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Effect of construction sequence in design of RC network arch bridge

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ABSTRACT: Network Arch Bridges are aesthetically beautiful and economical for long span bridges. Network arch bridges in developed countries are mostly made of steel. Now a days, RC Network Arch Bridges are getting popular in the subcontinent due to low maintenance requirements after construction. However, creep and shrinkage of concrete introduce additional challenges for design and construction of RC Network Arches. In this study, the effect of construction sequence on the design of a four lane 90m single span RC Network Arch has been investigated. A numerical FE model has been developed and different construction sequences have been investigated and compared with the static analysis in Bangladesh context.

1 INTRODUCTION

Arch bridge is an old concept in bridge engineering. Over time, concept of arch bridge evolved to more and more efficient and optimum solution. Finally, the most optimum arch solution was introduced by the Norwegian professor and engineer Per Tveit (Tveit, 1966), the concept was defined as network arch bridge. Network arch bridge (NWAB) is a tied arch bridge, where, each hanger intersects multiple hangers. Due to intersecting hangers, bending moment in arch and tie reduces significantly compared to tied arch bridge with vertical hangers, resulting slender and aesthetic design of the bridge. After first introduction, professor Per Tveit worked further to improvise and optimize the NWAB (Tveit, 1980, 2006, 2008, 2010). Other researchers also worked on the NWAB to reach more optimized solution (Islam, 2016; Pipinato, 2018)

After first introduction, many NWABs have been constructed of different spans. These bridges are mostly steel bridges. Steel bridges need periodic inspection and maintenance. However, in Bangladesh this is a challenge. Therefore, the first and third author of this paper started research to develop a methodology to design and construct RC NWAB using local technology and material in 2013, which lead to design and construction of the NWAB at Rayerbazar Graveyard, the first NWAB in Bangladesh as well as in the subcontinent. Rayerbazar NWAB was constructed in 2014-2015 as cast-in-situ. It has been observed in the West Seventh Street Bridge in USA, the first precast RC NWAB (Yousefpour, 2015), that, precast NWAB significantly reduce onsite construction time and better-quality control; however, it needs sophisticated field quality control and monitoring system with heavy lifting and shifting mechanism with accuracy. Therefore, cast-in-situ RC NWAB is still preferred by the client and contractors in Bangladesh. Precast RC NWAB is definitely an appealing solution and further work needs to be done to develop proper methodology and to develop the capability of local contractors.

RC NWABs have additional challenges than steel NWABS. First challenge: steel tie can easily withstand the tension developed due to arch thrust; whereas, RC tie is weak in tension and needs excessive reinforcement to withstand direct tension. This can be overcome in two ways. First solution is to make the NWAB monolithic with abutment; so that, abutment pile system takes the major portion of lateral thrust of arches. This solution was applied in Rayerbazar NWAB. In this method, design of substructure becomes robust and expensive and design of superstructure also becomes robust; since, seismic and temperature loads fully induced in the superstructure due to fixed support condition. The second solution is to apply post tensioning to the RC tie for eliminating tension force and to rest the NWAB on bearing as simply supported. This philosophy was applied by DPM Consultants Ltd. in the design and construction of 50m span 3-lanes RC NWAB in Kathmandu, Nepal (construction completed in 2018) and 50 m span 2-lanes RC NWAB in Bhutan (construction completed in 2018). The authors of this paper were part of design team. The authors of this paper are currently designing a 90 m RC NWAB, part of Prottasha Bridge project, using the same philosophy and the first author is the team leader of the design team. Prottasha bridge is located near Prottasha Housing Area over the Turag river at Savar Thana in Dhaka.

Second challenge of RC NWAB is the presence of long-term deformation in concrete, like creep and shrinkage. Construction stage analysis is required to determine the effect of creep and shrinkage. In this study, the effect of long-term deformation properties of concrete has been observed for RC NWAB. The 90 m span RC NWAB, currently under design as a part of Prottasha Bridge Project, has been taken as a sample bridge to observe the significance of construction stage analysis in design of RC NWAB.

