Session-5: **Bowstring Girder Bridge** - Construction & **Design Challenges**

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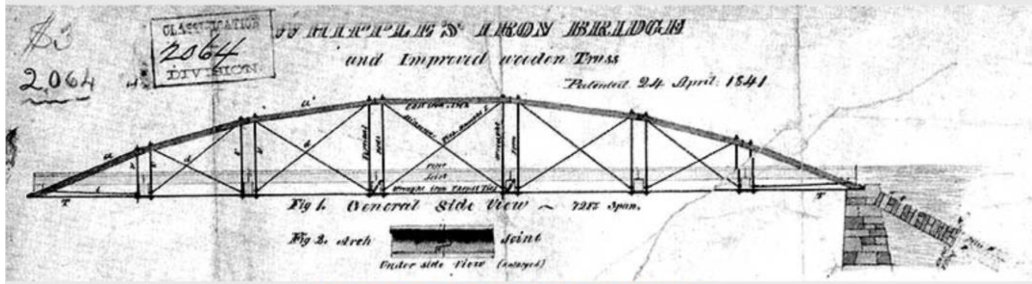
Bowstring Girder Bridge - Design Challenges

Mr. Umesh Rajeshirke, Managing Director of Spectrum Techno Consultants Pvt Ltd, has Over 35 years of experience in the Planning & Design of Bridges, Flyovers, Large Span Steel Structures, Marine facilities, Industrial structures, Prestressed and Reinforced Concrete Structures, Shell Structures.

He graduated from VJTI, Mumbai in 1987 and did his masters from IIT, Madras in 1991.

He is a member of various BIS and IRC committees and published number of papers in national & international conferences and journals.

Bowstring Girder Bridge - Design Challenges



Detail, Whipple Patent Application Drawing

Bowstring iron truss arch in USA, 1840 by **Squire Whipple**

(Sources: internet)

Bowstring Girder Bridges

- Efficient form of the structure
- Cost effective
- Aesthetically appealing
- Clear flow of the forces
- Track record since 1840s

However, there are challenges both in its design as well as construction.

Bowstring Girder Bridge - Design Challenges

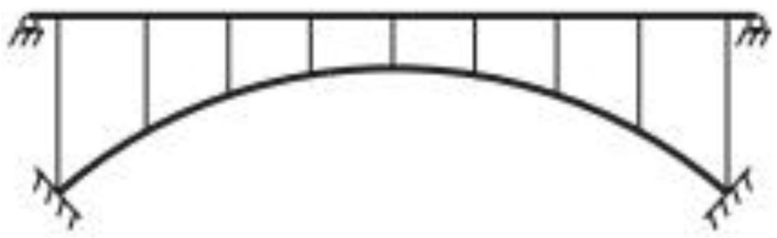
Challenges in Design

- Buckling
- Susceptibility to Fatigue
- Design of end joint – local FEM
- Connections details of hangers – types (steel members, bars, strands)

Types of Arch bridges and their suitability

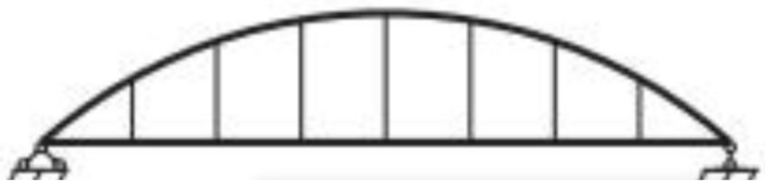
Bowstring Girder Bridge - Design Challenges

