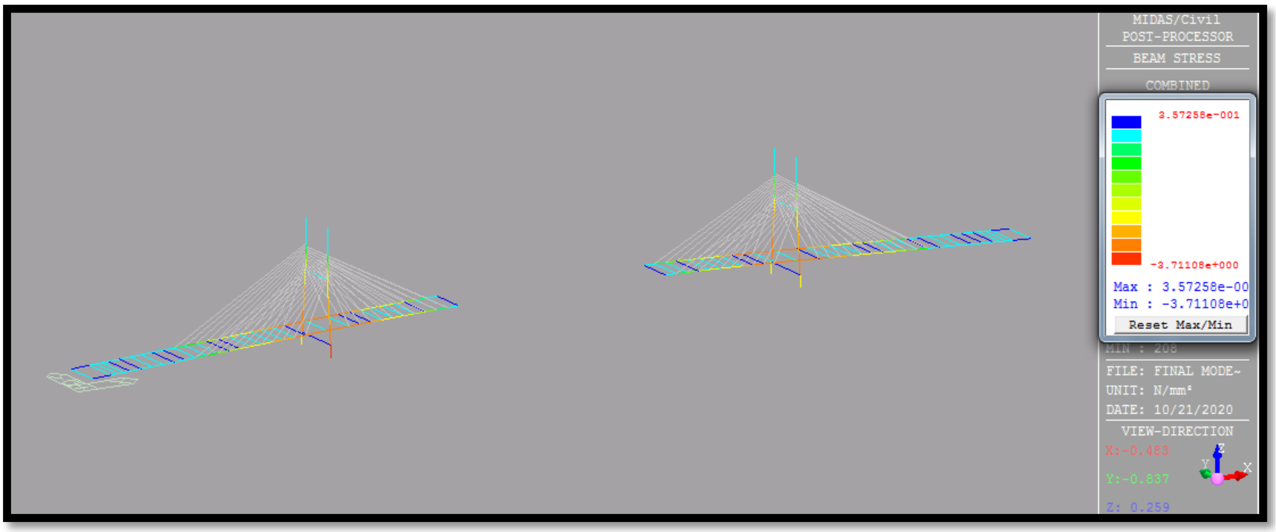

Fig. 17 Main girder and tower stresses for each Construction stage

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Table (5): Deformed Shape for Each Construction Stage

Construction Stage	Vertical displacement	Horizontal displacement	Construction Stage	Vertical displacement	Horizontal displacement
Cs0	- 10.3	-97.44055	Cs32	-127.76010	-95.33509
Cs1	-10.03454	-97.44055	Cs33	-127.02850	-100.98680
Cs2	0.01545	-154.29320	Cs34	-139.23120	-6.39725
Cs3	-1.16383	-159.49210	Cs35	-123.56560	-88.50378
Cs4	14.52486	-114.30140	Cs36	-122.73490	-95.01644
Cs5	3.90967	-146.87500	Cs37	-130.01760	-0.40667
Cs6	2.58016	-152.32190	Cs38	-113.31360	-107.73530
Cs7	14.88466	-108.44090	Cs39	-112.49350	-115.06580
Cs8	3.79699	-141.76040	Cs40	-116.19890	-26.46180
Cs9	2.39613	-147.29890	Cs41	-99.91570	-157.55240
Cs10	9.08832	-106.39160	Cs42	-99.18617	-165.43420
Cs11	-1.74802	-139.98470	Cs43	-100.45270	-85.98063
Cs12	-3.11654	-145.49560	Cs44	-85.71919	-234.57710
Cs13	-2.89066	-107.60180	Cs45	-85.12448	-242.58540
Cs14	-12.72077	-141.05000	Cs46	-84.75350	-170.01030
Cs15	-13.95854	-146.44290	Cs47	-72.26201	-327.06060
Cs16	-24.55289	-112.61260	Cs48	-71.81554	-334.69810
Cs17	-32.18589	-145.52430	Cs49	-70.12215	-264.35820
Cs18	-33.15378	-150.71880	Cs50	-60.18661	-420.09140
Cs19	-52.87154	-116.67660	Cs51	-59.87806	-426.87600
Cs20	-57.28549	-149.24220	Cs52	-56.59470	-350.11310
Cs21	-57.89316	-154.20110	Cs53	-49.22558	-495.05360
Cs22	-83.30624	-114.46440	Cs54	-49.02219	-500.36380
Cs23	-83.67364	-147.73020	Cs55	-43.21503	-406.45420
Cs24	-83.88716	-152.50620	Cs56	-38.16840	-531.73650
Cs25	-111.47450	-100.34250	Cs57	-38.05169	-534.54360
Cs26	-107.15960	-136.80700	Cs58	-28.28876	-414.74640
Cs27	-106.98480	-141.55940	Cs59	-24.88302	-510.49750
Cs28	-131.96910	-71.77645	Cs60	-25.12800	-514.00000
Cs29	-122.87710	-116.37060	Cs61	32.87635	39.45670
Cs30	-122.36930	-121.38650	Cs62	43.48860	39.45670
Cs31	-140.82740	-35.24723			

المستخلص:

نجد بان هنالك العديد من التقنيات والطرق المستخدمة في تشييد الجسور المدعمهبالكوابل .وتوثر طرق التشييد هذه علي الاجهادات التي يتعرض لها المنشأ اثناء فترة التشييد وكذالك في المرحله النهائيه للتشييد. في هذه الدراسة تم تحليل الجسر المدعم بالكوابل توتي – بحري الذي يربط بين منطقة الخرطوم بحري وجزيرة توتي(تحت الدراسة) لمراحل التشييد المختلفه للجسر باستخدام برنامج الحاسب الالي Midas civil معتمدا في التحليل بطريقة backward analysis,وحيث ان البرنامج يتميز بالطريقة المثلي في ايجاد معامل الحمل لحساب قوة الشد المطلوبه في الكوابل التي تمثل عاملا مهما فيعملية التشييد. نجد بان الهدف من مراحل التشييد هو التعرف علي الاجهادات والتشوهات للعارضة الخرسانية والابراج المكونه للجسر وايضا اجهادات الشد للكوابل .ونسبة لحدوث انحراف كبير للجسر اثناء التشييد فانه من الضروري عمل تحليل للجسر في هذه المراحل من التشييد. تم مقارنة النتائج المتحصل عليها من التحليل مع المدونه الامريكيه AASHTO 2010 وكانت في الحدود المسموح بها .