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Lessons learnt: Design & construction of first network arch bridge in Bangladesh

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ABSTRACT: The authors, considering the available materials, technological capabilities of the Bangladesh national contractors, and prevalent maintenance practices in the country improvised the design by blending the concept of Nielsen and Network arch bridges. This paper aims at exploring the design and analysis of the first network arch bridge analyzed, designed and constructed at Rayerbazar Graveyard in Dhaka, Bangladesh. The concepts of through and tied arch deck have been combined in the design of the Rayerbazar Network arch Bridge. At deck level it's designed as a 3-span bridge. The span length of the two network arches at the top of the foundation pile cap level is 56.50 meters and at the deck level is 40.00 meters. It's a single carriageway bridge of 5.50 meters carriageway widths and the arch rise is 6.80 meters. The sixteen intersecting suspenders of the deck enabled to keep the girder depth low to 600 millimeters. The arch hangers are Grade 72 steel reinforcement bars embedded inside stainless steel pipe casings for corrosion protection, are placed at 55^0 angles with horizontal axis. Maximum stress at hanger is kept below 50% of the yield strength at service condition to avoid developing fatigue under repetitive stress. Arch and deck-abutment connections are designed as monolithic joint. AASHTO LRFD 2007 is followed for pedestrian and vehicular loads and BNBC'93 have been used for environmental loadings. The extract of the key design features from the finite element model is given to illustrate the rational of the design assumptions

1 INTRODUCTION

Norwegian Professor Per Tveit originally developed the concept of Network Arch Bridge (NWAB) in the decade of 1950s. His design considered the bridge deck to be suspended from the elevated arch by a network of intersecting and interconnected hangers crossing each other at least twice at defined inclinations. He showed that this gives substantial advantages in design by inducing virtual prestressing effect in the deck girders by the crossing hangers. This system enables the network of hangers and arch segments work as truss. The arches are in compression which is susceptible to buckling. The network of hangers coupled with the wind bracings of the arches help prevent buckling. Per Tveit has designed two steel arch bridges of 80.00 and 83.00 meters span in Norway which are open for traffic since 1963. O. F. Nielsen has developed one similar looking bridge in the decade of 1930s known as Nielsen type arch bridge, where the intersecting hangers cross each other only once. Per Tveit proved that NWAB is two times more efficient and economical than Nielsen type arch bridge (Per Tveit 2006).

Dhaka North City Corporation (DNCC) took up development of the largest graveyard project near Rayerbazar National Martyred Memorial to accommodate more than 85,000 burial plots in 2011. Bangladesh Army's 14 Independent Engineering Brigade has been implementing the scheme covering over 96.23 acres at a cost of BDT 5056.00 million. The first Network Arch Bridge (NWAB) of Dhaka City, Bangladesh was undertaken over the Haikkar Khal flowing through the project area ensuring uninterrupted vehicular movement both above and below the bridge. The Terms of Reference (TOR) of the consultants demanded the bridge to be aesthetically pleasant looking. Design Planning & Management Consultants Ltd. (DPM) was the consultant of this bridge, and M/S. Mir Akhtar Hossain Ltd. (MAHL) was the contractor. The bridge has been constructed during 2014 & 2015 and has been opened for traffic movement since April, 2015. The construction cost of the bridge was BDT 62.15 million.

The design of this bridge incorporates both concepts of NWAB and Nielsen type bridges. Further innovations have been induced to enable the local contractors build this new type of bridge using the local materials and technology available in the country. The first Author as the Team Leader and the coauthors are part of the

Design and Construction Supervision Team narrate from their first hand experiences about the salient features of the planning, design and implementation of this NWAB stressing on the lessons learnt from. In the end, important recommendations are made for future design and construction of NWAB in Bangladesh.

2 BRIDGE PLANNING & DESIGN

2.1 *Bridge Location, Dimension & Structural System*

Figure 1 shows the location of the Network Arch Bridge at Rayerbazar Graveyard, Dhaka.

