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Structural Optimization of hangers in Network Arch Bridges

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Abstract: *Road over bridges (ROB) frequently use tied arch bridges with vertical hangers. Hanger spacing and arrangement has greater influence in the structural behaviour of tied arch bridges. A network hanger arrangement is a set of slanted hangers used in tied arch bridges. In this study a parametric study was conducted on different network profiles and the behaviour of arch was investigated considering Hanger's inclination, number, and reduction in bending moment and axial force, and Hanger's relaxation in Network arch bridges. The variations in structural forces for different profiles are discussed in detail, and it was observed that network profile with radial hangers is efficient for IRC live loads. This study is aimed to give an insight and confidence to the bridge designers and structural engineering fraternity for adopting network arch bridges for road over bridges (ROB) in India.*

***Keywords**: Network arches, Cable profile, Slanted hangers, ROB's.*

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I. INTRODUCTION

Tied arch bridges, also known as bowstring arch bridges, are a type of arch bridge design that use a horizontal tie beam or truss to connect the tops of the two arches. The arches and the tie beam work together to support the bridge deck and distribute the weight of the bridge and its loads evenly. This design provides stability and strength while also allowing for a clear span, reducing the need for intermediate supports. Tied arch bridges are often used for pedestrian and bike bridges, or to span waterways or valleys where the height of the bridge is not a concern. The combination of arches and tie beams creates a visually striking appearance, making tied arch bridges a popular choice for iconic or signature bridges. The arches carry the vertical load of the bridge deck and distribute it evenly to the abutments. The tie beam acts as a horizontal tension member, resisting the horizontal forces acting on the bridge and preventing the arches from spreading apart. When a load is applied to the bridge deck, it creates a vertical force on the arches, causing them to bend downward. This downward bending increases the tension in the tie beam, which helps counteract the load and keep the arches from spreading apart. The arches and tie beam work together to form a balanced structure, where the compressive force in the arches is equal to the tensile force in the tie beam.

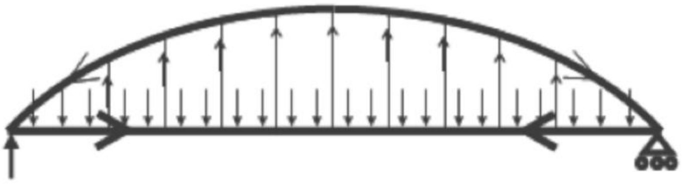


Figure 1 Tied arch bridge-force flow

Hangers in arch bridges are predominantly tension members that connect the arch rib to the deck or roadway. They transfer the weight of the deck and loads to the arch rib and hold the deck in place. Hangers provide stability to the bridge and prevent the arch from collapsing. They are typically made of steel cables, rods, or chains that are attached to the deck and anchored at the top of the arch. The number and arrangement of hangers depend on the size and design of the bridge, as well as the type of loads it is expected to carry.

Traditionally hangers are vertical but there are inclined hangers also in arch bridges which are diagonal supports that connect the bridge deck to the arch. These hangers provide additional stability to the bridge structure and help distribute weight evenly across the arch. The incline angle of the hangers is chosen based on the specific design requirements of the bridge, such as the load capacity and the intended use of the bridge. Inclined hangers are often used in network arch bridges, where the lattice-like structure provides additional stability compared to traditional arch bridges.

The stability of an arch also depends on the distribution of the loads on the arch, with evenly distributed loads providing better stability than concentrated or angled loads.

1.1 Network Arch Bridges – Around the World

Even though this concept of inclined hangers was introduced in early 19th century. Most of the early network hangers were made up of concrete because of high compression forces and the non-availability of high strength steel. Below image shows the existence of network arch bridges all over the world. We can clearly see the gap in adoption of these inclined hanger bridges in India and ASEAN countries.

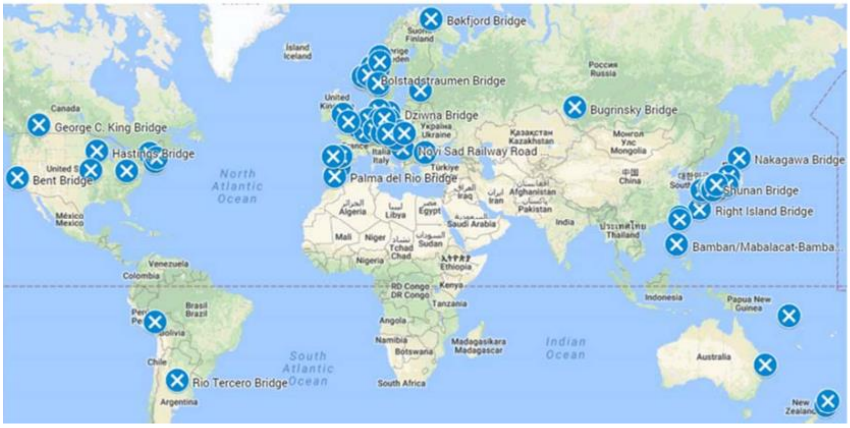


Figure 2 Network Arch bridge-locations all around the world [11]

1.2 Challenges in Adoption

The main reason for lesser adoption of these types of bridges is perceived to be the tension loss in hangers and the maintenance of these hangers in long run. However these bridges are lesser in weight when compared to traditional vertical hanger tied arch bridges which can also lead to lesser foundation expenses and they are also aesthetically appealing. The range of spans this particular network arch bridges are familiar is shown below.

