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# Analysis of Long Span Steel Tied Arch Bridges

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***Abstract: Arch bridges construction has reappeared around the world thanks to the cantilever launching method, and nowadays these structures represent one of the three major types of long-span bridges, with the other two types being suspension and cable-stayed bridges. The arch rib is an element mainly subjected to a large axial compression force caused by dead loads, and that's why arch bridge structures exhibit a complex behavior during strong earthquakes. Furthermore, when a bridge is located close to a fault system, the near field effects must be considered, since the structure could experiment with large displacements. This research work aims the analysis and structural stability of a Network arch bridge – a tied-arch bridge with inclined hangers that cross each other at least twice. A comparative analysis with other type of hanger arrangements i.e. a tied-arch bridge with vertical hangers is performed. Possible analysis solutions with respect to spans, materials and carriageway width are presented and succinctly discussed. Earlier this kind of analysis was not possible due to limited processing power, but with better software and available processing power, it is possible to estimate the response of structure more accurately. Modelling using a tri dimensional finite element model of the arch bridges are described through MIDAS CIVIL Software in this research work. Two arch bridges are modelled with different arrangements of hangers – a vertical and inclined network type arrangements – under same load parameters. Comparative analysis is carried and studied in terms of fluctuations in member forces, bending moments, deflections, and behavior under seismic excitation.***
***Keywords: Tied arch bridge, Network arch bridge, Elastomeric bearing, Eigenvalue analysis, Seismic analysis, MIDAS Civil, Member forces and bending moments & Time period.***

## I. INTRODUCTION

Arch bridges construction has reappeared around the world thanks to the cantilever launching method, and nowadays these structures represent one of the three major types of long span bridges, with the other two types being suspension and cable-stayed bridges. Many ancient and well know examples of stone arches still stand to this day. Arches are good choices for crossing valleys and rivers since the arch doesn't require piers in the center. Arches can be one of the more beautiful bridge types. Arches use a curved structure which provides a high resistance to bending forces. Unlike girder and truss bridges, both ends of an arch are fixed in the horizontal direction (i.e. no horizontal movement is allowed in the bearing). Thus, when a load is placed on the bridge (e.g. a car passes over it) horizontal forces occur in the bearings of the arch. These horizontal forces are unique to the arch and as a result arches can only be used where the ground or foundation is solid and stable. Structurally there are four basic arch types: hinge-less, two-hinged, three hinged and tied arches. The hinge-less arch uses no hinges and allows no rotation at the foundations. As a result, a great deal of force is generated at the foundation (horizontal, vertical, and bending forces) and the hinge-less arch can only be built where the ground is very stable. However, the hinge-less arch is a very stiff structure and suffers less deflection than other arches. The two hinged arch uses hinged bearings which allow rotation. The only forces generated at the bearings are horizontal and vertical forces. This is perhaps the most used variation for steel arches and is generally a very economical design. The three-hinged arch adds an additional hinge at the top or crown of the arch. The three-hinged arch suffers very little if there is movement in either foundation (due to earthquakes, sinking, etc.) However, the three-hinged arch experiences much more deflection and the hinges are complex and can be difficult to fabricate. The three-hinged arch is rarely used anymore. The tied arch is a variation on the arch which allows construction even if the ground is not solid enough to deal with the horizontal forces. Rather than relying on the foundation to restrain the horizontal forces, the girder itself "ties" both ends of the arch together, thus the name "tied arch."

The present work deals with comparative analysis of 'Network arch bridge' and 'Tied-arch bridge with vertical hangers' under same loading parameters and dimensional specifications (i.e. main span, carriageway width, central rise etc.). A Network arch bridge is a type of bridge in which deck portion is hung below arch beam on inclined suspenders. Analysis of Network arch bridge and Tied-arch bridge is done according to IRC 06:2017, IRC 114:2018, IRC 83 Part 2:2018 etc. The Response spectrum analysis is done considering that the bridges are in zone IV & V. Main span for both arch bridge is taken as 100 m, carriageway width as 7.5 m, central rise as 17 m. The loads that are applied to the bridges are dead load, live load, superimposed dead load, vehicle load, wind load and earthquake load.

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Model is created followed by properties for various structural members are defined. Load patterns are assigned. After model creation the structure is analysed for dead load, live load, super dead load, vehicle load, wind load and earthquake load. Parameters such as axial force, shear force, bending moment etc. can be studied and we can obtain the results of respective member of bridges i.e arch beam, tie beam, cross girders, bracings, hangers etc.

Based on the literature, it can see that very limited comparative analysis study is carried out on types of steel arch bridges under same loading parameters. Many literatures focused on the seismic analysis results by changing structural pattern of bridge, input parameters etc. On the other hand Kharde N. V., *et al.* (2022) presented comparative analysis of suspension cable bridge and tied arch bridge using SAP 2000.