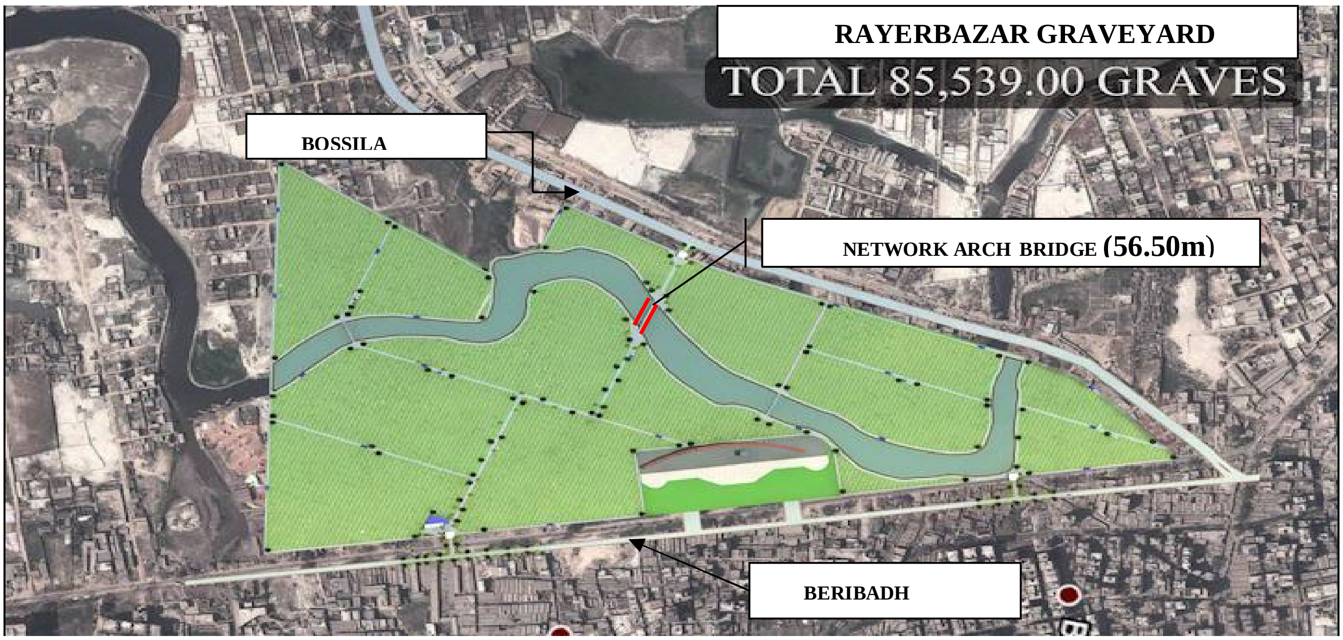

Figure 1. Location Map of Network Arch Bridge at Rayerbazar Graveyard in Dhaka City

The length of the bridge measured out to out abutment back wall is 56.50 meters, and c/c arch legs at deck level is 40.00 meters. The rise of the arch between C/L deck and C/L arch measured at arch crown is 6.80 meters, which is 17% of the arch span at deck level (Figures 2 & 3). The height of the two abutments at both ends is 5.95 meters measured along C/L carriageway.

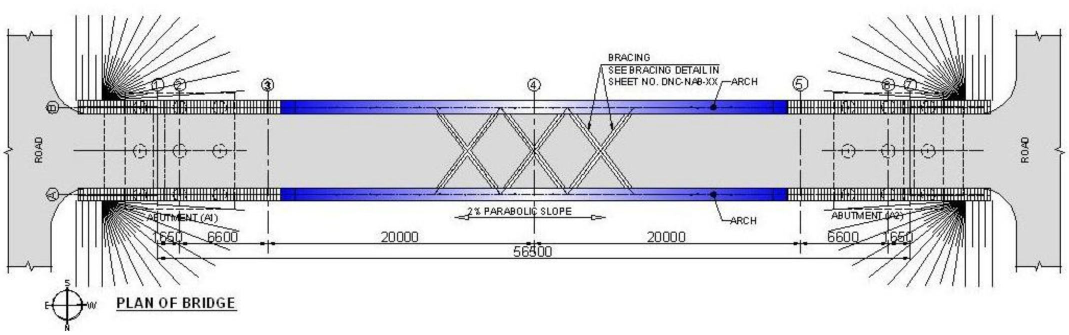

Figure 2. General Elevation and Plan of Bridge

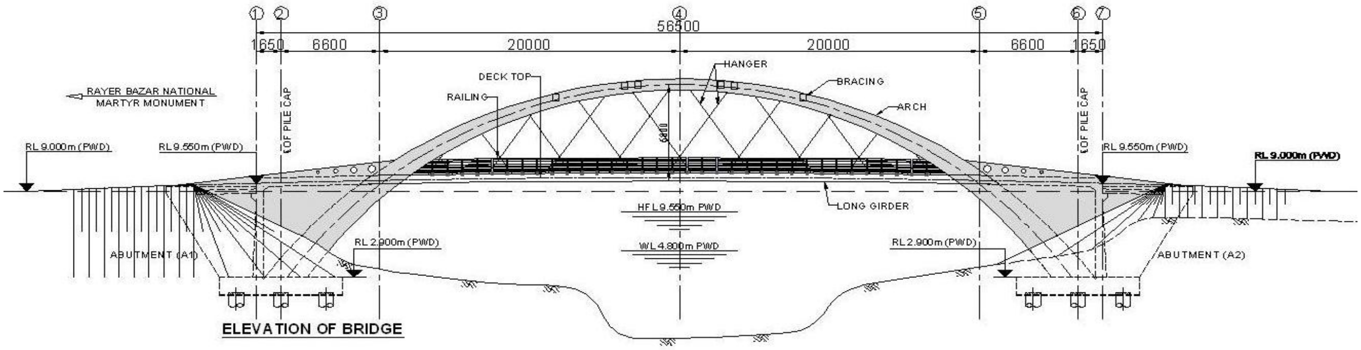

Figure 3. General Plan of the bridge

The bridge carriageway width is 5.50 meters with 1.00 meter width of long girder at both sides. Thus, the total out to out deck width 7.50 meters as shown in Figure 4. This 1.00 meter widths have been developed as longitudinal main girders on both sides, and also they accommodate the carriageway side bridge curbs.