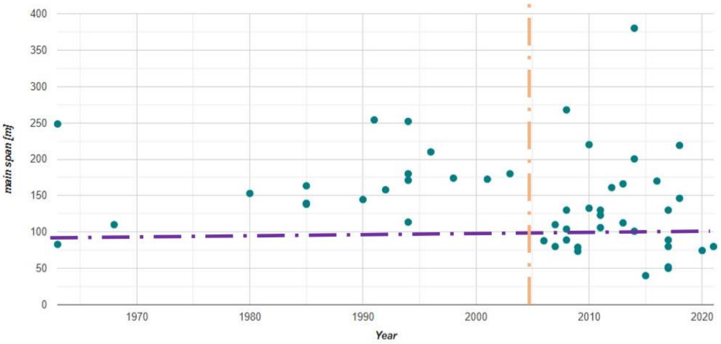


Figure 3 Network Arch bridge- bridge-Years vs. Span [6]

As the adoption of this network arch bridge is getting increased over the years this network arch bridges has the potential to replace the vertical arch bridges where erection and stronger foundations are the governing criteria

1.3 Research Methodology

The scope of the work is limited to obtain optimal network hanger profile of Network arch bridge for a 60m span road over bridge with IRC loadings by conducting parametric study on different hanger arrangement and performing linear static analysis of the arch bridge with optimum network pattern in Midas civil

II. PARAMETRIC STUDY

A parametric study of network hangers is required because the hanger arrangement decides the forces and force variations within the network arches. Hence, by analyzing the effect of changing specific parameters, such as the inclination, number and spacing of hangers, on the overall behaviour of the tied arch structure. This study will identify the optimal configuration of hangers that provide the necessary functionality while minimizing weight and cost. This study is performed using computer models and simulation tools of Midas civil.

2.1 Need for parametric study

The following parameters have effects on behaviour of network arch bridges

- *Span:* The span length of the tied arch bridge affects the bending moments and stresses in the hangers. As the span length increases, the bending moments and stresses in the hangers increase, requiring larger and stronger hangers.
- *Arch rise:* The arch rise, or the height of the arch, affects the compressive forces in the hangers. As the arch rise increases, the compressive forces in the hangers also increase, requiring stronger hangers.
- *Hanger quantity:* The quantity of hangers affects the overall stability and support of the tied arch structure. Increasing the number of hangers can provide more support, but it also increases the weight and cost of the bridge.
- *Hanger arrangement:* The arrangement of hangers can affect the distribution of loads and the stress and deformation of the structure. The parametric study can help optimize the arrangement of hangers to minimize stress and deformation.
- *Loading:* The loading conditions, such as the type and distribution of loads, can affect the stress and deformation of the hangers. The parametric study can help optimize the distribution of loads to minimize stress and deformation.
- *Arch curvature:* The curvature of the arch affects the bending moments and stresses in the hangers. The parametric study can help determine the optimal curvature for a specific tied arch bridge to minimize stress and deformation.
- *Cross sections:* The cross-sectional properties of the hangers, such as the shape and size, can affect the strength and stiffness of the structure.

By systematically varying these parameters and analyzing the response of the structure, the parametric study can help determine the optimal configuration of hangers for a specific tied arch bridge with adequate strength and stiffness.

As there are number of parameters that influence the structural behaviour which leads to complexity. So, for this study except hanger inclination and number of hangers all other parameters were assumed to be constant through the study. The values of fixed parameters adopted for the study are shown below

Parameter	Value
Span	62 m
Rise	10m
Rise / Span ratio	0.16
Typology	Through Type Tied Arch
Width of the bridge	16.044m
Depth of Tie Girder	1.2 m
Width of the Tie Girder	0.8m
Depth of the Arch	1.2m
Width of the Arch	0.8m
Spacing of the Cross girders	3.1m

Table 1 Validation model parameters

The parametric study can help optimize the distribution of loads across the hangers to minimize stress and deformation. The parametric study can also help ensure that the tied arch structure and hangers have adequate strength and stability to resist applied loads however stability analysis is not a part of this study.

2.2 Optimization Criteria:

The following criteria is adopted for optimization study of hangers in network arch Bridges,

- Lesser and almost equal bending moments in arch and tie.
- Almost equal tension in all the hangers with same hanger cross section i.e. maximum utilization of the cable cross section.
- Reasonable resistance against some hangers getting relaxed.

2.3 Study Cases:

Based on the above criteria and literature review, The following study cases were formulated to obtain an optimal profile for a particular span and rise of arch bridge as mentioned above.

Case/ Model No	Parameter	Remarks
Case-1/M1	Vertical hanger ROB	Validation Model
Case-2/M2	Inclined hanger 45 constant angle varying spacing	
Case-3/M3	Inclined hanger 60 constant angle varying spacing	
Case-4/M4	Inclined hanger 54 constant angle equidistant spacing	

Table 2 Study cases for parametric study

2.4 Loadings:

The following loads were considered for the study

Dead load (DL)

The self-weight of the various structural components are considered in the dead load. The unit weight of concrete is taken as 25 kN/m3 and unit weight of steel is taken as 78.5 kN/m3.

Superimposed Dead Load (SIDL)

The superimposed dead loads consist two components ie. SIDL-Fixed and SIDL-Variable where SIDL-Fixed component consists of weight of crash barrier and weight of Hand rails and SIDL-Variable component consist of weight of wearing course over the carriageway and footpath.

Foot Path Live Load

The Foot path Live load is considered as per IRC 6

Live Load

The Live loads considered in the analysis are Special vehicle, Class 70R , Class A and Fatigue Vehicle as per Cl.204 of IRC:6. For the combinations of Live loads considered for analysis of 3 lane carriage way with Footpath and 4 lane carriage way without footpath,. The appropriate impact factor is calculated as per clause 208 of IRC: 6 and applied to the live load forces and moments in the combinations for superstructure. For Fatigue Vehicle 50% of the impact factors considered.

2.4 Modeling and Analysis

Modeling and analysis is carried out using MIDAS software. Section properties are applied as Box sections for bowstring members except for End bottom cross girders and Intermediate bottom cross girders which are modeled as composite Sections. The live loads are applied with impact factor.

The deck slab is modeled as plate element resting on Bottom cross beams. Self-weight of Slab, Crash Barrier and wearing course are applied over the plate element as Plane loads. Live loads used are Class-A, special vehicle, 70-R (Bogie and Tracked) .Live loads are placed as a patch load over plate element and results are extracted at critical location.