In RC network arch bridge, depth of long girder is smaller than that of the traditional bridge types. For 90 m span PC box girder, the required depth at middle span is 2500 mm. The depth of long girder from deck top is only 700 mm in the 90 m span RC NWAB discussed in this study. This reduces the length of viaducts and approach road and consequently, saves the project cost significantly. Moreover, the longer span of NWAB helps to reduce the number of piers in the river, resulting an environmentally friendly aesthetic solution. Therefore, the popularity of RC NWABs is growing in Bangladesh. This study will help to develop optimized design and construction methodology for longer span RC NWAB in Bangladesh context.

2 SAMPLE BRIDGE

2.1 *Description of the Bridge*

This is a 90 m span four lane RC network arch bridge with 3-arches, as shown in Figure 1.This bridge has two foot paths of 1500 mm width at two outer side of the bridge. Middle long girder (LG-2) serves as the divider of 4 lanes carriage way as shown in Figure 2.

Figure 1. 3D view of the 90 m span network arch bridge.

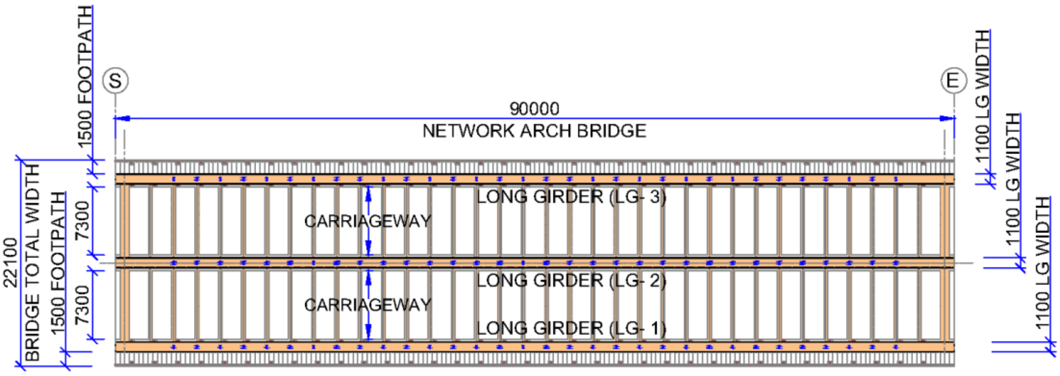

Figure 2. Plan of the 90 m span network arch bridge.

20000 kN post tensioning is applied in order to minimize tension using six 19k15 tendons at each long girder. Rise of the arch is m as shown in elevation of the bridge in Figure 3. 1030 MPa high strength 40 mm diameter bars have been used for hangers. Each arch has 64 hangers. This bridge rests on the pier through high damping rubber bearing.

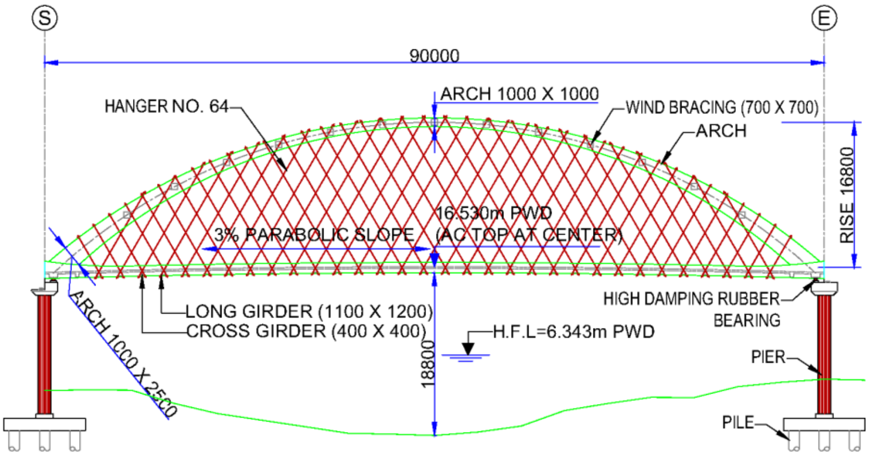

Figure 3. Cross section of the 90 m span network arch bridge.