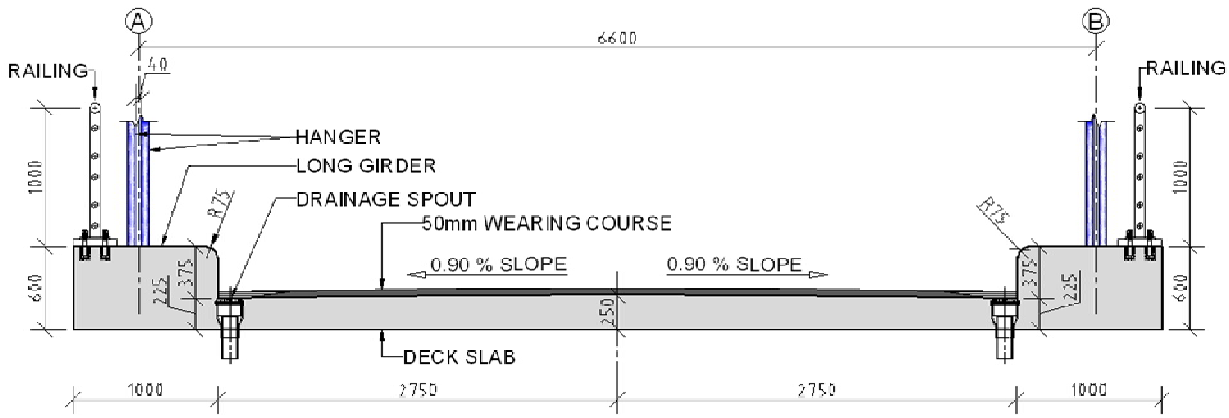

Figure 4. Typical Cross-Section through arch

The 16 intersecting hangers are placed parallel, 8 in each direction at 55^0 angles with the horizontal and anchored at bottom level inside the longitudinal main girders and at top level inside the arches. Each hanger comprises 3-T28 bars of minimum yield strength f_y = 500 MPa with T6 bar spirals spaced @ 75 millimeters c/c. These bars are embedded inside noncorrosive stainless steel pipe of 100 millimeters outer diameter and 3 millimeter wall thickness. This is filled with cement grout using nonshrink admixtures as shown in Figure 5.

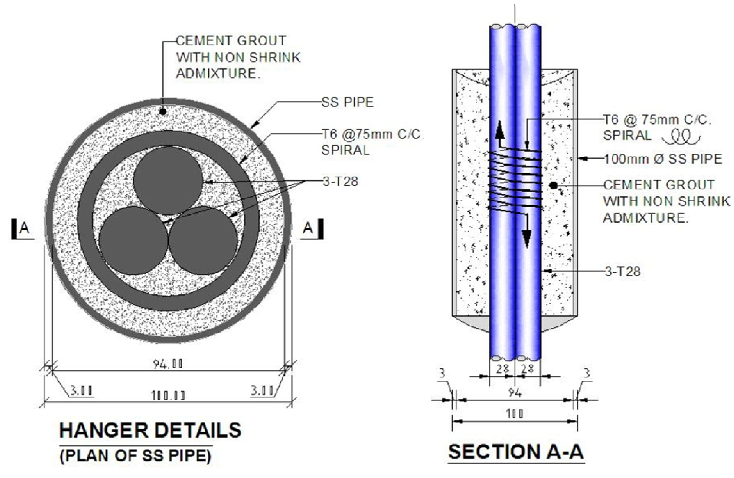

Figure 5. Hanger details

2.2 *Material*

Concrete compressive strength in cylinder (28 days) for all components (arch, long girder, top bracing, deck slab, abutment, pile cap and approach slab) of the bridge is $f_c' = 35$ MPa, and considering the current margin, the trial mix was designed for 47 MPa. For the cast-in place bored piles, concrete strength of $f_c' = 25$ MPa is used, and its trial mix was designed for 33 MPa. High strength deformed bars with minimum yield strength f_y = 500 MPa is used for all the structural components of this bridge.

2.3 *Design Code*

For bridge loadings and structural design of the Bridge, AASHTO Load Resistance Factor Design Method (LRFD) has been used (AASHTO LRFD 2007). Bangladesh National Building Code 1993 (BNBC'93) is used for calculating earthquake and wind loads and load effects.