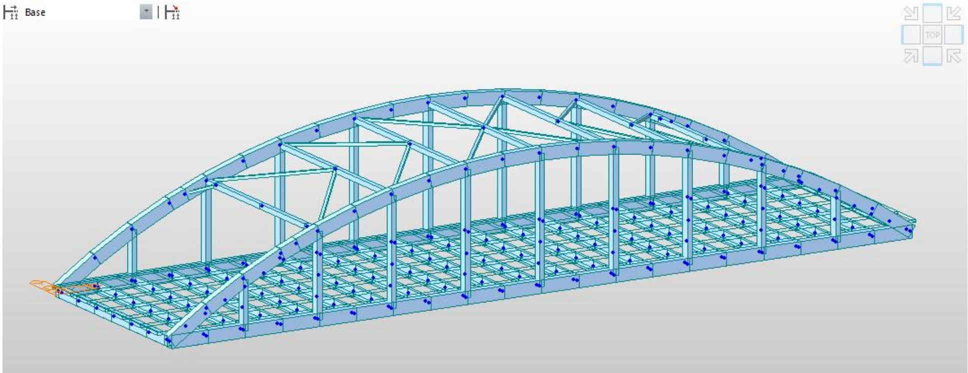


Figure 5 3D view of created model

2.5 General arrangement of bridge superstructure:

The superstructure consists of Bowstring girder and RC deck slab at bottom level of the arch for each 3 lane carriage way. The two planes of the truss are placed 16.044m(c/c) apart. The arch planes are connected together through cross girders at bottom level and tie beams at top level of superstructure. The center to center distance between bearings of bowstring superstructure is 62m.The General arrangement is shown below

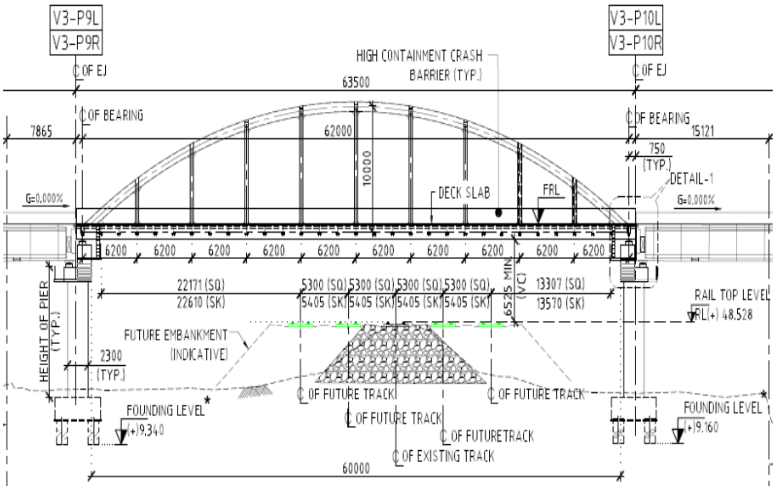


Figure 4 Elevation of the bridge superstructure

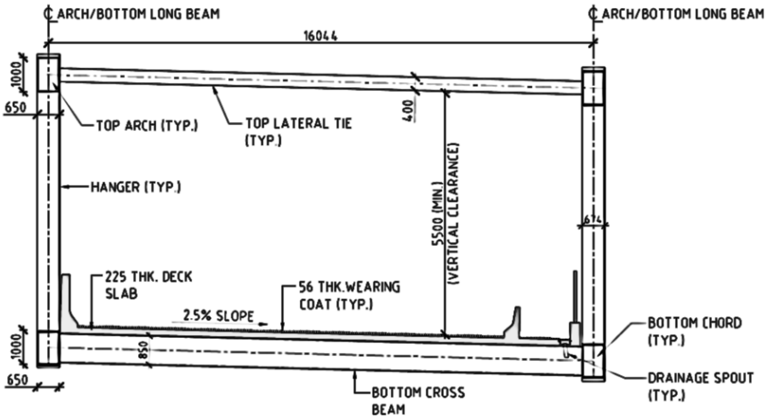
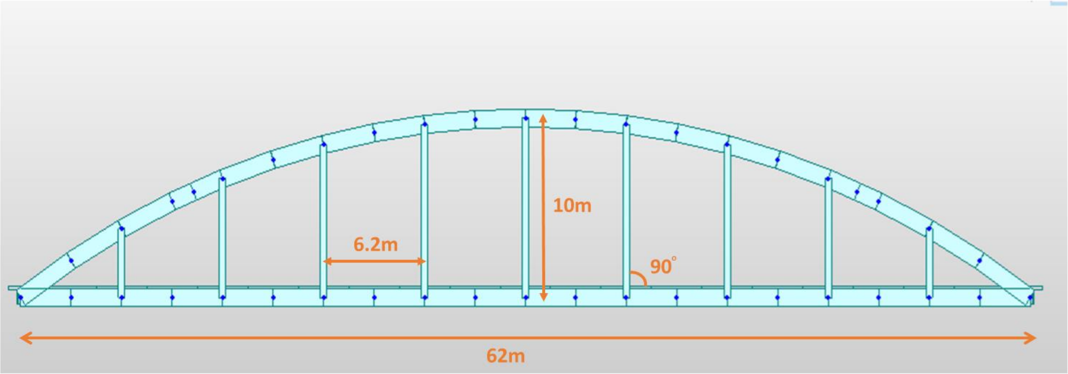