Types of Arch bridges and their suitability



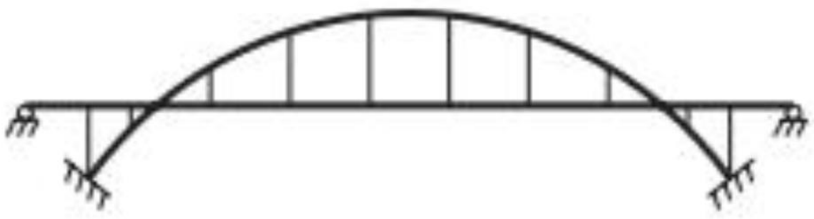
Deck Arch Bridge

For crossing the valley with strong foundation at both sides



Through Arch Bridge

When the strata is weak
Unable to bear the horizontal thrust

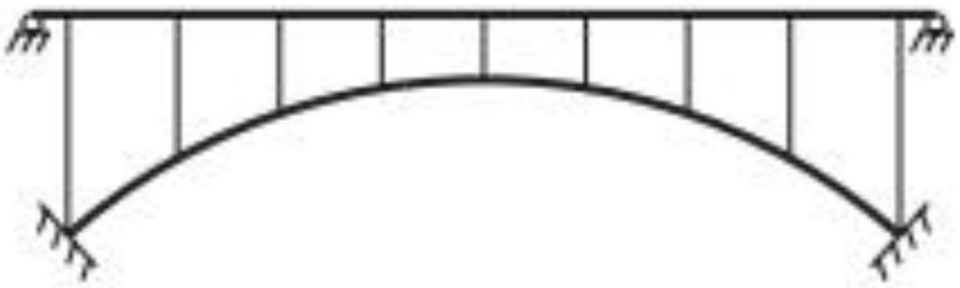


Semi Through Arch Bridge

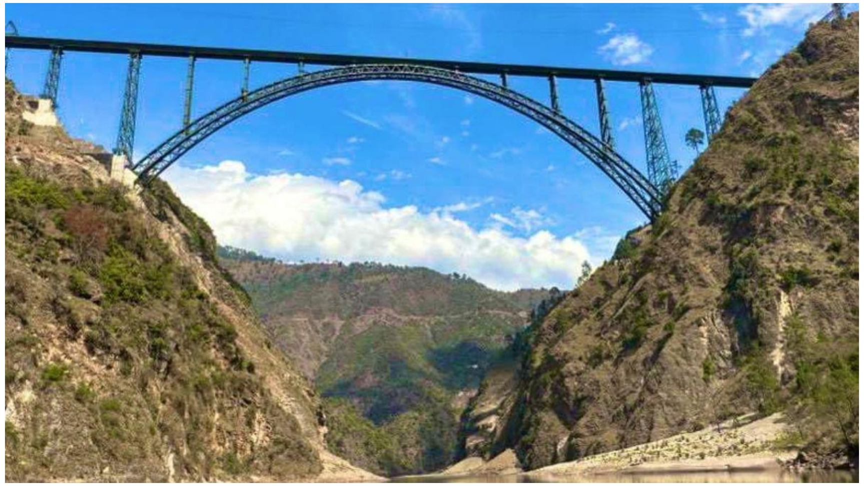
When the strata is strong,
The level of deck is fixed

Bowstring Girder Bridge - Design Challenges

Deck Arch Bridge



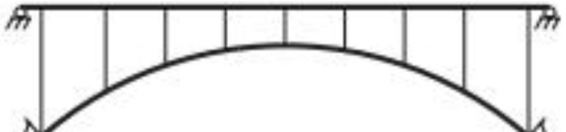
Spandrel (filled)



Spandrel (open)

Bowstring Girder Bridge - Design Challenges

Deck Arch Bridge



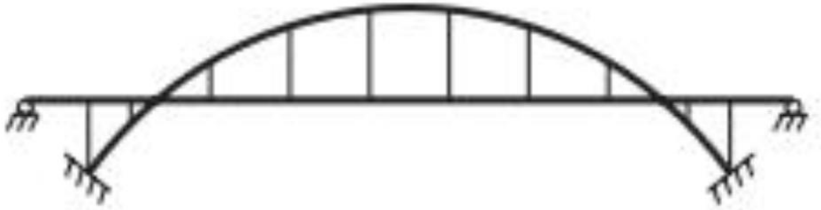
Spandrel (open)