2.4 *Design Load*

As the carriageway width of the bridge is 5.50 meters which is less than 6.00 meters, single design lane is considered for finite element analysis (AASHTO LRFD 2007). Components of the bridges are analyzed based on strength, service and extreme limit states. Pedestrian and vehicular loads are considered over the 5.50 meters width of the bridge carriageway. The loads from deck will be transferred through the long girders and hangers to the arches, and thereafter to pile caps and piles.

2.4.1 *Dead Load*

50 mm wearing course is considered over deck as asphaltic concrete black top is preferred for wearing course to reduce thermal gradient and stresses. Railing load is considered as line load over long girder. Design of the substructures are done considering vertical earth pressure on pile cap and horizontal active earth pressure on abutment and wing walls. Earth surcharge pressure is also considered in accordance with the AASHTO LRFD 2007.

2.4.2 *Live Load*

The bridge has been designed for AASHTO HL-93 Loading consisting of truck or tandem load and lane loading. Uniformly distributed load (UDL) of 3.10 kN/m^2 is considered as lane load along with truck tandem. 33% dynamic load allowance is considered with static truck load. This bridge has no sidewalk at either side. Even then, pedestrian load 3.60 kN/m^2 has been considered along with vehicular load over the full length of the bridge.

Braking force is considered as nodal load at the middle span of the lane as per AASHTO LRFD 2007.

2.4.3 *Wind and earthquake loading*

Basic wind speed has been taken as 210 km/hr as per BNBC'93 as the site is located in Dhaka City. The earthquake loading has been taken considering the site in Zone 2, as per BNBC'93

2.5 *Finite Element Model (FEM) Analysis*

FEM analysis is done using software MIDAS Civil 2011. Figure 6 shows all the structural components and elements including hangers, wind bracings, substructure abutment wing walls, pile cap and piles used in the model.

2.6 *Design*

The maximum bending moments obtained from the FEM analysis under strength combination are given in Figure 7. This shows that the maximum bending moments in the arch is +2,850.00 kN-m which occurs at the intersecting points between deck and arch. BM values are found as -1,550 kN-m at the springing points and 450 kN-m at arch crown for AASHTO strength combination.

The maximum axial forces obtained from the FEM analysis under strength combination are given in Figure 8. This shows that the maximum axial force in the arch is 2,180.00 kN at the location of the crossing points of the deck with the arch. The value of axial force is at the springing points and at the arch crown are 2,000 kN and 1,750.00 kN respectively.

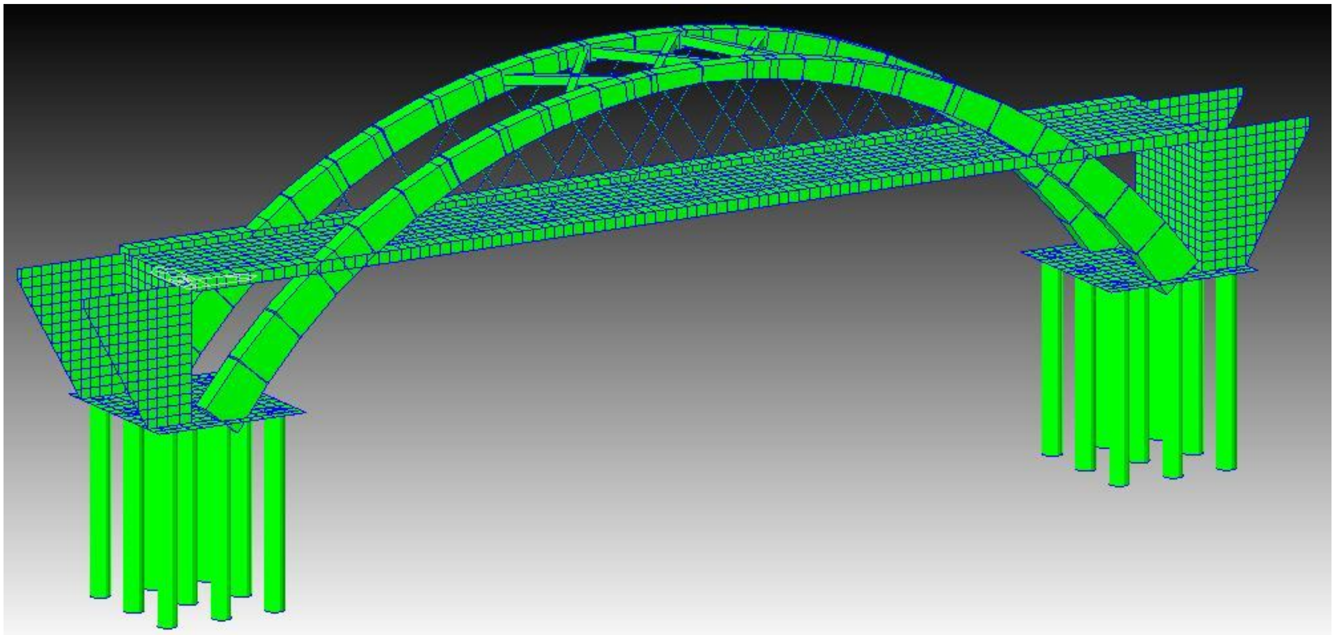

Figure 6. The geometry of the structural elements considered in the FEM Model

The maximum torsional moments obtained from the FEM analysis under strength combination are given in Figure 9. This shows that the maximum torsional moments in the arch is 390.00 kNm at the crossing of the deck with the arch which then varies from 202,00 kN-m at the springing points upto 25.00 kN-m at the arch crown.