This paper focuses on the behavior of two types of long span steel arch bridges i.e. network arch bridge and tied arch with vertical hangers using MIDAS Civil 2023 by comparing not only the seismic analysis results but also fluctuations in the member forces, moments, eigenvalue analysis results etc. First, the network arch bridge is modelled followed by loading conforming IRC codes. Then, member results are observed under two different seismic zones. Same work flowchart was followed for tied arch bridge with vertical hangers. Based on the analyses, interesting results with respect to bridge behavior were found. Finally, it has been observed that the network arch bridge delivers safer results and more strength than tied arch bridge with vertical hangers.

## II. OBJECTIVE

1) To estimate the wind forces, seismic force and temperature loads to be applied on arch bridge for various spans and carriageway width using relevant codes, standards & literature.
2) To study the seismic effect of Steel arch bridge for support condition equivalent to Elastomeric bearing as per IRC 83 Part 2:2018.
3) To study the fluctuation of axial forces, moments, displacements in various structural components of arch bridge during seismic excitation.
4) To study the nodal results of response spectrum.
5) To study the time period (Vibration mode shapes) of structure.
6) To analyze the arch bridge structure in Seismic zone IV and zone V with Hard rock condition to obtain the results.
7) To compare the performance of Tied arch with vertical hangers and Network arch bridge to draw conclusion about which bridge delivers safer results and more strength.

## III. METHODOLOGY

### A. Bridge Dimensional Details

| Dimensional details | Analytical Model 1 | Analytical Model 2 |
|---|---|---|
| Main span | 100 Meter | |
| Central rise | 17 Meter | |
| Carriageway width | 7.5 Meter | |
| Type of Bridge | Network arch bridge | Tied arch bridge with vertical hangers |

Table. No. 1: Table for bridge dimensional details

### B. Sectional Details

| Structural components | Type of section | Flange plate details (mm) | Web plate details (mm) | Material Grade |
|---|---|---|---|---|
| Arch beam | Plate built up girder (Box girder) | 800 x 32 x 2 Nos. | 836 x 32 x 2 Nos. | E350-BR |
| Tie beam | Plate built up girder (Box girder) | 800 x 32 x 2 Nos. | 636 x 32 x 2 Nos. | E350-BR |
| Cross girder | Plate built up girder (Single web) | 300 x 16 x 2 Nos. | 700 x 10 x 1 Nos. | E350-BR |
| Plan bracing | Plate built up girder (Box girder) | 320 x 10 x 2 Nos. | 280 x 10 x 2 Nos. | E350-BR |
| Hanger | Post tension bar (Macalloy 1030) | 56 mm Dia. | | E520 |

Table. No. 2: Table for Sectional details

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### C. *Support Bearing Details*

| Bearing type | Stiffness coefficient for restrain condition | Stiffness coefficient for release condition |
|---|---|---|
| Elastomeric bearing | $10^7$ to $10^8$ KN/m | 100 to 1000 KN/m |

Table. No. 3: Table for Bearing details

### D. *Wind Load Parameters*

| Parameters | Value | Reference |
|---|---|---|
| Basic wind speed, Vb | 47 m/s | |
| Bridge location | Plain terrain | |
| Gust factor | 2 | Cl. 209.3.3 of IRC 6:2017 |
| Truss spacing ratio = (C/c dist. Between Trusses)/(Depth of windward truss) | 1.09 | |
| Solidity ratio = (Net Area)/(Gross Area) | 0.194 | |
| Shielding Factor (n) | 0.93 | Table C-2; Annex C, IRC 6:2017 |
| Drag Coefficient (Cd) | 1.83 | Table C-1; Annex C, IRC 6:2017 |
| Lift coefficient (CL) | 0.75 | Cl. 209.3.5 of IRC 6:2017 |

Table. No. 4: Table for Wind load parameters

### E. *Seismic Load Parameters*

| Parameters | Analytical model 1 | | Analytical model 2 | | Reference |
|---|---|---|---|---|---|
| | Seismic Zone IV | Seismic Zone V | Seismic Zone IV | Seismic Zone V | |
| Zone Factor (Z) | 0.24 | 0.36 | 0.24 | 0.36 | Table 4.2 of IRC 114:2018 |
| Importance Factor (I) | 1 | | | | Table 4.3 of IRC 114:2018 |
| Soil Type | 1 | | | | Rock or Hard soils refer table 5.1 of IRC 114:2018 |
| Response reduction factor | 2.5 | | | | Table 4.1 of IRC 114:2018 |