2.2 *Design Parameters*

This sample bridge has been designed as per AASHTO 2017.Vehicular and pedestrian load have been taken as per AASHTO 2017. 35 MPa concrete and 500 MPa reinforcement have been considered to design the superstructure of this bridge. High strength 1030 MPa bars have been designed for hangers. 50 mm wearing course has been considered over deck as asphaltic concrete black top. Design wind speed has been taken 210 km/hr and seismic zone has been considered as zone 2 as per BNBC 2006.

2.3 *Size Structural Members and Concrete Volume*

Size and reinforcement of the structural members of this bridge have been optimized according to AASHTO 2017.Size and volume of different structural members are mentioned in Table 1.

Table 1. Size and concrete volume of structural members of 90 span RC NWAB.

Description	Size of Structural members (mm)	Number	Volume (m^3)
Arch	Support: 1000 x 2500 Top: 1000 x 1000	3	431
Long girder	1100 x 1200	3	374
Cross girder-Middle	400 x 600	34	86
Cross girder- at support	1000 x 600	2	13
Deck + Footpath	Thickness: 200		338
Wind bracing-perpendicular to traffic	700 x 700	13	102
Wind bracing-inclined	600 x 500	48	87
Total concrete volume			1431

2.4 *Construction Methodology*

Construction sequence is very important for Network arch bridge; since, it is a part of design. The assumed construction steps considered in the design of this bridge are as follows.

- Cast piers.
- A firm scaffolding, made of props/truss and formworks, needs to be set, so that, it is capable of carrying entire bridge self-weight and load of construction activities. Figure 4 & 5 show one option of scaffolding composed of three sets of 30 m span trusses. This will allow river traffic during construction.
- Cast long girders keeping construction joints with kickers for deck and cross girders.
- Deck and cross girders to be cast in several steps, from center to side.
- Then, each arch to be constructed in several phases. Same phase of all three arches to be cast at the same time.
- 28 days after casting of arches and wind bracings, post tensioning to be applied to long girders.

- Then, hangers to be installed and tightened properly. Hanger to arch and girder joint detail is shown in Figure 6.
- Finally, scaffolding to be removed and bridge to be tested prior to open for traffic.

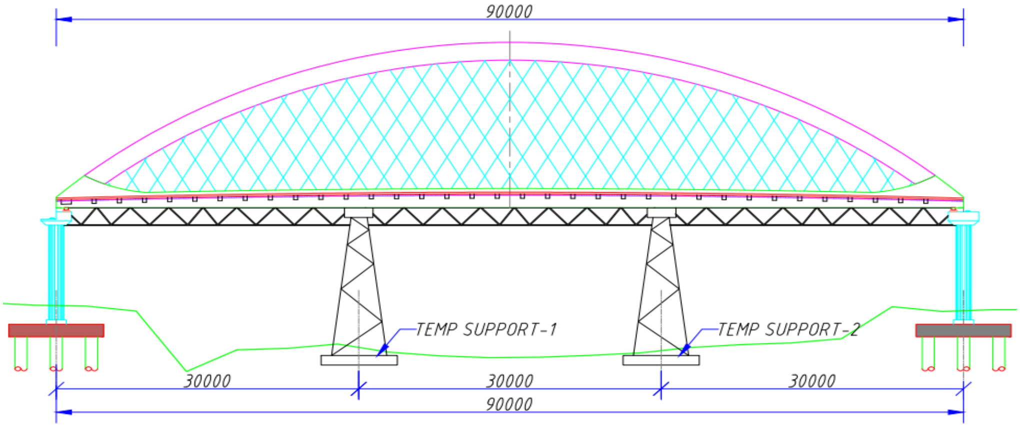

Figure 4. Elevation of formworks on 30m span truss.