The maximum shear forces obtained from the FEM analysis under strength combination are given in Figure 10. This shows that the maximum shear forces in the arch is 635.00 kN at the crossing points of the deck with the arch, 120.00 kN at the springing points and 25.00 kN at the arch crown.

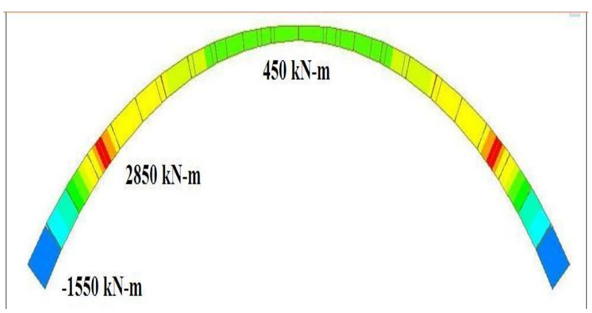

Figure 7. Maximum Bending Moments

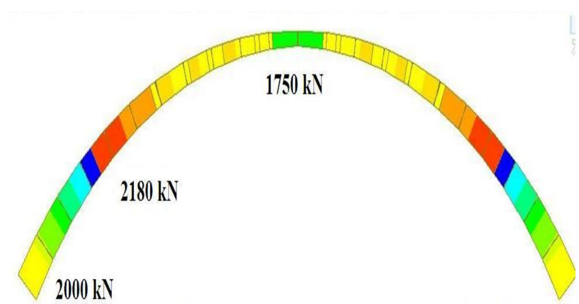

Figure 8. Maximum Axial Forces

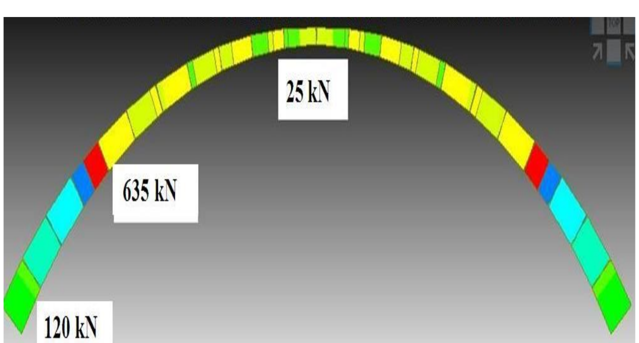

Figure 9. Maximum Torsion

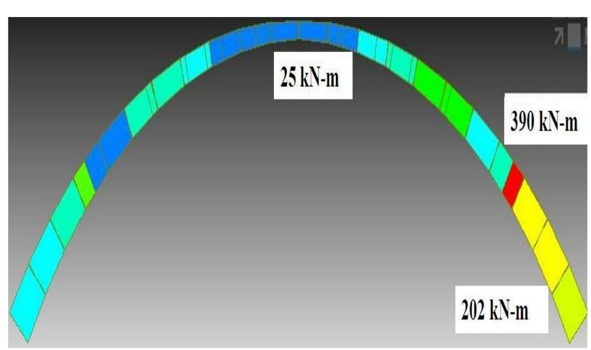

Figure10. Maximum Shear Force

Accordingly the FEM model gives the maximum bending moment $M_{y\text{-}y}$ = 800.00 kN-m over the junction between the abutment wall and the longitudinal main girders at the deck end.

The model gives the maximum and minimum axial force on the hangers 323.80 kN tension and 0.10 kN compression on the extreme end hanger with inclination towards the arch springing point.

The concrete outline and the reinforcement details of the arch and the other structural components have been determined based on the values obtained from the FEM analysis. Figure 11 gives the concrete outline and reinforcement details at deck end over the abutment wing wall.