Table. No. 5: Table for Seismic load parameters

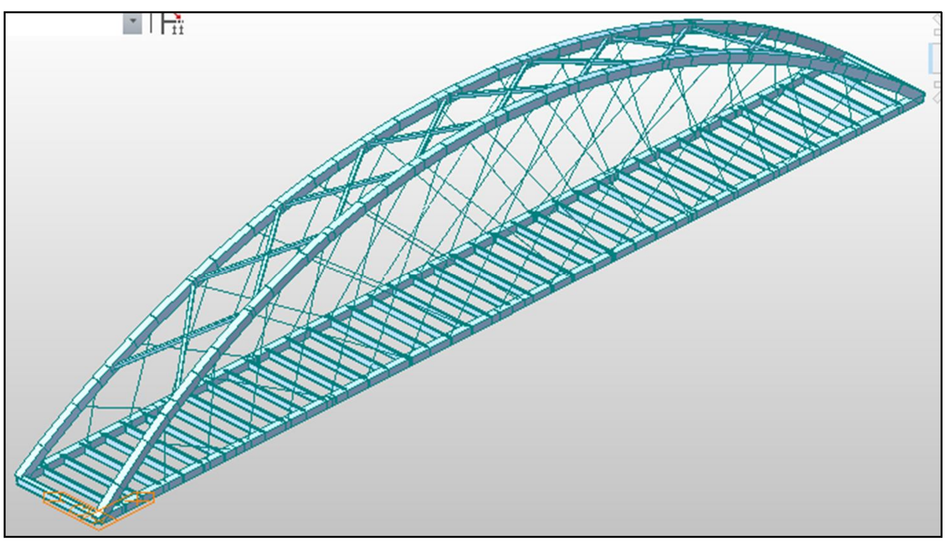

Figure 1: 3-D Model of Analytical model 1

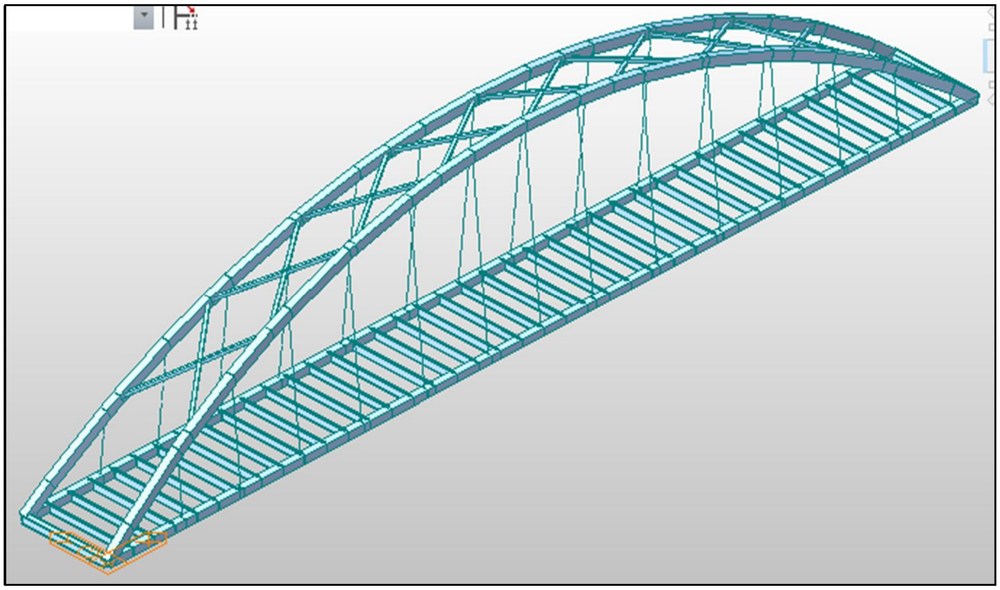

Figure 2: 3-D Model of Analytical model 2

*F. Design Load Parameters (Other Than Seismic)*

1) *Dead load (Self weight of structural steel + Super imposed dead load):* Self-weight of structural steel members is increased by 15% to account for Stiffeners, Battens, Connections etc. Load due to Deck slab & wearing course is applied on Cross girders. Crash barrier load is assumed as 8 KN/m over Tie beam with eccentricity of 0.79m.
2) *Live load (IRC 6:2017):* With respect to the Carriageway width, arch bridge is designed for 1 Lane of Class 70R or 2 Lanes of Class A as per Table 6A of IRC 6:2017, whichever produces severe effects.
3) *Wind load (IRC 6:2017):* Computation of wind loads on Truss type Bridge superstructure, are done with live load and without live load. For both the cases the design wind loads i.e. $F_{transverse}$ (Ft) & $F_{longitudinal}$ (FL) shall be derived separately for the areas of the windward and leeward truss girder and deck elements.

The bridges shall not be carrying any live load when the wind speed at deck level exceeds 36 m/s (as per clause 209.3.7 IRC 6:2017).

| Design Wind Load (WL) on various members considering Live load | | Wind conditions | | | |
|---|---|---|---|---|---|
| | | Wind ward side | | Leeward side | |
| | | Service Case | Construction case | Service Case | Construction case |
| Arch at H1 Level | Ft (KN/m) | 2.191 | 1.533 | 1.931 | 1.352 |
| | FL (KN/m) | 1.095 | 0.767 | 0.966 | 0.676 |
| Arch at H2 Level | Ft (KN/m) | 2.464 | 1.725 | 2.173 | 1.521 |
| | FL (KN/m) | 1.232 | 0.862 | 1.086 | 0.760 |
| Arch at H3 Level | Ft (KN/m) | 2.587 | 1.811 | 2.281 | 1.597 |
| | FL (KN/m) | 1.294 | 0.906 | 1.141 | 0.798 |
| Crash Barrier | Ft (KN/m) | 8.957 | 6.270 | 0.000 | 0.000 |
| | FL (KN/m) | 4.479 | 3.135 | 0.000 | 0.000 |
| Hangers at all Levels | Ft (KN/m) | 0.174 | 0.122 | 0.154 | 0.108 |
| | FL (KN/m) | 0.087 | 0.061 | 0.077 | 0.054 |

Table. No. 6: Table for Wind Forces (Considering Live load).