Figure 5 Cross section of the bridge superstructure

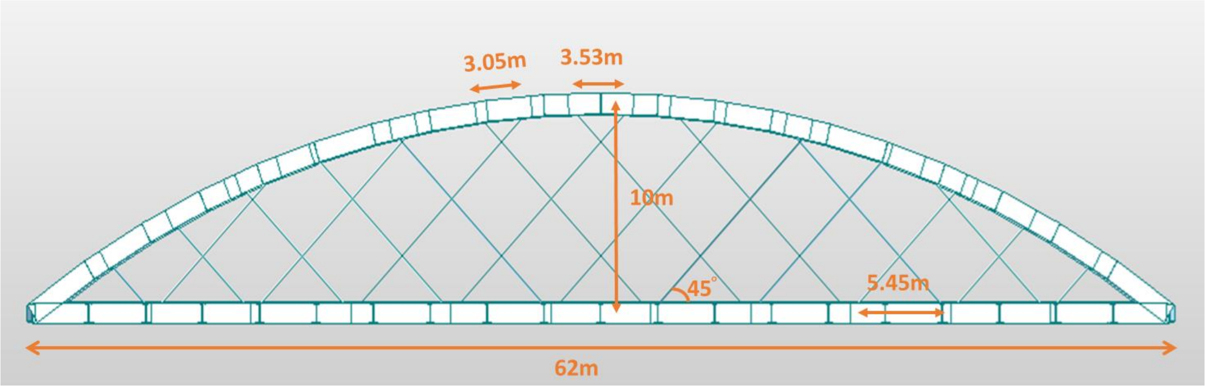
2.6 Hanger configurations and forces:

The geometric configuration of the various cases and its 3D model are shown below

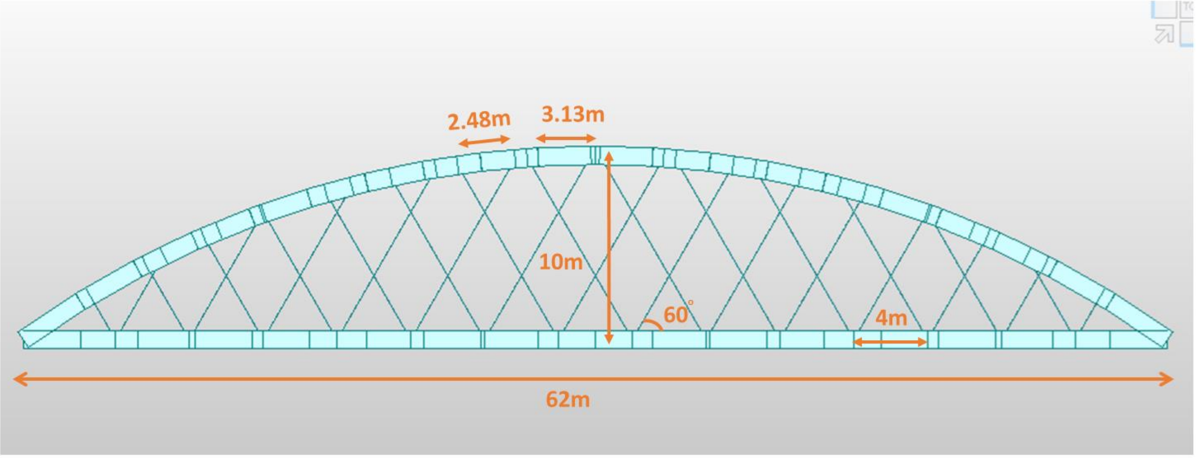
Case-1: Vertical hangers-Validation model



Case-2: Hangers with 45 degree inclination



Case-3: Hangers with 60 degree inclination



Case-4: Hangers with 54 degree inclination

In this case the hangers are projected radially and the inclination is obtained after fanning out the hangers and the inclination depends on the radius of curvature of the arch.

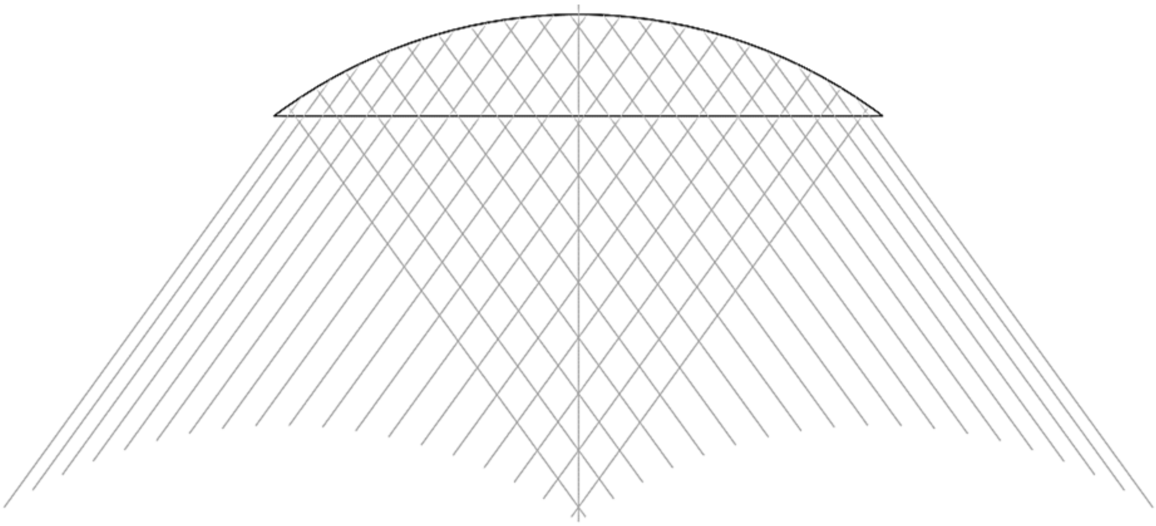
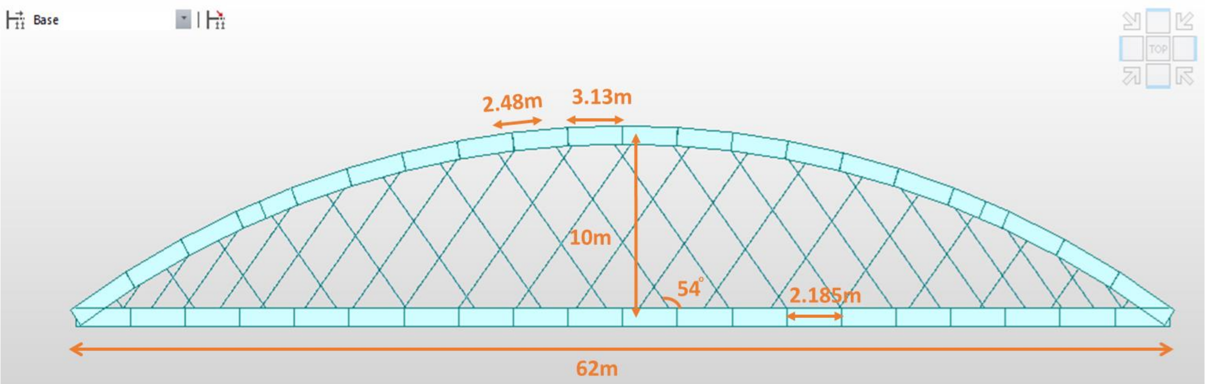