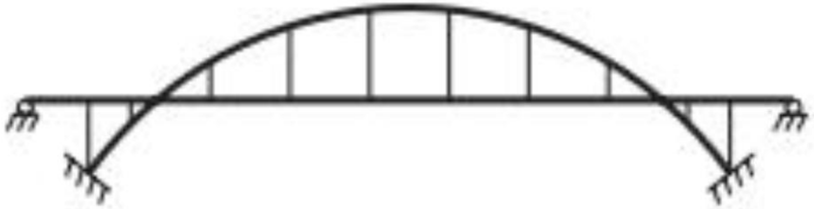
Braced Spandrel Arch

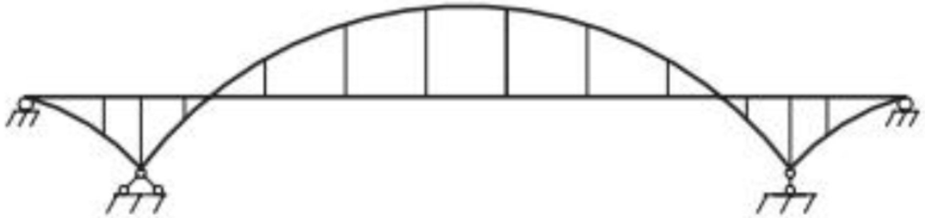
Rigid framed Spandrel Arch

Bowstring Girder Bridge - Design Challenges

Half Through Arch Bridge



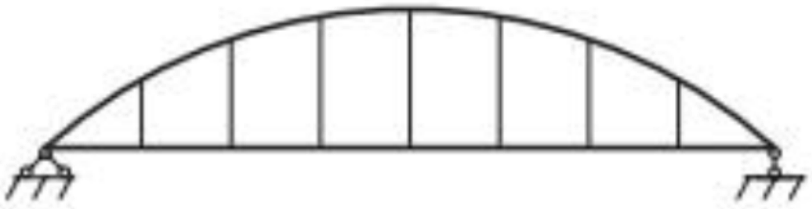




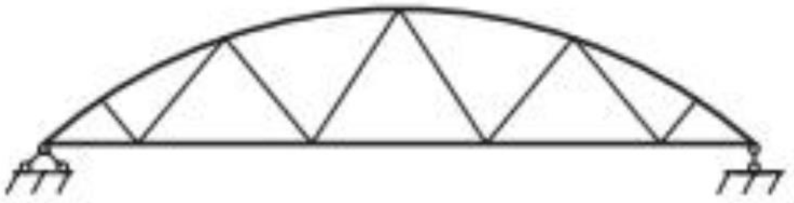
Wahrew Arch Bridge - Sohbar, Meghalaya

Bowstring Girder Bridge - Design Challenges

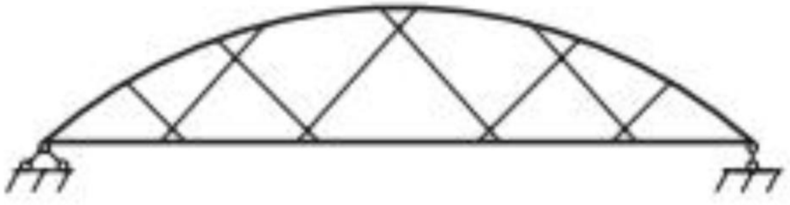
Through Arch Bridge



Vertical Hanger Arch Bridge



Nielsen Arch Bridge



Network Arch Bridge

Bowstring Girder Bridge - Design Challenges

Types of Ribs

Solid

span < 200 m
Needs stiffening members to avoid buckling

I - shaped

for small spans say from 80 to 100m (not popular now a days)

Circular / Box

up to 200m used for 550m span (Lupu bridge, China)

Truss

span > 200 m
As members of truss are smaller and lighter, ease in delivery and erection

Built up using plates

More popular due to welding tech

Circular sections

suitable for windy areas as circular sections reduces wind pressure

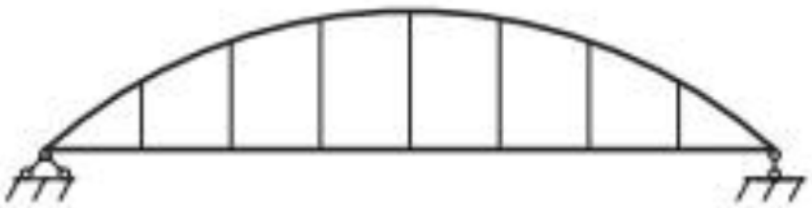
Bowstring Girder Bridge - Design Challenges

Preliminary design and Sizing of the elements

The depth of Rib to Span ratio

Uniform solid arch rib:

For general arch, = 1/70 to 1/80
For tied arch = 1/140 to 1/190



Non-Uniform solid arch rib:
Depth can be reduced towards hinges in hinged bridges, towards crown for fixed arches