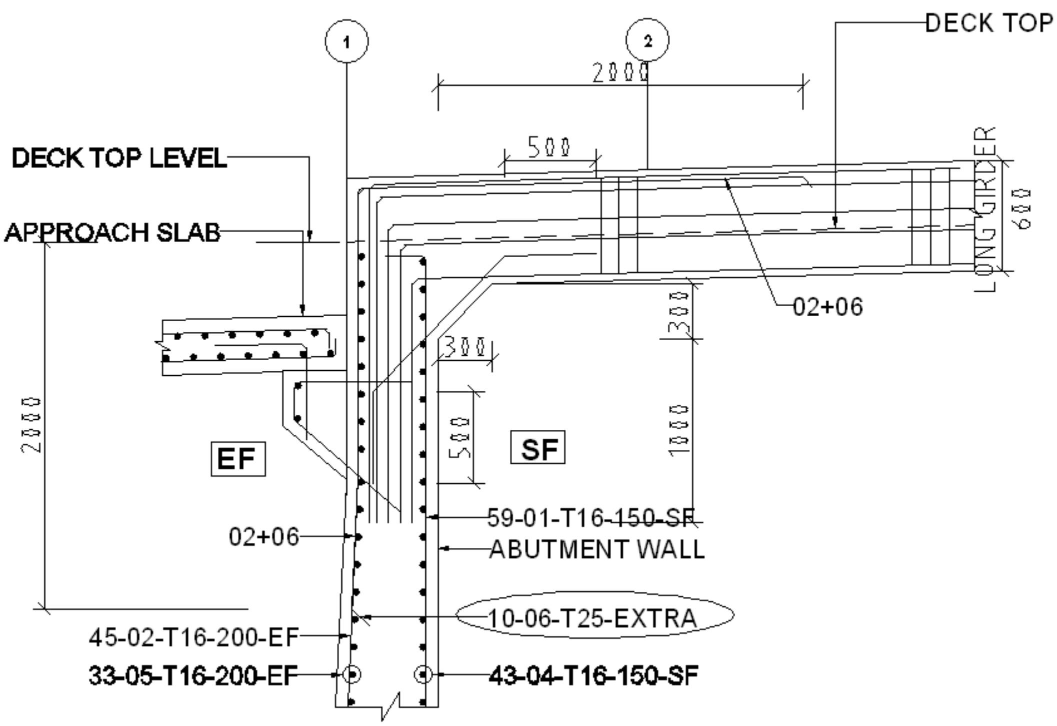

Figure 11. Reinforcement details at the monolithic connection between abutment wall and longitudinal main girder

2.7 *Dynamic Analysis*

From the FEM Analysis, 15 mode shapes of the bridge have been evaluated, and Mode 6, has been found critical (Figure 12). In this mode 98.63% mass is mobilized in X direction, and the corresponding natural frequency of vibration f_n is found as 1.684 cycle/sec whereas the natural period is 0.594 sec.

For the concrete and steel vehicular bridges the AASHTO LRFD 2007 specifies use of 33% dynamic load amplification factor even for the service load, in addition to the compliance of the criteria of maximum deflection not exceeding L/800 limit, where L is the length of the simply-supported span; AASHTO do not specify any other check of the criteria for vibration control.

For Rayerbazar NWAB, the 9.78 millimeters maximum deflection obtained from the FEM model is far less than the AASHTO allowable maximum deflection of 50 millimeters. Besides, the NWAB comprises intersecting hangers comprising Grade 500 bars embedded inside the 100 millimeters outer diameter stainless steel pipes with grouted infill of the voids, which intersects each other at least twice, and also wind bracings for the arches.

As the AASHTO does not specifically cover the NWAB, it needs to be monitored whether relaxation of any of the hangers particularly in the end hanger occurs during extreme event. For the Rayerbazar NWAB the intersecting hangers haven't been interconnected at the joints as recommended by Per Tveit, rather a gap of 50 millimeters have been kept in between the crossing hangers to avoid pounding, if any occurs during earthquake or strong winds.

After evaluating the dynamic behavior of the bridge if the stiffness of the arch needs to be improved further, this can be done by providing bracing or coupler or putlog connections at the intersection points of the hangers, so that the system behaves like the network of trusses with shorter member lengths restricting the L/R ratio where R is the radius of gyration.