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| Design Wind Load (WL) on various members without considering Live load | | Wind conditions | | | |
|---|---|---|---|---|---|
| | | Wind ward side | | Leeward side | |
| | | Service Case | Construction case | Service Case | Construction case |
| Arch at H1 Level | Ft (KN/m) | 3.089 | 2.162 | 2.873 | 2.011 |
| | FL (KN/m) | 1.545 | 1.081 | 1.436 | 1.006 |
| Arch at H2 Level | Ft (KN/m) | 3.364 | 2.355 | 3.129 | 2.190 |
| | FL (KN/m) | 1.682 | 1.177 | 1.564 | 1.095 |
| Arch at H3 Level | Ft (KN/m) | 3.567 | 2.497 | 3.317 | 2.322 |
| | FL (KN/m) | 1.783 | 1.248 | 1.659 | 1.161 |
| Crash Barrier | Ft (KN/m) | 8.495 | 5.947 | 0.000 | 0.000 |
| | FL (KN/m) | 4.248 | 2.973 | 0.000 | 0.000 |
| Hangers at all Levels | Ft (KN/m) | 0.234 | 0.164 | 0.218 | 0.152 |
| | FL (KN/m) | 0.117 | 0.082 | 0.109 | 0.076 |

Table. No. 7: Table for Wind Forces (without considering Live load).

*4) Temperature load*

Maximum Shade air temp. = +48.4$^0$C & Minimum Shade air temp. = -2.2$^0$C, As per Table no. 15 of IRC 6:2017, mean of maximum and minimum air shade temperature is (48.4 + 2.2)/2 = 25.3$^0$C.
Temperature rise (+10$^0$C) = 35.3$^0$C & Temperature fall (-10$^0$C) = 15.3$^0$C.
Hence Overall differential temperature to be applied on structure = +-(35.3 + 2.2) = +-37.5$^0$C i.e. 99.5 Fahrenheit.

### *G. Load Combinations*

Load combinations are considered as per **Table B-2 of IRC-6 2017** i.e various load combinations are prepared to account for the worst-case scenario in Ultimate Limit State (ULS).

## IV. RESULTS AND DISCUSSIONS

### *A. Axial Tensile Force*

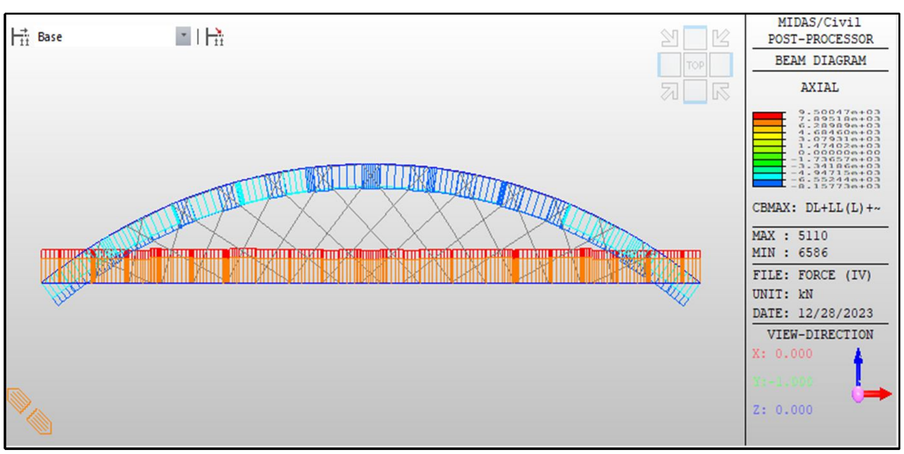


Figure 3: Axial tensile force diagram for Model 1

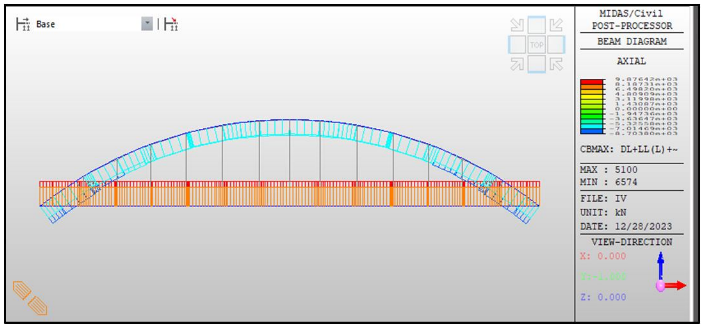

Figure 4: Axial tensile force diagram for Model 2

| Members | Model 1 | Model 2 | % increase/decrease in Axial tension | Governing load case for Model 1 | Governing load case for Model 2 |
|---|---|---|---|---|---|
| Arch Beam | 0.000 | 0.000 | NA | NA | NA |
| Tie Beam | 943.745 | 987.642 | 5% | DL (Add/Add) + LL (L) + WL 36 (L) | DL (Add/Add) + LL (L) + WL 36 (L) |
| Cross Girder | 86.105 | 90.972 | 6% | DL (Add/Add) + LL (L) + WL 36 (L) | DL (Add/Add) + LL (L) + WL 36 (L) |
| Top Bracing | 75.633 | 73.680 | -3% | DL (Rel/Add) + WL 47 (L) | DL (Rel/Add) + WL 47 (L) |
| Hangers | 83.326 | 104.680 | 26% | DL (Add/Add) + LL (L) + WL 36 (L) | DL (Add/Add) + LL (L) + WL 36 (L) |

Table. No. 8: Table for comparative analysis for Axial tensile force (in T).