Figure 6 Hanger profile generation

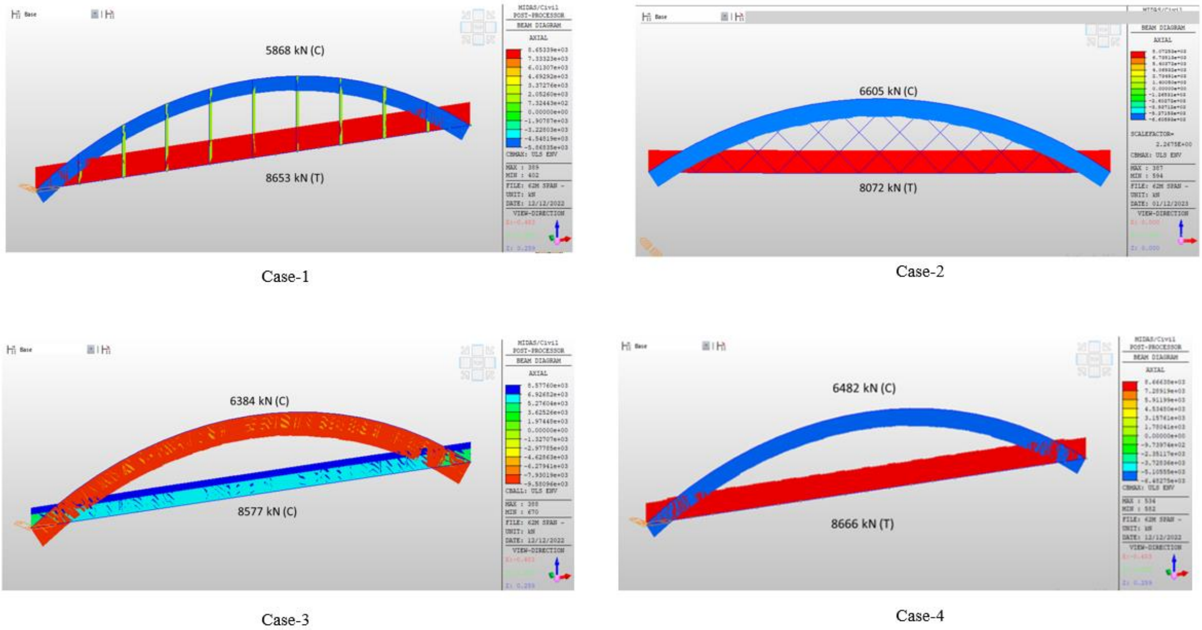


2.7 Analysis results

Linear static analysis of the model is carried out considering hangers as truss member. The Axial force bending moment in arch rib and tie beam are investigated also the bending moment in arch rib and tie beams are studied. Critical hanger forces for the minimum stress criteria are checked and the maximum tension force in hangers is obtained for ULS (ENV) maximum load case.

2.7.1 Variation in axial forces:

Linear static analysis of the model is carried out considering hangers as truss member. The Axial force bending moment in arch rib and tie beam are investigated also the bending moment in arch rib and tie beams are studied. Critical hanger forces for the minimum stress criteria are checked and the maximum tension force in hangers is obtained for ULS (ENV) maximum load case.



Case-1

Case-2

Case-3

Case-4

Figure 7 Axial force for different cases.

When comparing the axial force flow of different models, the reduction in axial force from vertical hangers (case 1) to other hanger profile are evident. Whereas, in tie the axial force for vertical hangers are close to the higher inclination hanger profiles 60 degree inclination and 54 degree inclination profiles however when we adopt 45 degree inclination there is considerable reduction in tie force when compared to other inclination profiles. The maximum force values are plotted and the variation of these forces with reference to vertical hangers is also shown below in bar chart. For maximum axial force reduction in arch and tie members 45-degree inclination hanger profile is suited.

