Design of Network Arch Bridge

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Abstract. In this paper, the design and construction aspects of a 100 m span steel ladder deck network arch bridge is presented. The bridge is constructed over the river Tlawng on NH44A, Mizoram, India. It has a deck width of 14.25 m, including footpaths on both sides. The design employs equivalent unique global and local imperfection (EUGLI) method to cater the buckling effects of the sections. This methodology incorporates both local and global imperfections applied in the form of the arch's buckling shapes for assessing the second order effects. The hanger configuration has also been optimized to minimize the bending moments in the arch. The detailed analysis including construction stage analysis is performed using SOFISTIK which is a state-of-the-art FEM based structural analysis software. The paper also addresses the key challenges and solutions for constructing the bridge in a geographically difficult terrain. Notably, for the first time in the world, such heavy arch steel framework is erected on one side of a deep gorge and then suspended from a suspension cable to transport over it. With only 420 MT of structural steel, the bridge is designed for 100 MT 2-lane live load and 385 MT special vehicle (SPV) load making it remarkable in terms of economy, aesthetics and innovation.

***Keywords*:** Network arch bridge; EUGLI method; Buckling; Second order effects; Ladder deck; Cable transport; Steel structures

1 Introduction

The network arch bridge project which is a state government project of Mizoram under Public work department is constructed over the river Twang on NH44A in Mizoram, India. The project aims at providing better connectivity of Aizawl city centre to Lengpui airport by replacing the old existing bailey bridge. The project faces complex engineering challenges due to the geographically difficult terrain located in high seismic zone.

The bridge has a total length of 103 meters with a straight alignment (see Fig. 1). It spans 9.52m between bearing center to center in transverse direction with 14.25 meters in width, with 7.5-meter-wide carriageway and 1.5-meter-wide footpaths on both sides (refer to the typical cross-section in Fig. 2). The bridge is situated in seismic zone V and subjected to 100MT 2 lane live loading and 385MT special vehicle loading as mentioned in IRC-6:2017.

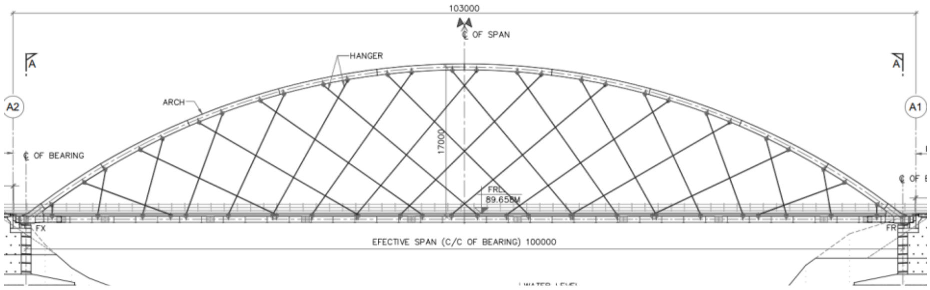

Fig. 1. Elevation of network arch bridge.

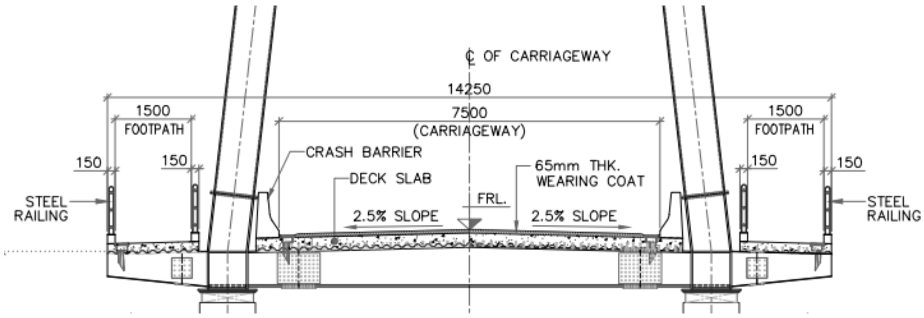

Fig. 2. Cross section of the bridge.