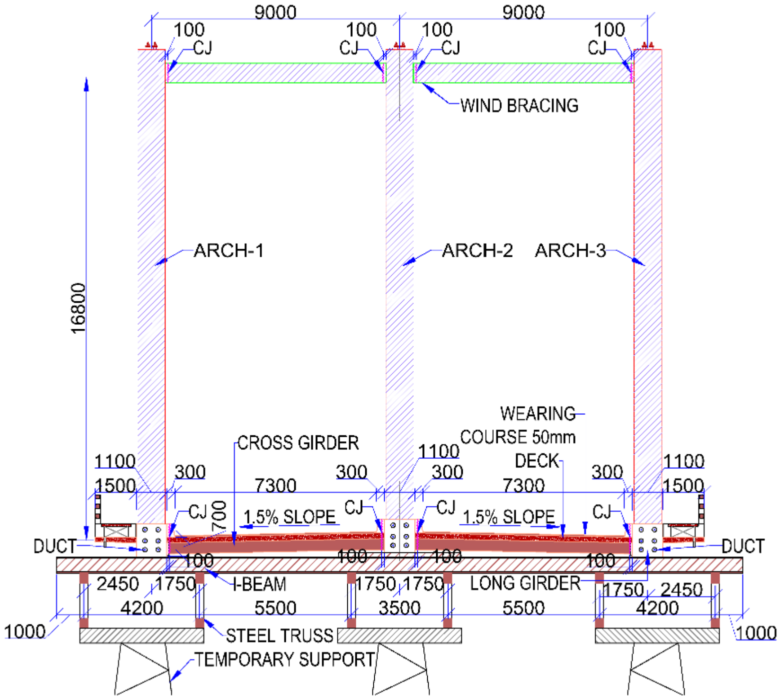

Figure 5. Cross section of formworks on 30m span truss with construction joints (CJ).

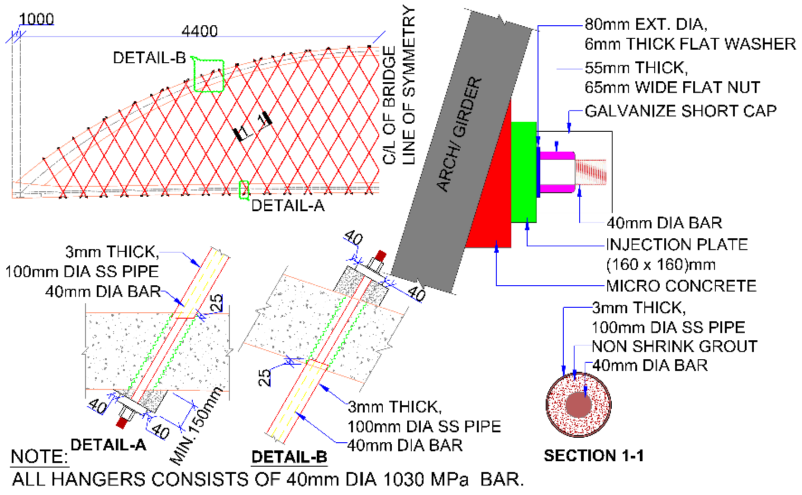

Figure 6. Cross section of formworks on 30m span truss with construction joints (CJ).

Volumetric capacity of concrete casting dictates the time for casting. Time required for concrete casting depends on the capacity and number of batching plants available. In this study, two options of batching plant availability will be explored: a) one 25 m^3/hr batching plant and b) two 25 m^3/hr batching plants.

3 CONSTRUCTION STAGE ANALYSIS

3.1 *Option-1: Concrete Casting Using One 25 m^3/hr Batching Plant*

Long girder of this network arch bridge is a critical member; since, it is post-tensioned and is subjected to significant torsion. No construction joint is allowed in long girder. Therefore, each long girder needs to be cast in single phase. Volume of concrete in one long girder is 124.67m3; thus, time required for casting one long girder with one 25m3/hr batching plant is almost 5 hours. Final setting time of concrete is assumed 10 hours (ref). So, LG-1 can be cast before the final setting time. If, LG-2 and LG-3 are cast in the same day, LG-1 is will get disturbed after the final setting time; since, same scaffolding is supporting all three long girders. So, using one 25m3/hr batching plant, one long girder can be cast in one day. Scaffoldings must not be disturbed for at least 3 days after casting each long girder. There should be at least 3 days interval between casting of each long girder. After casting LG-1, LG-3 needs to be cast in order to reduce asymmetry due to differential shrinkage. Effect of differential shrinkage of three long girders, due to casting in different time, has been taken into consideration in construction stage analysis.