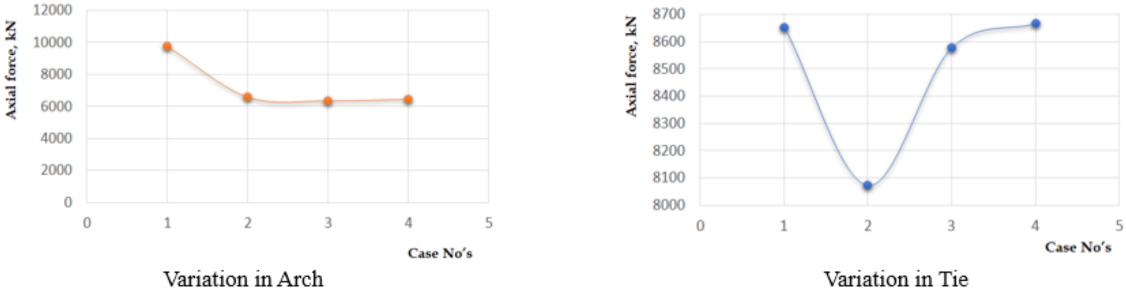
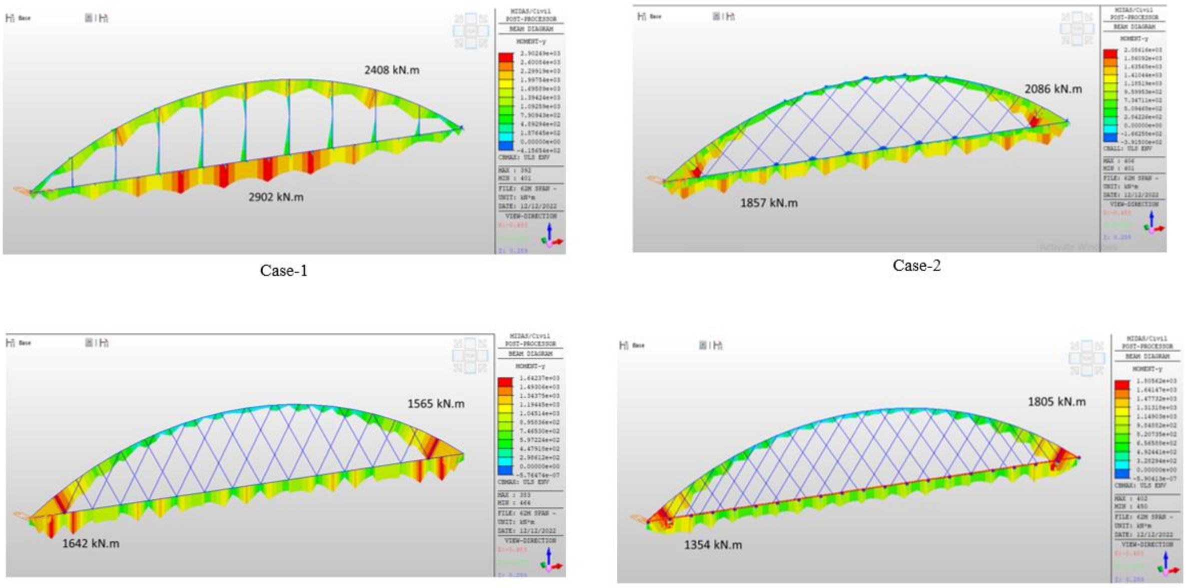


Figure 8 Axial force Variation's

2.7.2 Variation in Bending Moments:

When comparing the bending moment diagrams of different models the reduction in bending moment in arch and tie from vertical hangers (case-1) to other hanger profile are evident. The maximum reduction in arch bending moment is achieved at 60 degree and the maximum reduction in tie bending moment is achieved in 54 degree inclination profile. The maximum force values are plotted and the variation of these forces with reference to vertical hangers is also shown below in bar chart. For maximum bending moment reduction in arch and tie member's 54 degree inclination hanger profile can be preferred.



Case-1

Case-2

Case-3

Case-4

Figure 9 Bending Moment for different cases

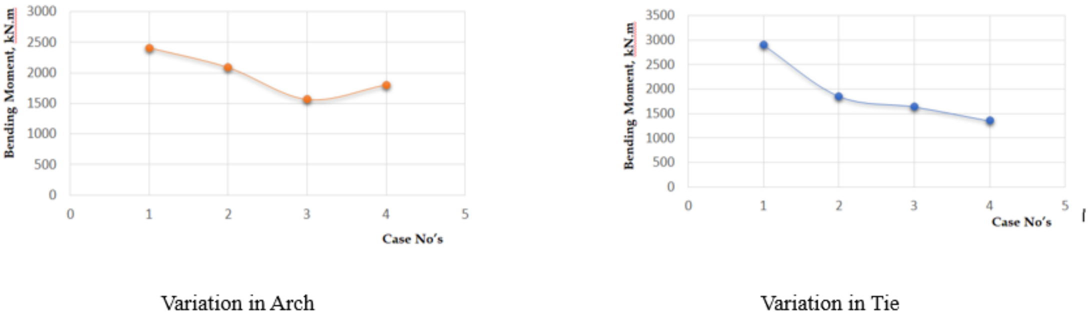
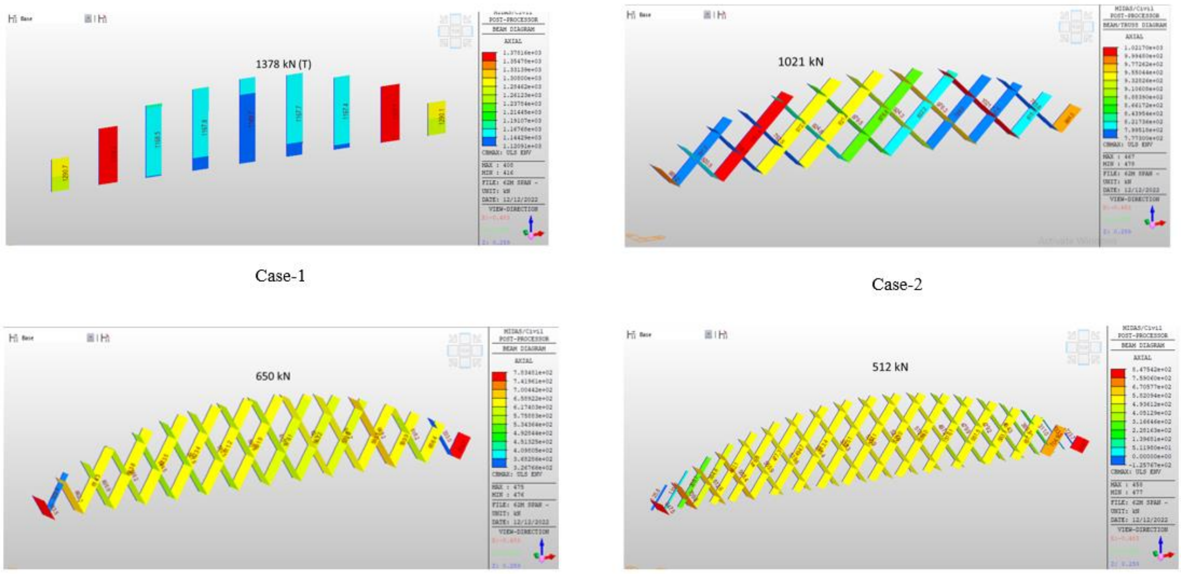


Figure 10 Bending moment variation for different cases:

2.7.3 Maximum Hanger force in different hanger profiles:

After observing the maximum hanger forces for various hanger profiles the hanger force in vertical hanger is high this is mainly attributed to the fact that it has the least number of elements to transfer the deck forces. However when we compare the case-3 and case-4 the number of hangers are almost equal but the variation in forces are also very less. This confirms to the statement provided by [2nd reference]. Hence the effect of number of hangers depends on the spacing of the hangers and as such increase or decrease is not required unless, the necessity to control the maximum force within the hangers is needed. Both in case-3 and case-4 the number of hangers getting almost equal forces are maximum hence a single cross section can be adopted with maximum utilization criteria.