2 Why Network arch?

The tender specifications call for the construction of an arch bridge over the Tlawng River on NH44A, a vital connector between the airport and the city of Aizawl. Given its prominent location and importance, the bridge must be designed with a focus on its visual appeal. The bridge proposed in the tender specification was an arch bridge with vertical hangers (Fig 3). However, the author has chosen a network tied arch bridge as it is a more economical and better engineering solution.

The idea of the network arch was invented by PER TVEIT. He defined network arch bridge as an arch bridge in which some hangers intersect at least twice. Tied arch bridges with vertical hangers (Fig 5) subjected to semi span loading tend to move in horizontal direction resulting in higher deflection and bending moment is arch and tie.

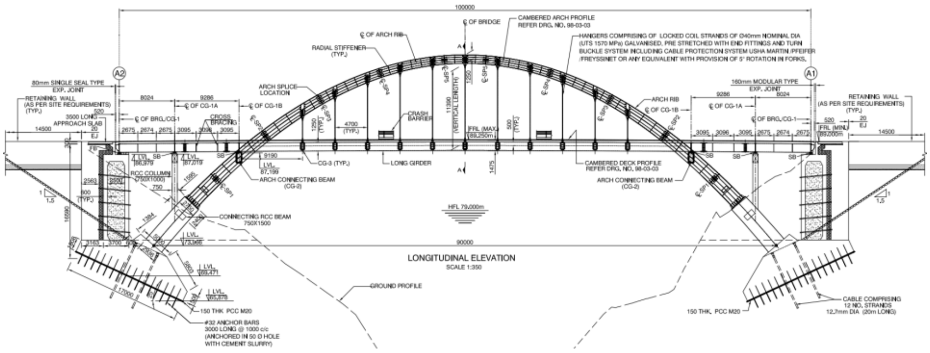

Fig. 3. Bridge proposed in tender drawings by the client

However, the inclined hangers in a arch bridge help limit deflections and increase the overall stiffness, especially under partial loading conditions as shown in Fig 6. When the hangers are inclined, this horizontal movement is counteracted. As a result, bending only occurs locally between the points where the hangers are attached to the arch and tie. According to Per Tveit (2011), using the network arrangement of the hanger in the arch (Fig. 1) can cut superstructure costs by around 40% to 50% when compared to other steel bridges and also presents a comparison of steel weights for various bridge designs (see Fig 4). He also suggests that it could save around 35% to 45% of cost per square meter when compared with traditional arches with vertical hangers.

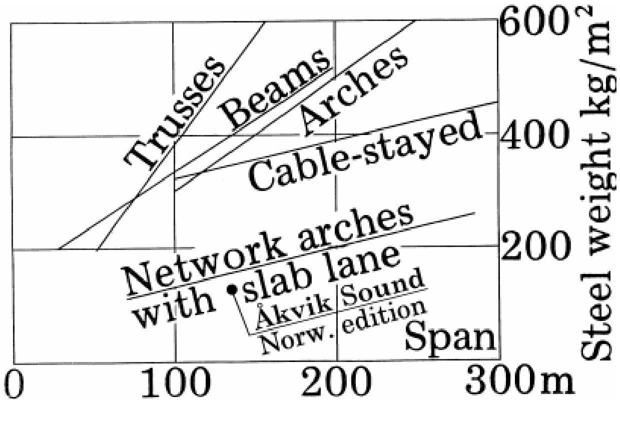

Fig. 4. Steel weight comparison for different type of bridges (Per Tveit -2011)

The lower part of Fig. 7 shows the comparison of the influence lines for bending moments in arch with vertical hanger and a network arch presented in systematic study of network arch by Per Tveit. Here the ratio of the maximum bending moment in arch with network arrangement and vertical hanger is almost 0.67. Hence it is evident that network arch bridge has an upper hand in terms of better structure integrity and performance when compared to its counterpart.