Deck and cross girders need to be cast in several phases maintaining symmetry along the width and length of the bridge, 3 days after casting of LG-3. Concrete volume of deck and cross girders is 437m3. Thus, almost 18 hours of casting will be required. Therefore, 3 days will be required for casting and there should be at least 3 days intervals between the days of casting. In this study, it is assumed that, deck and cross girders are cast symmetrically; therefore, there is no effect of differential shrinkage in the bridge.

In this study, it is assumed that, contractor will use three formworks for three arches; so that, the same phase of all three arches can be cast simultaneously and maintaining symmetry along the width and length of the bridge. Volume of concrete of arches is 431m3; thus, almost 18 hours are needed to cast. Therefore, arches need to be cast in 3 phases. Each phase will require 6 hours of casting for all three arches and there should be at least 3 days intervals between the days of casting. Due to symmetry, no differential shrinkage affect will act on bridge for arches.

Volume of wind bracing is 189 m3, requires almost 8 hours of casting. So, one day is sufficient for casting of wind bracings.

28 days after casting of arches and wind bracings, all three long girders need to be post tensioned simultaneously.

3.2 *Option-2: Concrete Casting Using Two 25 m^3/hr Batching Plants*

Volume of three long girders is 374m3. Using 25 m^3/hr batching plants, it will take 7.5 hours to cast all three long girders and within time limit for final setting time; thus, can be cast simultaneously in one day. Unlike in option-1, there will be no differential shrinkage effect on the bridge in option-2.

Deck-cross girders and all three arches may be cast in one day using two 25 m^3/hr batching plants; however, it is assumed that, these will be cast in two phases, with 3 days interval between each casting days.

3.3 *Construction Stage Analysis*

Finite element model of the 90 m span Network Arch Bridge has been developed using CSiBridge. Construction stage analyses have been conducted using CEB-FIP model [Computers and Structures (2013)] for option-1 and option-2.50% relative humidity has been considered for shrinkage analysis. In this study, effect of differential shrinkage of three long girders has been observed for option-1. In option-2 there will be no differential shrinkage effect; however, effect of overall creep and shrinkage has been taken into account.

3.4 *Comparison of Results*

Adequacy of each structural member of the bridge needs to be checked considering static analysis and construction stage analysis. It is important to observe the effect of construction stage analysis for construction options 1 and 2 on the member forces due to service load, comprised of dead load, wearing course and post tensioning force, and to compare with the member forces static analysis. In this study, one sample arch segment, one hanger and one sample long girder segment of middle frame and one side frame of the bridge have been chosen as highlighted in Figure 7.

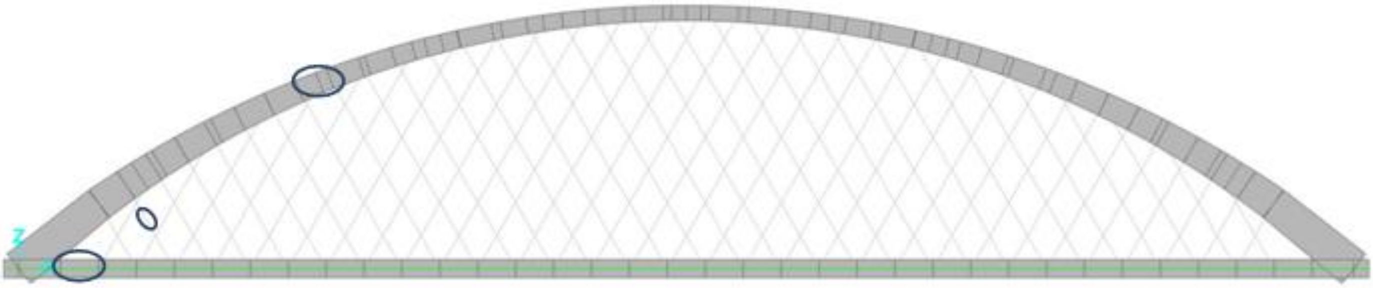

Figure 7. Frame of the 90 m span network arch bridge highlighting the sample segments of arch and long girder and the sample hanger, focused in this study for result comparison.