Trussed Ribs:
For spans >200m
For both clear and tied arch = 1/25 to 1/50

Bowstring Girder Bridge - Design Challenges

Challenges in Design

1. Buckling

Bowstring Girder Bridge - Design Challenges

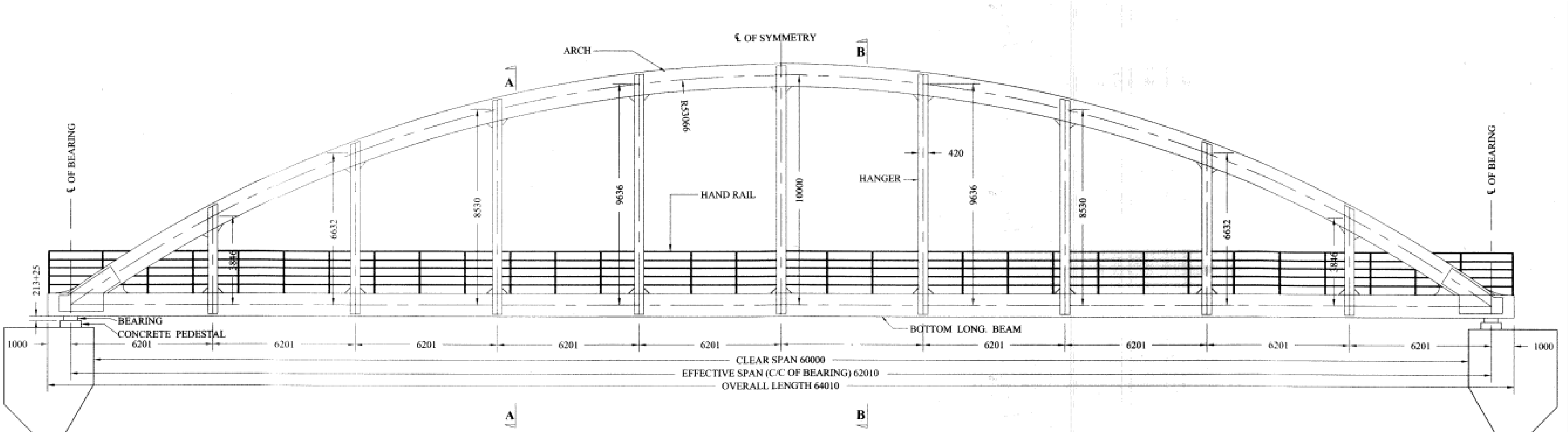
Challenges in Design

Buckling

The problem is discussed with a practical example i.e. RDSO’s standard Drawing of 62.1 m span girder

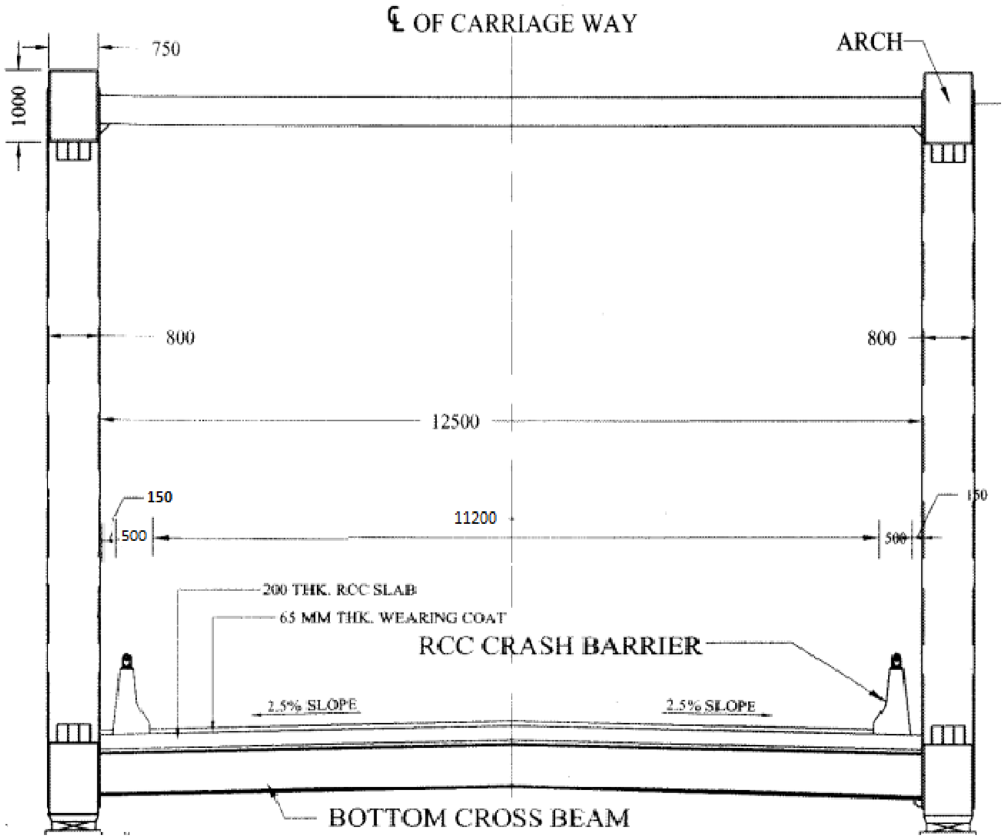
Bowstring Girder Bridge - Design Challenges