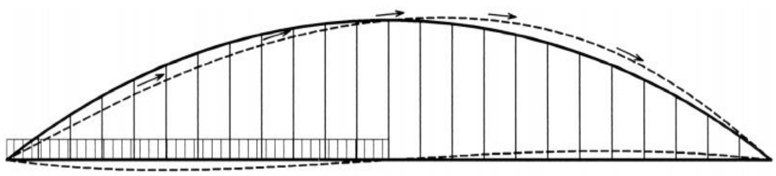

Fig. 5. Tied arch with vertical hangers, behaviors under semi span loading (Brunn & Schanack)

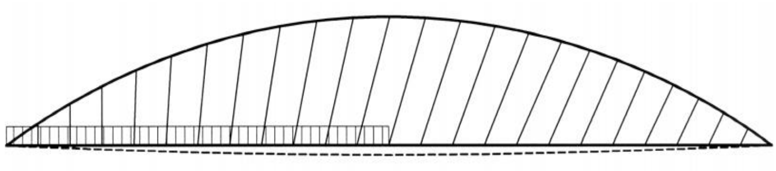

Fig. 6. Network arch with one set of inclined hangers, behavior under semi span loading (Brunn & Schanack)

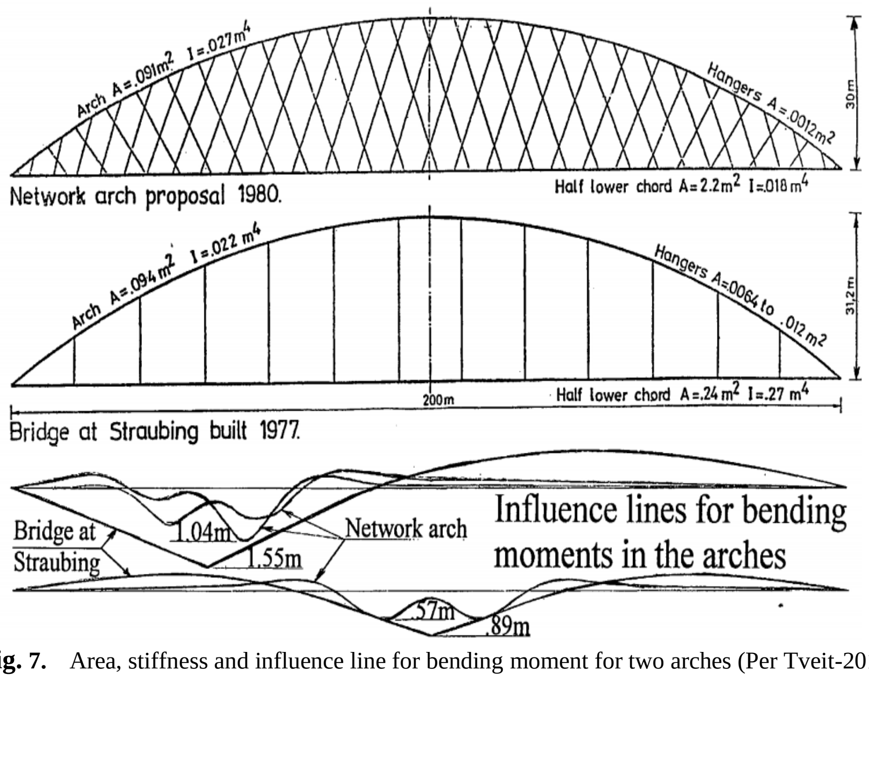

Fig. 7. Area, stiffness and influence line for bending moment for two arches (Per Tveit-2011)

3 General arrangement of the bridge

3.1 Arch and deck arrangement

The bridge design features an arch composed of 10 segments, along with two knuckle plate segments at each end. All segments are interconnected using flange connections with high-strength friction grip bolts (HSFG). All structural steel is of grade E350.

Arch Specifications

- . Knuckle Plate Segments: Size: 900x800x32 mm
- Two end segments with varying dimensions:
  - Depth varies from: 900 mm to 700 mm
  - Width varies from: 800 mm to 700 mm
  - Thickness: 32mm
- Remaining segments:
  - Size: 700x700x25 mm
- Rise of arch at center: 17 m.
- Tilt: 6 degrees in the transverse direction, creating a basket-handle shape.
- Curvature: The arch maintains a constant curvature with a radius of 80 m.

Deck Specifications

The bridge features a ladder deck with a thickness of 200 mm, spanning between cross girders that are built up I-section and spaced 2.5 meters apart. These cross girders are connected to longitudinal ties, which are box sections of size 700x800x20 mm.