### B. *Axial Compressive Force*

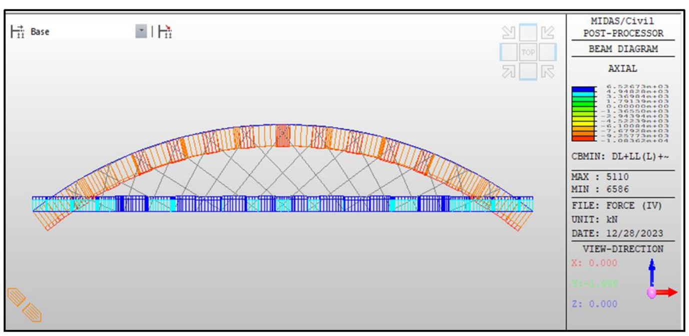

Figure 5: Axial compressive force diagram for Model 1

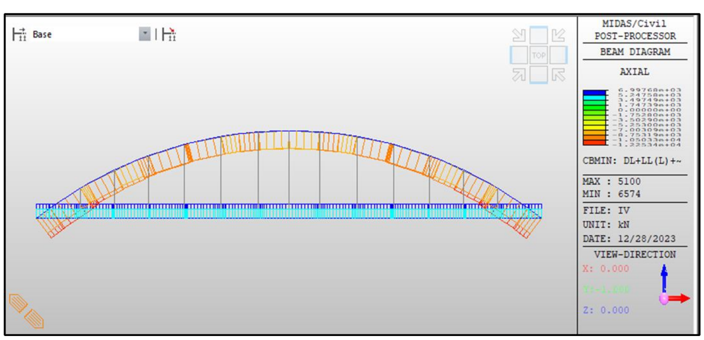

Figure 6: Axial compressive force diagram for Model 2

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| Members | Model 1 | Model 2 | % increase/decrease in Axial compression | Governing load case for Model 1 | Governing load case for Model 2 |
|---|---|---|---|---|---|
| Arch Beam | 1164.824 | 1225.338 | 5% | DL (Add/Add) + LL (L) + WL 36 (L) | DL (Add/Add) + LL (L) + WL 36 (L) |
| Tie Beam | 0.000 | 0.000 | NA | NA | NA |
| Cross Girder | 40.909 | 39.777 | -3% | DL (Rel/Rel) + LL (L) + WL 36 (L) | DL (Rel/Rel) + LL (L) + WL 36 (L) |
| Top Bracing | 110.122 | 113.258 | 3% | DL (Add/Rel) + WL 47 (L) | DL (Add/Rel) + WL 47 (L) |
| Hangers | 0.000 | 0.000 | NA | NA | NA |

Table. No. 9: Table for comparative analysis for Axial compressive force (in T).