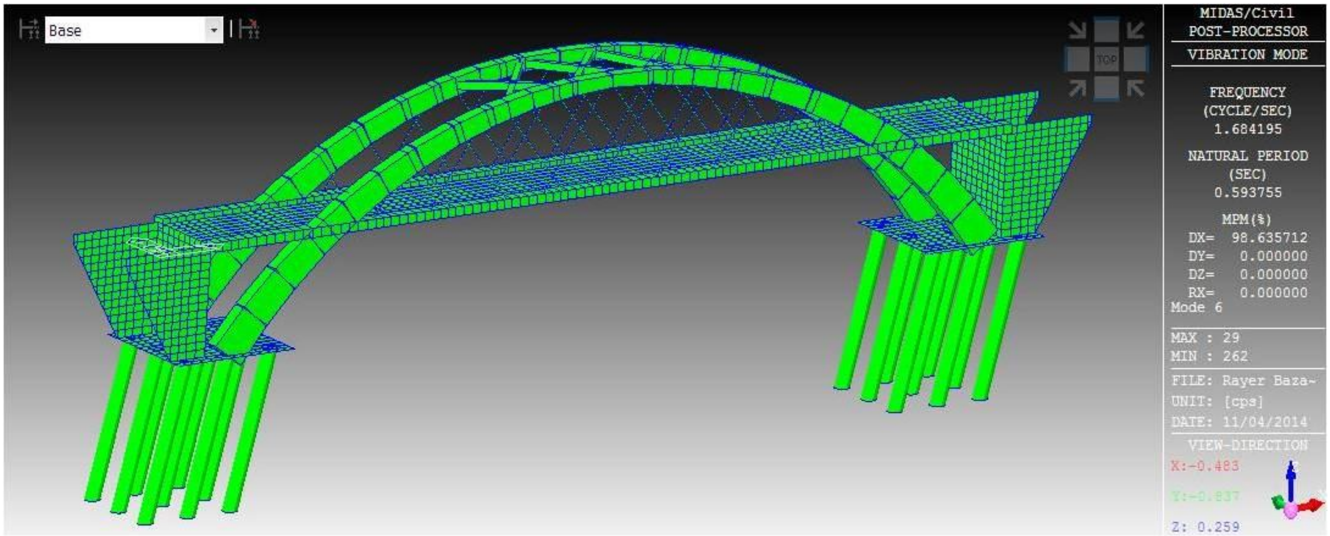

Figure 12. FEM analysis results of the bridge

3 CONSTRUCTION METHODOLOGY

3.1 *Scaffolding System and Formwork*

The traditional methods of construction prevalent in the country had been followed. The scaffolding system used steel props with adequate bracings. The formwork was mainly fabricated with steel plates and sections. First the site was prepared by compacted sand fill and then steel scaffolding system had been erected over concrete blocks placed on this compacted fill. Figure 13 shows the system.

Figure 13. Photograph of scaffolding system and formwork of the bridge

3.2 *Construction Stages*

5-stage construction sequences had been used: Stage I, piles and pile caps; Stage II, the portion of abutment wing walls, portion of arch below the deck; Stage III, the screen walls; Stage IV, deck, long girder and the remaining screen walls and wing walls; Stage V, the arches above deck level and hangers (Figure 14). Deck and long girder have been cast simultaneously as monolithic elements. To ensure monolithic nature of arch, it has been cast at single stage.

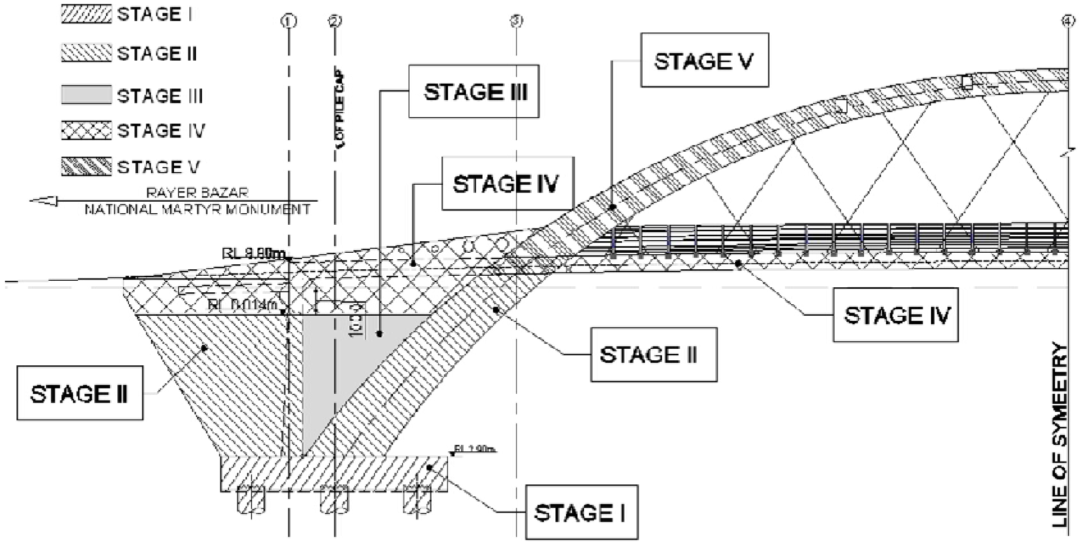

Figure 14. Construction sequence

3.3 *Completed Bridge*

Figure 14 shows the photograph of the completed bridge with slope protection works at both sides of each end. It has screen wall of reinforced concrete between arch and pile cap. Stainless steel rail pipes are used for railing on the bridge section and reinforced concrete section has been enhanced above deck level and merged with arch to work as railing for the deck length beyond arch span.