Elevation



Overall Length is **64.01 m** (Bearing c/c Span Length is **62.01 m**)
Crown height is **10 m** (distance between centerline of Tie Girder and Arch Rib at Centre)

Bowstring Girder Bridge - Design Challenges

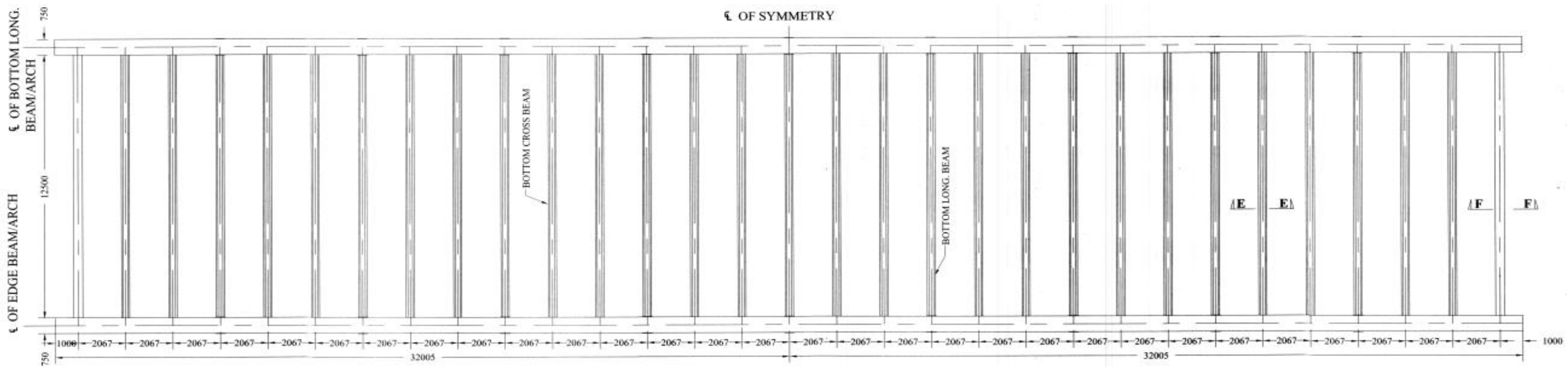


Section

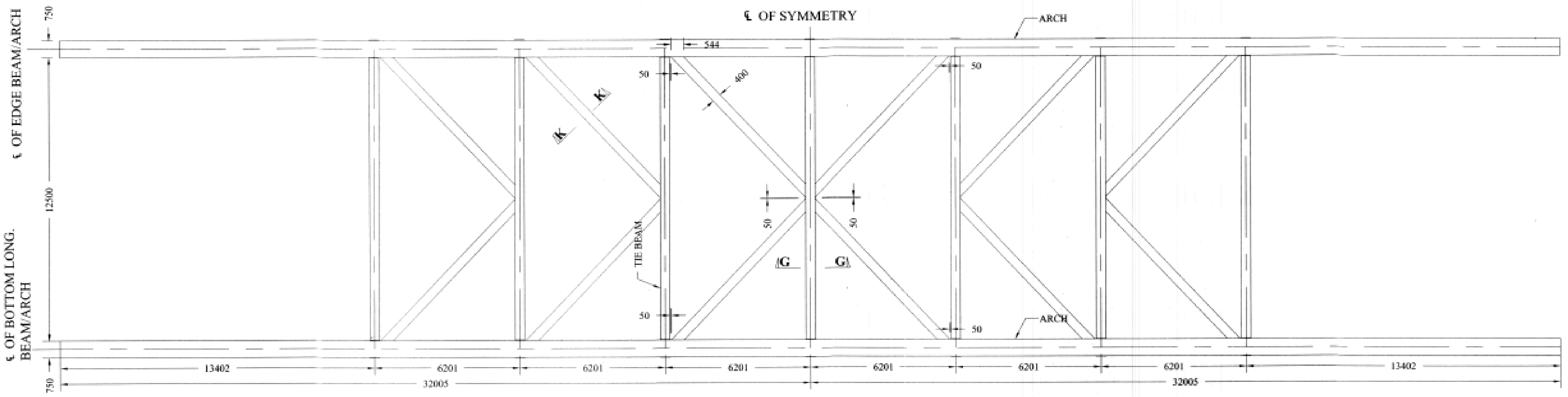
Deck width **12.2 m** (Carriageway width **11.2 m**)