### *C. Shear Force*

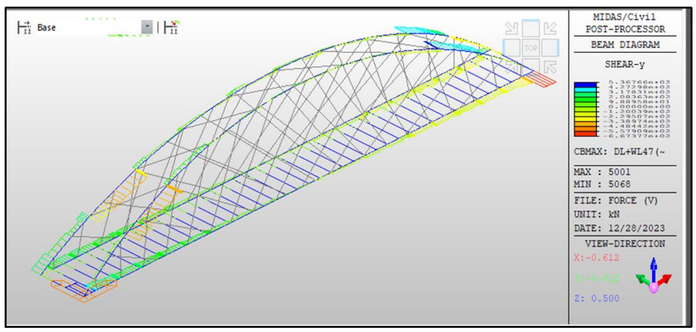


Figure 7: Shear force diagram for Model 1

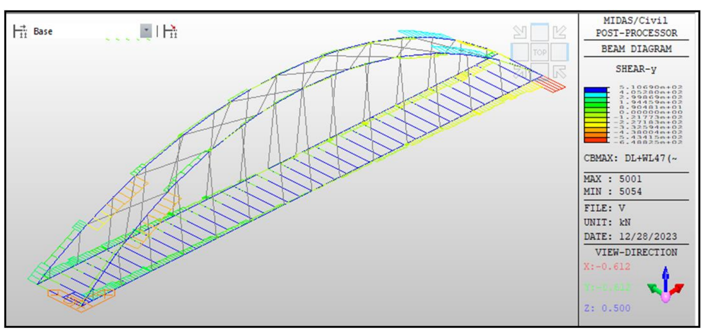


Figure 8: Shear force diagram for Model 2

| Members | Model 1 | Model 2 | % increase/decrease in Shear | Governing load case for Model 1 | Governing load case for Model 2 |
|---|---|---|---|---|---|
| Arch Beam | 44.572 | 80.359 | 80.3% | DL (Add/Add) + WL 47 (L) | DL (Add/Add) + LL (L) + WL 36 (L) |
| Tie Beam | 78.852 | 82.145 | 4.2% | DL (Add/Add) + LL (L) + WL 36 (L) | DL (Add/Add) + LL (L) + WL 36 (L) |
| Cross Girder | 50.240 | 50.235 | -0.01% | DL (Add/Add) + LL (L) + WL 36 (L) | DL (Add/Add) + LL (L) + WL 36 (L) |
| Top Bracing | 0.000 | 0.000 | NA | NA | NA |
| Hangers | 0.000 | 0.000 | NA | NA | NA |

Table. No. 10: Table for comparative analysis for Shear force (in T).

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### D. *Torsional Moment*

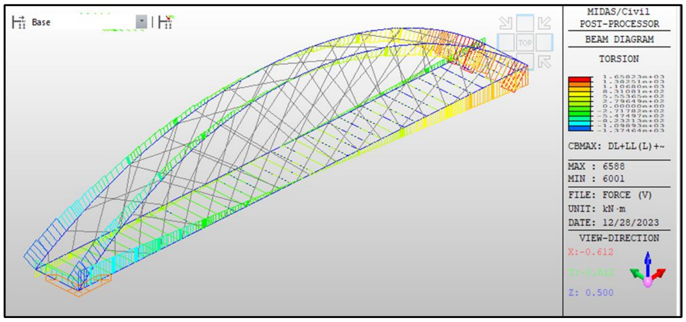


Figure 9: Torsional moment diagram for Model 1

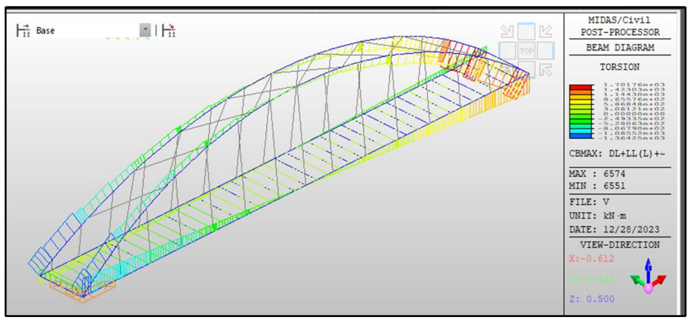


Figure 10: Torsional moment diagram for Model 2

| Members | Model 1 | Model 2 | % increase/decrease in torsion | Governing load case for Model 1 | Governing load case for Model 2 |
|---|---|---|---|---|---|
| Arch Beam | 165.844 | 170.176 | 2.6% | DL (Add/Rel) + LL (L) + WL 36 (L) | DL (Add/Add) + LL (L) + WL 36 (L) |
| Tie Beam | 118.748 | 121.899 | 2.7% | DL (Add/Add) + LL (L) + WL 36 (L) | DL (Add/Add) + LL (L) + WL 36 (L) |
| Cross Girder | 69.987 | 82.631 | 18.07% | DL (Add/Add) + LL (L) + WL 36 (L) | DL (Rel/Add) + LL (L) + WL 36 (L) |
| Top Bracing | 0.000 | 0.000 | NA | NA | NA |
| Hangers | 0.000 | 0.000 | NA | NA | NA |

Table. No. 11: Table for comparative analysis for Torsional moment (in T-m).