3.2 Hanger arrangement

To achieve minimal bending moments in an arch, the line of thrust should ideally be aligned with the centerline of the arch, which is facilitated when loads are uniformly distributed and applied radially. This radial loading ensures that the resultant forces align with the arch's shape, predominantly creating axial compression rather than bending. By directing forces radially towards the arch (Fig. 8), the structure maintains an ideal line of thrust close to the centroidal axis, effectively reducing bending moments and allowing the arch to operate efficiently under minimal bending stress. This will also lead to small hanger forces (Brunn & Schanack).

This can be facilitated by positioning a set of hangers equidistantly along the arch, as described by Per Tveit (2011). Each hanger slopes downward with a specific inclination until it reaches the tie, and this arrangement is mirrored by another set of hangers. The primary variable is the starting angle of the first hanger which is kept as 90 degrees with the horizontal (Fig. 9) and the slope adjustment for each subsequent hanger, with the total number of hangers in one plane being 14, where the slope changes by 4 degrees between consecutive hangers (Fig.9). This configuration ensures that the loads are distributed uniformly and radially, aligning the resultant forces with the arch's shape and thus minimizing bending moments.

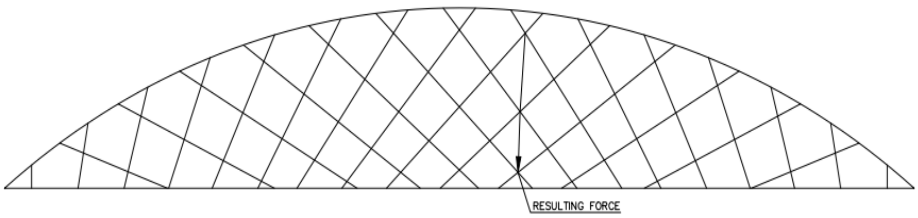

Fig. 8. The resultant force formed by the intersection of hangers in the arch is directed radially towards the center of the arch.

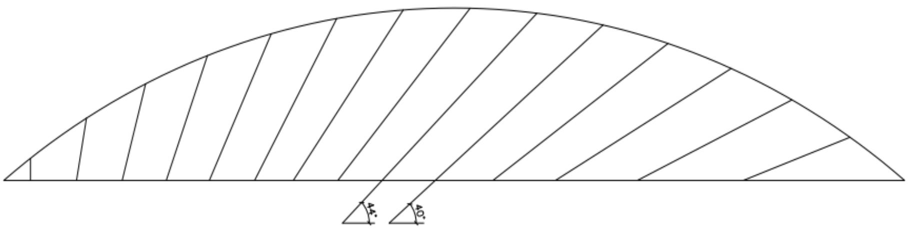

Fig. 9. The slope of the subsequent hanger in a single set differs by 4 degrees.

4 Analysis and design of the arch

An arch, as a predominant compression member, must be carefully analyzed and designed to ensure its stability under compression loads. Steel arches are particularly vulnerable to buckling phenomena, which can occur both in-plane and out-of-plane. To ensure proper design, it's essential to account for these buckling modes in the design process. This involves conducting thorough stability analyses and applying advanced design techniques.

Two different design methods are provided by the Eurocode for the design of arch structures incorporating buckling effects.

1. Substitute member (SM) method as per EN 1993-1-1.
2. The equivalent unique global and local initial imperfections method (EUGLI) as per EN-1993-1-1 cl 5.3.2(11).

The concept of a substitute member method is applicable to members with uniform sections subjected to uniform axial forces. Given the nature of the structural behavior of network arches it is not practical to use this method as it will lead to uneconomical design. Moreover, the identification of the most critical section is not possible while using SM method for design. Therefore, a more generalized method, such as the EUGLI method, is used to address these challenges effectively.

As outlined by M. Dallemule (2015), an equivalent unique global and local imperfection (EUGLI) is an equivalent imperfection that has shape affine to the form of a elastic buckling mode. It includes both global and local aspects for the verification of stability. The main idea of the method is described in detail by Prof. Eugen Chladný and Magdaléna Štujberová in paper magazine Stahlbau vol. 82. This paper explains the process of using this method in the design of network arches.