Case-1 Case-2

Case-3 Case-4

Figure 11 Maximum hanger force for different cases

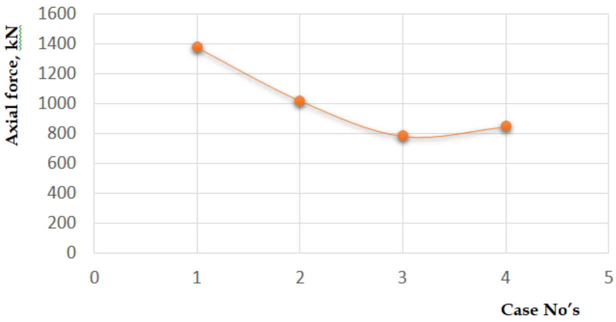
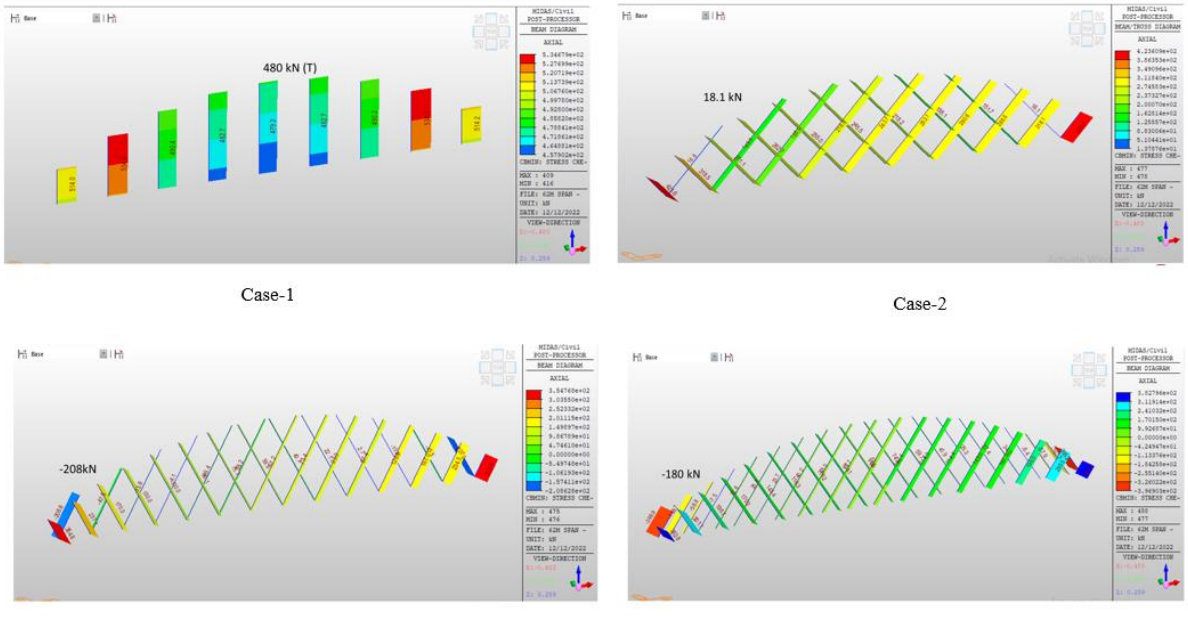


Figure 12 Hanger force variations

2.7.4 Minimum Hanger force in different hanger profiles:

Based on the analysis It can be observed that there is compression in some hangers for case-3 and case-4. However, for case-1 & case-2 the cables are completely under tension. This compression in certain hangers will lead to relaxation and make them ineffective in load transfer. Hence these identified cables may be pre-tension to certain limit to avoid theses relaxation. Another important aspect of the hanger's relaxation is that it can lead to hanger breaking/loss scenario due to the snapping of hangers under high compression. It is evident that with higher inclination the number of cables getting relaxed increases and the amount of pretension required also increases which is shown in below figure.



Case-1

Case-2

Case-3

Case-4

Figure 13 Minimum hanger force for different cases

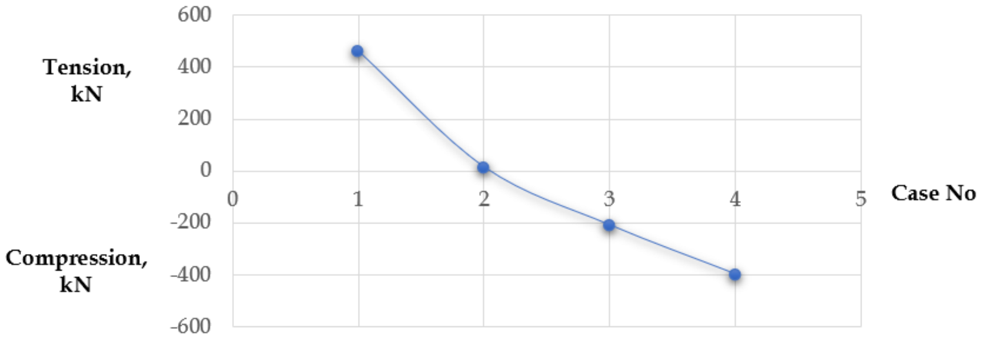


Figure 14 Variation in Minimum Hanger force

2.7.5 Maximum deformation in different hanger profiles:

The maximum deformation in different hanger profiles is listed below. It can be inferred that the inclined hanger arches are slightly stiffer than the vertical hanger arches. This can be due to two reasons. Firstly, the number of hangers in the arch which influences the in-plane rigidity and then the inclined hangers behaving like a web (beam behaviour) wherein the inclined hangers effectively transfer the in-plane shear forces. However, the case of hanger loss needs to be considered before selection of profile.