### E. *Bending Moment*

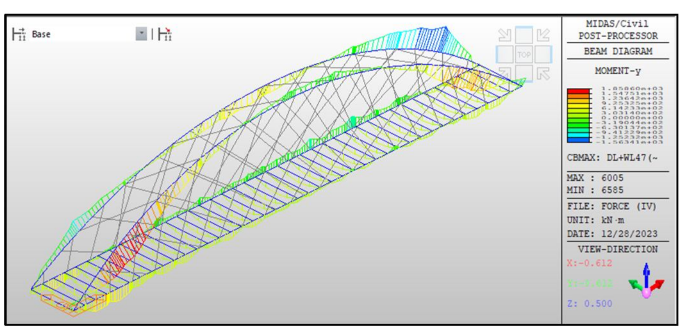


Figure 11: Sagging bending moment diagram for Model 1

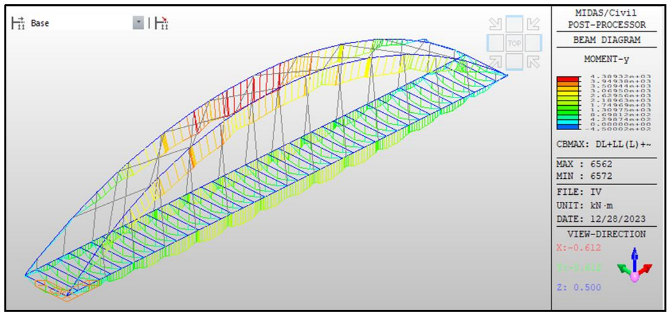

Figure 12: Sagging bending moment diagram for Model 2

| Members | Model 1 | Model 2 | % increase/decrease in Sagging BM | Governing load case for Model 1 | Governing load case for Model 2 |
|---|---|---|---|---|---|
| Arch Beam | 185.860 | 522.067 | 181% | DL (Add/Add) + WL 47 (L) | DL (Add/Add) + LL (L) + WL 36 (L) |
| Tie Beam | 134.765 | 319.100 | 137% | DL (Add/Add) + LL (L) + WL 36 (L) | DL (Add/Add) + LL (L) + WL 36 (L) |
| Cross Girder | 137.437 | 137.423 | -0.01% | DL (Add/Add) + LL (L) + WL 36 (L) | DL (Add/Add) + LL (L) + WL 36 (L) |
| Top Bracing | 0.000 | 0.000 | NA | NA | NA |
| Hangers | 0.000 | 0.000 | NA | NA | NA |

Table. No. 12: Table for comparative analysis for Sagging (positive) bending moment (in T-m).

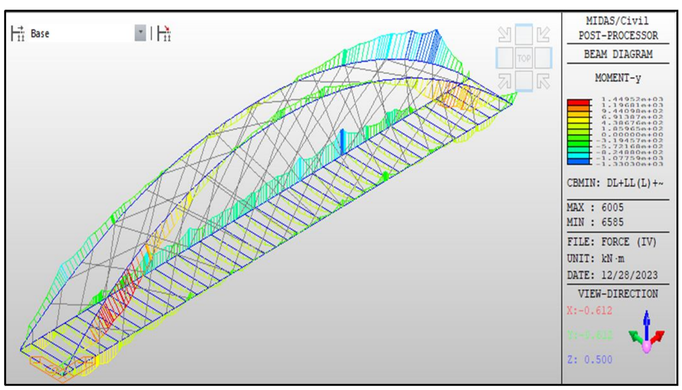

Figure 13: Hogging bending moment diagram for Model 1

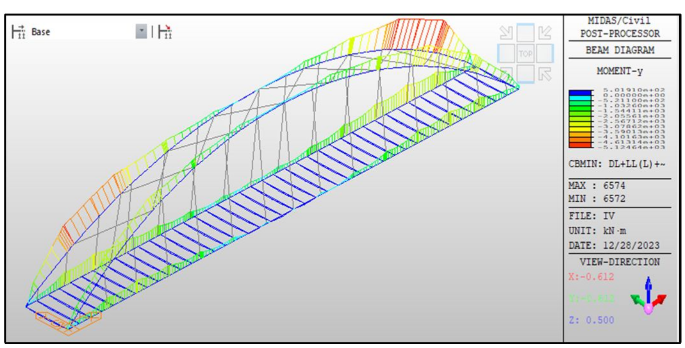

Figure 14: Hogging bending moment diagram for Model 2

| Members | Model 1 | Model 2 | % increase/decrease in Hogging BM | Governing load case for Model 1 | Governing load case for Model 2 |
|---|---|---|---|---|---|
| Arch Beam | 464.673 | 473.590 | 1.92% | DL (Add/Rel) + LL (L) + WL 36 (L) | DL (Add/Rel) + LL (L) + WL 36 (L) |
| Tie Beam | 537.661 | 540.695 | 0.56% | DL (Add/Add) + LL (L) + WL 36 (L) | DL (Add/Add) + LL (L) + WL 36 (L) |
| Cross Girder | 0.000 | 0.000 | NA | NA | NA |
| Top Bracing | 0.000 | 0.000 | NA | NA | NA |
| Hangers | 0.000 | 0.000 | NA | NA | NA |

Table. No. 13: Table for comparative analysis for Hogging (negative) bending moment (in T-m).

### *F. Eigenvalue Analysis*

| Mode No | Natural Period (seconds) | | Mode No | Natural Period (seconds) | |
|---|---|---|---|---|---|
| | Analytical model 1 | Analytical model 2 | | Analytical model 1 | Analytical model 2 |
| Mode 1 | 8.46 | 7.65 | Mode 11 | 0.30 | 0.40 |
| Mode 2 | 2.37 | 2.15 | Mode 12 | 0.28 | 0.38 |
| Mode 3 | 1.19 | 1.73 | Mode 13 | 0.26 | 0.33 |
| Mode 4 | 1.01 | 1.07 | Mode 14 | 0.24 | 0.29 |
| Mode 5 | 0.67 | 0.88 | Mode 15 | 0.24 | 0.28 |
| Mode 6 | 0.50 | 0.83 | Mode 16 | 0.24 | 0.26 |
| Mode 7 | 0.49 | 0.66 | Mode 17 | 0.24 | 0.21 |
| Mode 8 | 0.44 | 0.60 | Mode 18 | 0.23 | 0.21 |
| Mode 9 | 0.43 | 0.45 | Mode 19 | 0.23 | 0.20 |
| Mode 10 | 0.31 | 0.40 | Mode 20 | 0.21 | 0.17 |

Table. No. 14: Table for Natural time period (in Seconds).