Table 2 shows that, difference of forces is not significant in arch sample segment for Option-1 and Option-2 construction sequence. Static analysis gives similar or higher forces compared to the forces generated in construction stage analyses at zero days after construction. However, after 10 years of construction, the difference between forces generated in static analysis and construction stage analysis gets larger. Static analysis gives conservative results for bending moment in all cases as shown in Table 1. In case of shear and axial compression in middle frame, static analysis underestimates by 37.5% and 5% respectively. In case of side frame, static analysis is conservative for all forces except for shear force after 10 years of construction.

Except for shear force, results of static analysis have been found similar to the results of construction stage analyses for sample arch segment. In the middle frame, torsion should be zero; since, load is balanced at both the side. In static analysis it has been observed zero. However, even if, post tensioning has been applied at the same day in construction stage analyses; LG-1 has been post tensioned before LG-3. This resulted small amount of torsion in construction stage analysis. Thus, it is important to apply post tensioning to two side girders at the same time.

Table 3 shows that; hanger forces are observed almost same for construction option-1 and option-2. Hanger forces after construction are almost equal to the forces found in static analysis; however, after 10 years tension of sample hanger in middle frame increases by 12.5%. Therefore, static analysis underestimates the hanger tension in middle frame.

Table 2. Comparison of forces in sample arch segment.

Service load for dead load, wearing course and post tensioning force for sample arch segment		Static Analysis	Construction Stage analysis							
			Option 1				Option 2			
			After Construction	Variation from Static Analysis in percent	After 10 Years	Variation from Static Analysis in percent	After Construction	Variation from Static Analysis in percent	After 10 Years	Variation from Static Analysis in percent
Middle frame	Axial Compression (kN)	10823	10929	1.0	11465	5.9	10929	1.0	11465	5.9
	Shear force (kN)	101.2	104.8	3.5	139.2	37.5	104.8	3.5	139.2	37.5
	Bending Moment (kN-m)	325.3	313.3	-3.7	204.6	-37.1	313.2	-3.7	204.5	-37.1
	Torsion (kN-m)	0.0	0.2		6.9		0.3		7.3	
Side Frame	Axial Force (kN)	9366	9228	-1.5	9394	0.3	9228	-1.5	9356	-0.1
	Shear force (kN)	32.3	29.8	-7.8	33.5	3.8	29.7	-8.1	33.8	4.5
	Bending Moment (kN-m)	95.1	81.2	-14.6	27.6	-71.0	81.0	-14.8	27.0	-71.6
	Torsion (kN-m)	73.1	66.9	-8.5	40.6	-44.5	66.8	-8.7	40.0	-45.3

Similar to arch segment, difference of forces is not significant in the sample long girder segment for Option-1 and Option-2 construction sequence. However, unlike arch segment, static analysis underestimates almost all the forces than the forces generated in construction stage analyses as shown in Table 4. In the middle frame, bending moment right after construction is 11% higher than in static analysis, and the difference increases to 55% after 10 years of construction. In sample girder segment at side frame, bending moment is nearly 37% higher than the bending moment found in static analysis. Torsional forces right after construction, in girder segment at side frame, is 9% higher than that found in static analysis; however, torsional force reduces with time and after 10 years it reduces by 60% of the torsion in static analysis.

Table 3. Comparison of tensile forces in sample hanger.