Bearing c/c distance is **13.25 m** (in Transverse direction)

Bowstring Girder Bridge - Design Challenges

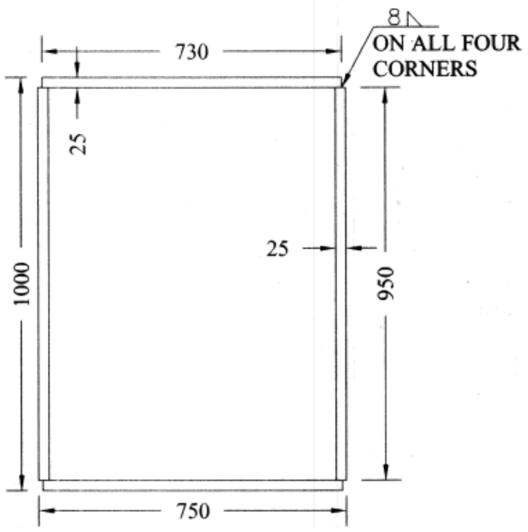


Plan at Deck Level

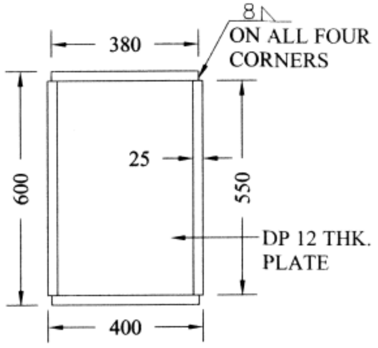


Plan at Top Girder Level

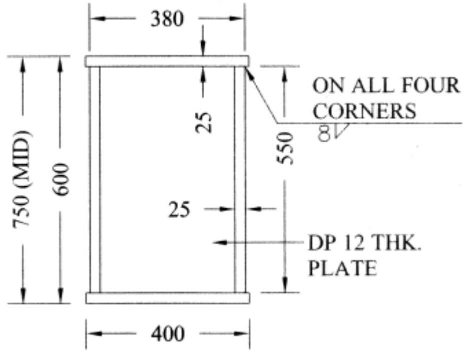
Bowstring Girder Bridge - Design Challenges