Figure 15. Photograph of the completed bridge

4 COMPARISON OF MATERIAL QUANTITIES AND COST

The Table 1 shows the comparison of material quantities, and Table 2 shows the comparison of cost between the Rayerbazar NWAB and an equivalent 4-girder prestressed concrete girder (PCG) bridges estimated using the Roads & Highways Department Rate Schedule (RHD 2011). The comparison is to about the comparative advantages and disadvantages between the NWAB and conventional bridge types for Bangladesh condition only. Table 1 doesn't show the quantities of piles; for Rayerbazar NWAB, the 1,000 diameters piles are 720.00 meters. The equivalent PCG bridge contains being a 3-span bridge contains 2 additional piers with pile foundations. But Table 2 total cost includes the cost of piles and all other ancillary bridge items.

Table 1 Comparison of Material Quantities between Rayerbazar NWAB and equivalent PCG bridge

Structural component	Concrete Volume, m^3		HY Rebars, mTon		High tensile prestressing steel, mTon	SS pipe 100mm Dia
	NWAB	PCG bridge	NWAB	PCG bridge	PCG bridge	NWAB
Substructure	742	1,135	122	156	-	-
Superstructure	228	241	84	18	13	227
Total	970	1,376	206	174	13	227
Savings NWAB/PCG	30%		-18%		100%	-100%

Table 2 Comparison of total cost between Rayerbazar NWAB and equivalent PCG Bridge

Rayerbazar NWAB	BDT 74 million
Equivalent PCG bridge	BDT 112 million
Savings of NWAB/PCG bridge	34%

5 DISCUSSION AND RECOMMENDATION

5.1 *Lessons Learnt*

The NWAB constructed so far are located mostly in the developed countries. These bridges have arches, hangers made of steel and standard steel anchorages. Rayerbazar NWAB has concrete arches with SS pipe-encased grouted steel re-bar hangers anchored inside the longitudinal deck girders and arches to enable the local contractors build the bridge using locally available material and technology. The risks involved were matching the assumptions by the condition of construction, and finally maintaining the designed geometric profile of the deck. This has been addressed by designing parabolic gradient of the deck, and then providing parabolic precamber for the relaxation of steel, deflection due to bridge loading, shrinkage, creep, compensating initial straightening of the re-bar hangers, yield of the formwork and scaffolding due to support settlement, and then multiplied by a factor. This worked well for this bridge as the photograph of figure 15 shows.

The hanger inclinations, at 55^0 angles with the longitudinal axis has been provided, which is within the Per Tveit's recommended range of inclination to derive maximum benefit in design. Although placing hangers at variable angles could help reducing the thickness of arch and deck or reinforcement, the parallel spacing of the hangers has been provided for aesthetic reasons. High density Polyethylene (HDPE) of equivalent thickness could be used instead of SS pipe as hanger protection material to reduce cost, and increase design life of up to 75 years under normal maintenance as per AASHTO.

The network of intersecting hangers of Rayerbazar NWAB generate much reduced bending moment, shear forces and other load effects in the longitudinal main girders at deck level compared to the other bridge types, which enable eliminating the robust girder section. Thus the 600 millimeters depth at bridge curb is found adequate to design as main girder for the 56.50 meters length of bridge, which is unimaginable for other types of bridges with identical AASHTO bridge loading. Light longitudinal prestressing could reduce the girder reinforcement further and may be used for design purpose in the future.

For Rayerbazar NWAB the network of inclined intersecting hangers are not interconnected at crossing joints to behave as truss, rather these are placed with a gap of 50 millimeters to keep the construction simple. The FEM analysis shows only one 2.68 meters long end hanger inclined towards the arch springing gives 0.10 kN compressive load and all other hangers are in tension. The compressive stiffness of 100 millimeter diameter SS pipe-encased grouted reinforcing steel hangers of 2.68 meters length is sufficient to carry this small compressive load. This combined with the wind bracing connected with the arches.

5.2 *Recommendation*

The lessons learnt from design and construction of first Network Bridge can be utilized to design single span arch bridges for 100.0-200.0m both at present and in the future. This will be particularly suitable for river bridges as piers cause local scour and hamper aquatic eco system. This way pier can be eliminated with more aesthetically pleasant looking arch bridges. The site specific construction methodology can be developed blending the capabilities of the local contractors and available latest technology.

Figure 16 shows recommended deck section for future design considerations to attain reduced deck section by extending slab beyond longitudinal girder as pedestrian footpath. This will balance out bending moment of deck slab and a slimmer deck section can be provided. It is strongly recommended to undertake one such bridge on pilot basis and test the capabilities of the local designers and contractors.

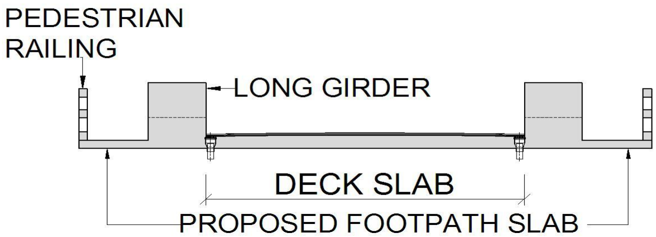

Figure 16. Proposed Deck Section of Network Arch Bridge.

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