The arch has been modelled and analyzed using Sofistik software (Fig. 10).

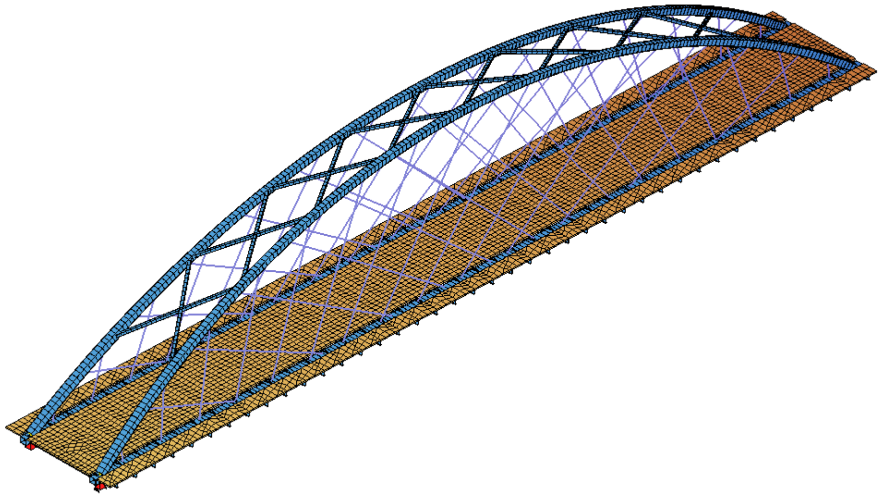

Fig. 10. 3-D model of arch in Sofistik software

The step-by-step procedure used for design of arch is as follows:

Step 1: Linear analysis has been performed and the utilization of sections has been noted corresponding to all load combinations.

Step 2: Elastic critical buckling load N_{cr} has been calculated using eigen value buckling analysis in Sofistik. Figs. 11 and 12 illustrate the first and second buckling mode shape where the buckling is in horizontal direction.

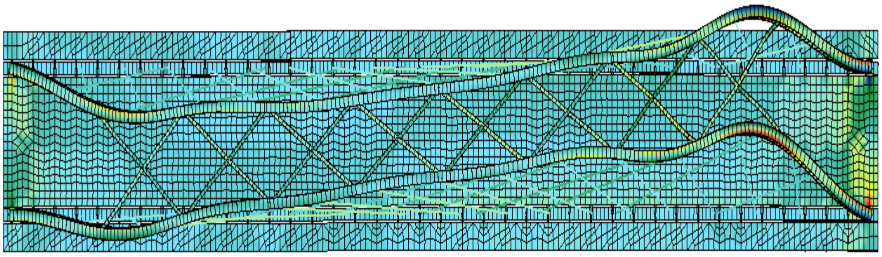

Fig. 11. The first buckling mode shape in horizontal direction.

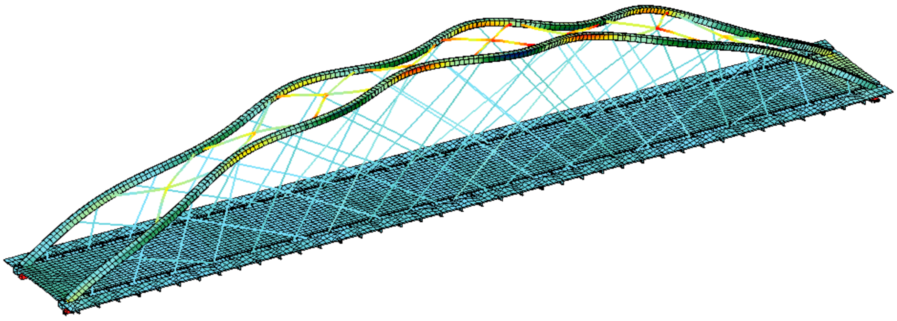

Fig. 12. The second buckling mode shape in horizontal direction.