## V. CONCLUSION

In the present study, an attempt is made to study the fluctuations in forces, moment induced in members along with seismic behavior of Tied arch bridge with vertical hangers and Network arch bridge under same load parameters. The axial tensile, axial compressive force, shear force, torsion, maximum bending moments for various structural components of arch bridge were obtained. The following are the conclusions obtained:

1) It is observed that there is 26% decrease in axial tensile force in Hangers.
2) There is a slight increase in axial compression of about 3% in Cross girders.
3) 80% decrease in shear force has been observed in Arch beam.
4) 18% decrease in Torsional moment has been observed in Cross girders.
5) 181% decrease in bending moment (sagging) has been observed in Arch beam.
6) 137% decrease in bending moment (sagging) has been observed in Tie beam.
7) Excess 16 to 17 radian rotation about Y-Y axis observed in tied arch bridge compared to that of network arch bridge.
8) An average 10% increase in natural frequency of structure observed in tied arch bridge. This change was observed due to the difference in dead weight of bridge (about 100 KN) as there is no change in the stiffness.

From the results and discussions, it can be concluded that for equal bridge spans, width, height, and similar sections with same material properties, Network arch bridge delivers safer results and more strength than tied arch bridge.

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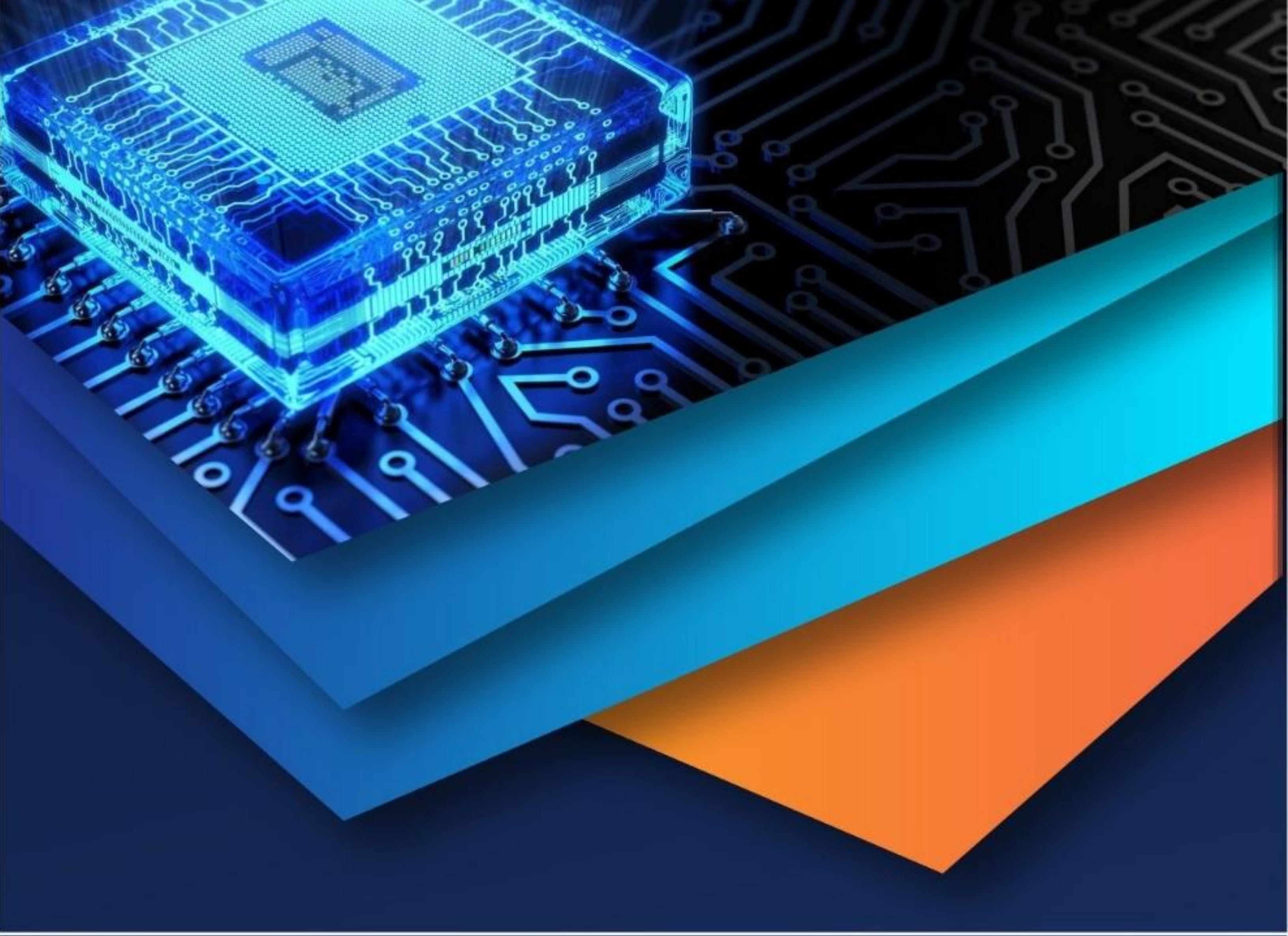


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