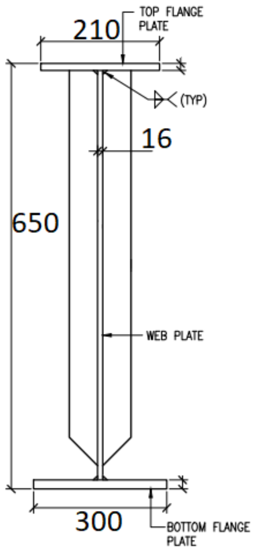
Tie Girder



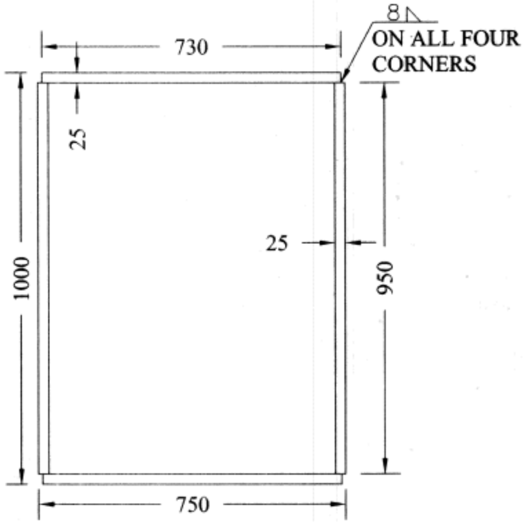
Top Cross Girder



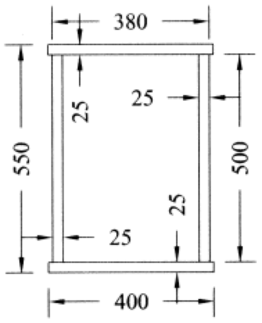
End Diaphragm



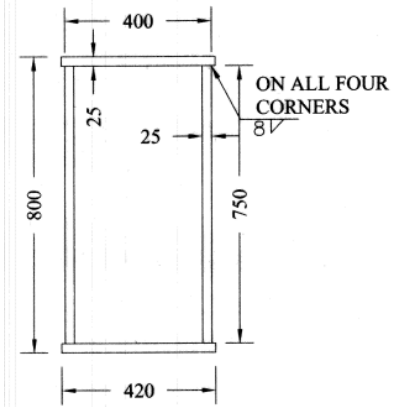
Intermediate Bottom Cross Girder



Arch Rib