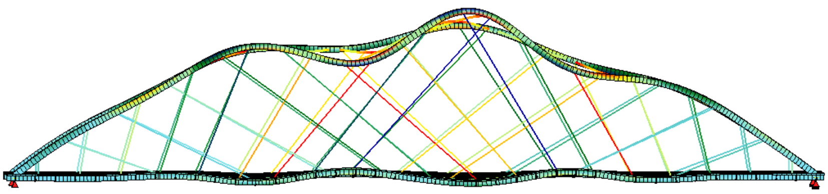

Fig. 13. Buckling mode shape in vertical direction

Step 2: After carrying out the eigenvalue buckling analysis, the next step is to calculate the magnitude of unique global and local imperfections. The imperfection shape should be affine to the deflected shape of the buckling mode. Above figure shows that no imperfection is found on point of inflection on arch for first buckling mode, therefore both modes have been considered separately for calculating imperfection in horizontal direction. Similarly, most critical buckling mode corresponding to vertical displacement (Fig. 13) is considered for calculating imperfection in vertical direction.

The amplitude of the EUGLI imperfection, $\eta_{init}(x)$, depends on three factors: e_0 (the design value of the initial bow imperfection as given by Equation (2)), $EI\eta''_{crmax}$ (the bending moment associated with the buckling mode at the critical cross-section), and η_{cr} (the deflected shape of the buckling mode). To determine $\eta_{init}(x)$, Equation (1) is used as specified in EN-1993-1-1 Clause 5.3.2(11). This imperfection is then applied as a load in the Sofistik software, as shown in Fig. 14.

To determine the magnitude of imperfections, the position of critical section is chosen first. Corresponding to this chosen section imperfection $\eta_{init}(x)$ is calculated.

$$\eta_{init} = e_0 \frac{N_{cr}}{EI \left|\eta''_{cr}\right|_{\max}} \eta_{cr} = \frac{e_0}{\bar{\lambda}} \frac{N_{Rk}}{EI \left|\eta''_{cr}\right|_{\max}} \eta_{cr} \tag{1}$$

Where e_0:

$$e_0 = \alpha \left(\bar{\lambda} - 0{,}2\right) \frac{M_{Rk}}{N_{Rk}} \frac{1 - \frac{\chi \bar{\lambda}^2}{\gamma_{M1}}}{1 - \chi \bar{\lambda}^2} \tag{2}$$

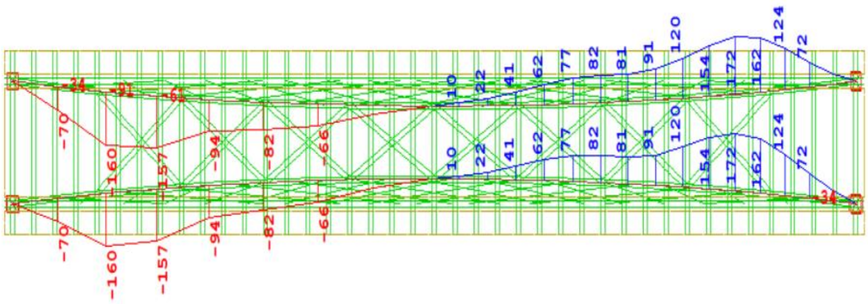

Fig. 14. Horizontal Imperfection shape corresponding to the first buckling mode.

Step 3: A second-order analysis is conducted by applying the imperfection $\eta_{init}(x)$ as a load in conjunction with other service loads. Based on the internal forces obtained from this analysis, the arch section is designed according to Clause 6.2 of EN-1993-1-1. The utilization of various sections is then recorded. It must be ensured that the selected section has the maximum utilization; otherwise, the process should be repeated. Summary of the utilization at different locations of the arch obtained for the most critical load combination is shown in Table 1.

Table 1. Utilization of section in arch corresponding to first buckling mode horizontal imperfection (Fig 12).

Location	Utilisation
Junction of arch and tie	0,85
Location of first transverse brace in arch (Chosen section)	**0,92**
Location of first hanger point in arch	0,86
Location of section variation between segment 3 and segment4	0,84
At mid of the arch	0,85

Step 4: Repeat step 2 to 3 by choosing a different critical section if the utilization of the chosen section is not maximum. In this case for the first iteration only the utilization of chosen section (location of first transverse brace in arch) is maximum.

Step 5: Step 2 to Step 4 shall be repeated for imperfections obtained corresponding to other critical buckling modes. In this case 2 more buckling modes have been considered (Fig 12 and Fig 13).