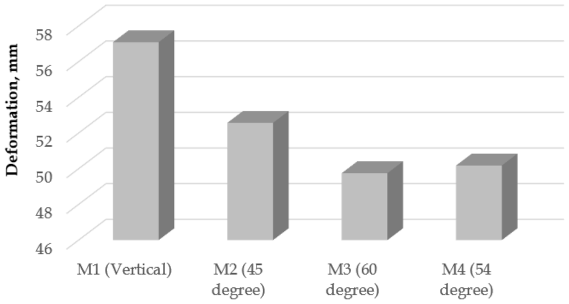


Figure 15 Maximum deformation in different cases.

2.7.6 Optimum Hanger profile:

From the results it can be inferred that the optimum hanger arrangement for the constant span, rise and loading are.

- ✓ Lesser and almost equal bending moments in arch and tie – Case-3 & Case-4 configuration in arch & tie respectively.
- ✓ Almost equal tension in all the hangers with same hanger cross section i.e. maximum utilization of the cable cross section – Case-4 configuration
- ✓ Lesser number of hangers getting relaxed – Case-4 configuration

Thus case-4 hanger profile is considered as optimum, and the network arch bridge is designed by considering the same.

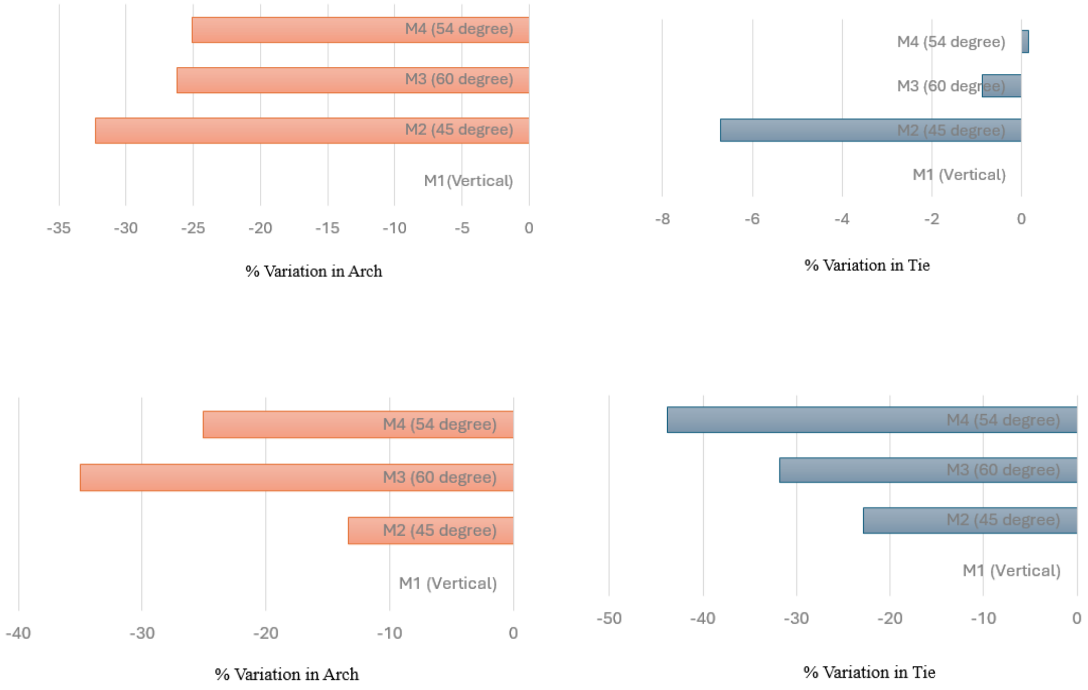


Figure 16 Force variation in comparison to vertical hangers (M1).

2.7.7 Hanger pre-tensioning:

It is also important to note that the slacking hangers make the network arch system discontinuous and in turn lead to over stressing other structural members. Based above analysis the number of cables which may be considered relaxed or lost can be obtained and the in-plane bucking capacity of the arch is revisited with this cable loss criterion. By inducing calculated pre-tension into the hangers/cables entire system will become stable and continuous.

III. CONCLUDING REMARKS

1. Parametric study for hanger optimization is carried out on 4 different three-dimensional models in Midas civil with different hanger profiles and the Optimum profile was selected based on the following criteria.
    - Lesser and almost equal bending moments in arch and tie.
    - Almost similar tension in all the hangers with same hanger cross section.
    - Lesser number of hangers getting relaxed
2. Based on the parametric study following results were obtained for different study cases all comparisons were made with respect to Vertical hanger profile (Case-1), Axial force in arch & tie was least for Case-2 with the forces being 32 % & 6 % lesser, Moment in arch was least for Case-3 with the forces 35% lesser, Moment in tie was least for Case-4 with the forces 43% lesser, Hanger forces were found almost equal in case-4 and also it was the configuration with only 8 no's of hangers getting compression in the entire span. Hence case-4 profile which is radial profile with 54-degree inclination came out to be the optimum cable profile for network arch.

3. Subsequently, pre-tension requirement for optimum profile was calculated and the model was again analyzed with pretension force and no hangers were getting relaxed after applying pretension.
4. Network arches are hybrid arches with predominantly beam behaviour rather than truss behaviour as in bow string arches.
5. Profiling hangers play vital role in the behaviour of network arch bridges.
6. Hangers relax for moving loads irrespective of inclination in Network arches.
7. Slacked hanger leads to discontinuous load path in network arches and may lead to loss of hangers (Broken hanger scenario)
8. Slacking can be prevented with sufficient pre-tensioning of the hanger rods.
9. Network arch bridge with inclined hangers can be adopted for road over bridges in similarity with bow string arch bridges.
10. Network arch bridges have appealing structural form with inclined hangers; hence this type of arch bridge can be proposed for locations where aesthetics of the bridge is a vital parameter.

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