Tensile force in sample hanger		Static Analysis	Construction Stage analysis							
			Option 1				Option 2			
			After construction	Variation from Static Analysis in percent	After 10 Years	Variation from Static Analysis in percent	After construction	Variation from Static Analysis in percent	After 10 Years	Variation from Static Analysis in percent
Middle frame	Tension Force (kN)	268.0	268.1	0.0	301.3	12.4	268.1	0.0	301.4	12.5
Side Frame	Tension Force (kN)	202.8	195.4	-3.7	204.1	0.6	195.4	-3.7	204.2	0.7

Axial compression in long girder comes from the post-tension force. It is desired that; the long girder remains in compression. In static analysis, it is assumed that shrinkage of the concrete occurs after post tensioning. In construction stage analyses, post tensioning is applied after shrinkage occurs; therefore, actual case scenario is represented in construction stage analyses. Thus, as shown in Table 4, compressive force in long girder sample segment has been observed significantly higher in construction stage analysis. Therefore, there is room of optimization of post tensioning force and cable number.

Table 4. Comparison of forces in sample segment of long girder.

Sample long girder segment		Static Analysis	Construction Stage analysis							
			Option 1				Option 2			
			After Construciton	Variation from Static Analysis in percent	After 10 Years	Variation from Static Analysis in percent	After Construciton	Variation from Static Analysis in percent	After 10 Years	Variation from Static Analysis in percent
Middle frame	Axial Compression (kN)	3189	5891	84.7	6782	112.6	5837	83.0	6737	111.2
	Shear force (kN)	261.9	274.6	4.8	218.5	-16.6	274.2	4.7	217.2	-17.1
	Bending Moment (kN-m)	369.6	410.3	11.0	571.7	54.7	409.1	10.7	573.6	55.2
	Torsion (kN-m)	0.0	0.3		2.9		0.4		2.8	
Side Frame	Axial Compression (kN)	3851.3	6446.5	67.4	7713.8	100.3	6356.4	65.0	7630.1	98.1
	Shear force (kN)	246.0	247.7	0.7	200.3	-18.6	247.1	0.4	197.8	-19.6
	Bending Moment (kN-m)	304.3	333.3	9.5	415.0	36.4	331.4	8.9	417.5	37.2
	Torsion (kN-m)	90.7	98.8	9.0	35.5	-60.8	98.9	9.1	36.0	-60.3

4 CONCLUSIONS

In this study, a 90 m span RC cast-in-situ NWAB has been described with a probable construction methodology. A comparison of resultant forces in structural members of the bridge from static and construction stage analysis has been presented. In this study one sample segment from arch and long girder, and one hanger has been taken from middle and side frame of the bridge for result comparison. The outcome of this study can be summarized as follows.

- Static analysis in some cases underestimates design forces. Specially, shear in arch sample segment, bending in long girder segment and tension in sample hanger has been found underestimated by static analysis.
- In this study two construction sequence options have been explored. Three long girders are cast in different days in Option-1, resulting asymmetrical casting of long girders; whereas, all three long girders are cast in the same day in Option-2; therefore, the full bridge has been cast symmetrically along the length and width of the bridge in Option-2. Since, the amount of asymmetry is small, small difference of results in Option-1 and Option-2 has been observed.
- It is important to determine the capacity contractor in terms of concrete casting in the design phase; since, it determines the steps of construction stage analysis. Assumptions in design must be strictly followed in construction of RC NWAB.

Large span network arch bridges should get attention in Bangladesh context, specially for the rivers, where piers of traditional bridges hamper the aquatic eco-system by triggering sedimentation. Network arch bridge is also a solution for the projects, where the length of approach road viaducts gets too high due to requirements larger vertical and horizontal navigational clearance with other bridge forms. Smaller girder depth of large span network arch bridges significantly reduces the length of approach road and viaducts.

This study shows the importance of synchronizing the design and construction procedure for RC NWAB. Projects for 40 m span and 50 m span RC NWAB has been successfully completed and generated confidence in both design and construction. Completion of 90 m span RC NWAB will definitely pave the path to accomplish further refinement in design and construction procedure and will generate confidence to proceed for even larger span of network arch bridges using local technology and material.

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