5 Arch erection scheme

Building a bridge in challenging geographical terrain, such as a valley, requires innovative construction techniques to overcome the limitations of traditional methods. Alternative solutions are required when conventional approaches like crane lifting of arch framework and push-launching on ground supports are not feasible due to the deep gorge. To address these challenges, following state-of-the-art methodology was devised which has been used first time in the world where such heavy arch steel framework is erected on one side of a deep gorge and then suspended from a suspension cable to transport over it.

The suspension system used for suspending the arch consists of several key parts. The trolley frame (see Fig. 16) is the main component, supporting all other components and allowing the trolley to move along the main suspension cable. Cable pulleys guide and support the movement of the suspension cables, ensuring smooth operation. The hoisting mechanism, which includes winches, provides the necessary lifting and lowering functions to suspend the arch. Suspension cables connect the trolley to the arch, bearing its weight during the suspension process. Additionally, the braking system controls the trolley's movement and secures it in place, while the control system manages the operation of the trolley which has been provided using winch-1 cable (see Fig.17), for precise adjustments.

Further the step-by-step process of the construction is described below.

1. The bridge's main structural components, including the arch-tie framework and hangers, are fabricated on the ground near the A1 abutment. As of the date of writing this paper, the arch fabrication has been completed and is scheduled to be launched in the coming month (see Fig. 15).

Fig. 15. Network arch steel framework fabricated at site

2. Towers are erected on each side of the valley near abutment A1 and A2 respectively and high strength main cable is suspended between the towers (see Fig.17).
3. Complete suspension system is put into place which includes trolleys, winches, suspension cables, restraining cables etc.
4. The fabricated arch-tie framework is then suspended using winch-2 cable from the main suspension cable employing specialized equipment and arrangements.
5. The suspended arch framework is then pulled towards abutment A2 using winch-3 cable in a controlled manner, allowing it to be positioned and placed on abutment A2. Upon reaching the location at abutment A2, the arch is jacked down onto the bearings.

Fig. 16. Transporting trolley frame on site which is used in suspension system

By employing this state-of-the-art suspension cable technique, the construction team can successfully build the bridge in the challenging valley terrain.

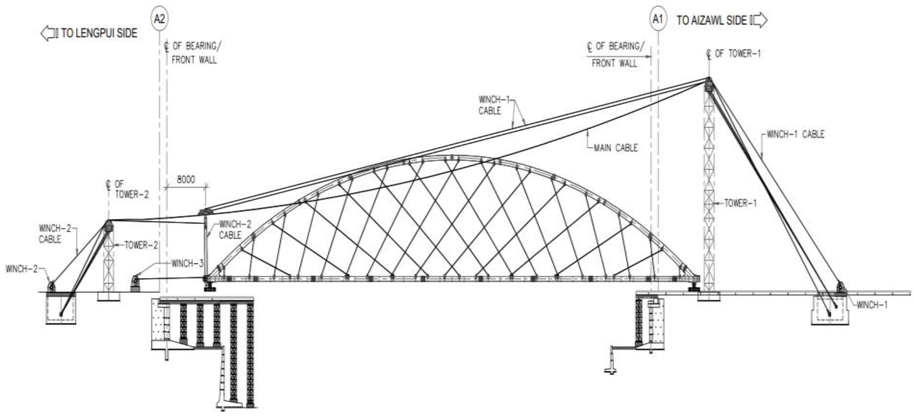

Fig. 17. Construction operation arrangement drawing

6 Conclusion

In summary, network arch bridges present a more economical solution compared to tied arch bridges with vertical hangers, largely due to their efficient structural design. The arrangement of hangers is essential for the optimal performance of a network arch bridge, influencing its stability and load distribution. Identifying the critical section in arch bridges can be challenging with traditional methods like the substitute member approach, especially in complex geometries. The EUGLI method proves invaluable in this context, as it allows for accurate determination of critical sections by incorporating imperfections modelled after buckling modes. Additionally, the unique construction methodology employed has demonstrated significant benefits, particularly for the feasibility of building arch bridges in deep gorges.

Acknowledgement

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