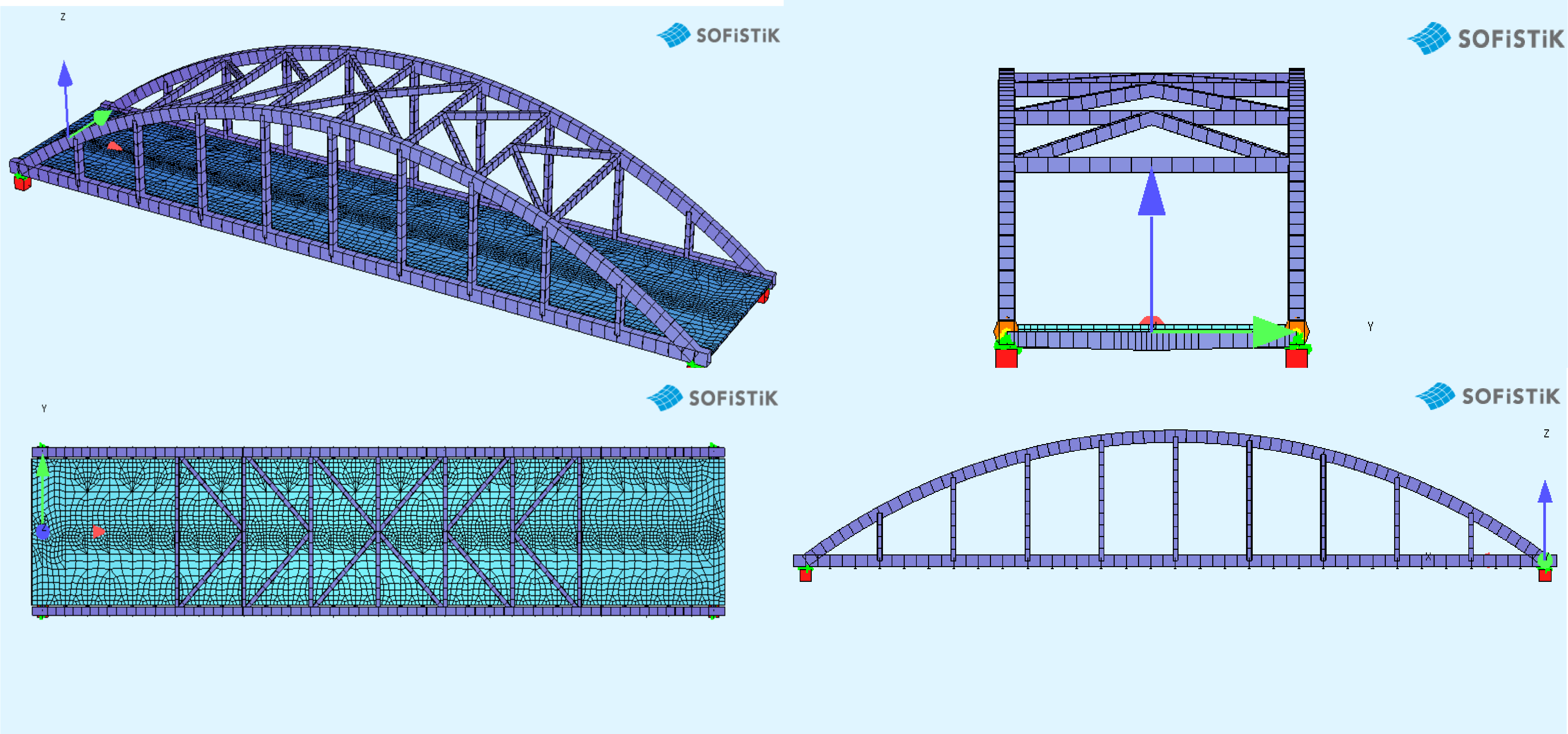
Top Bracing



Hanger

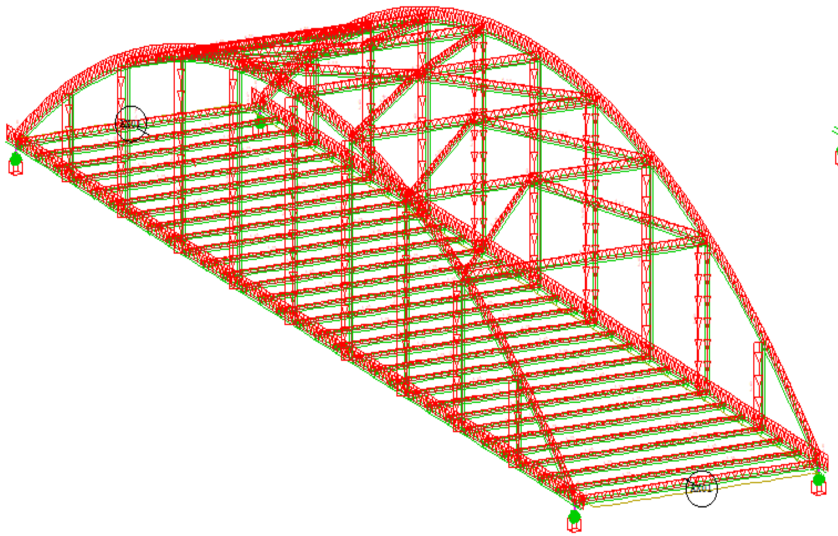
Bowstring Girder Bridge - Design Challenges

SOFiSTiK Model of the Arch

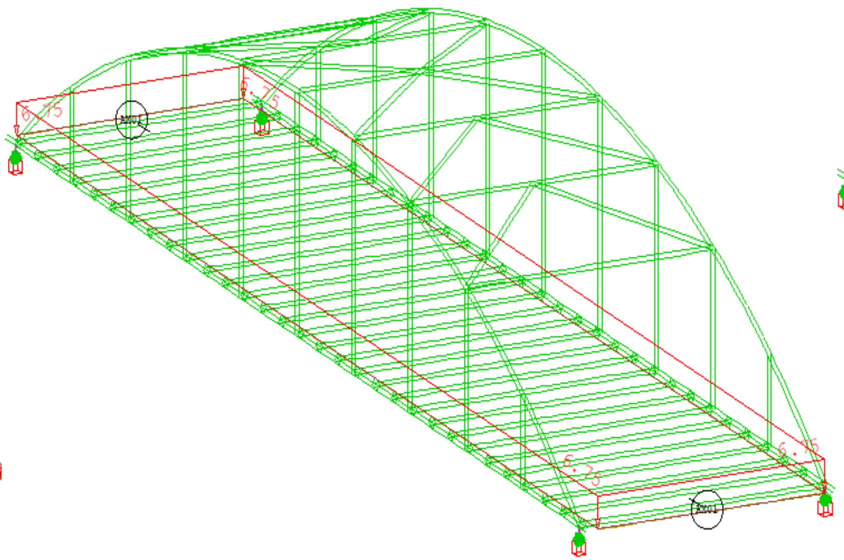


Bowstring Girder Bridge - Design Challenges

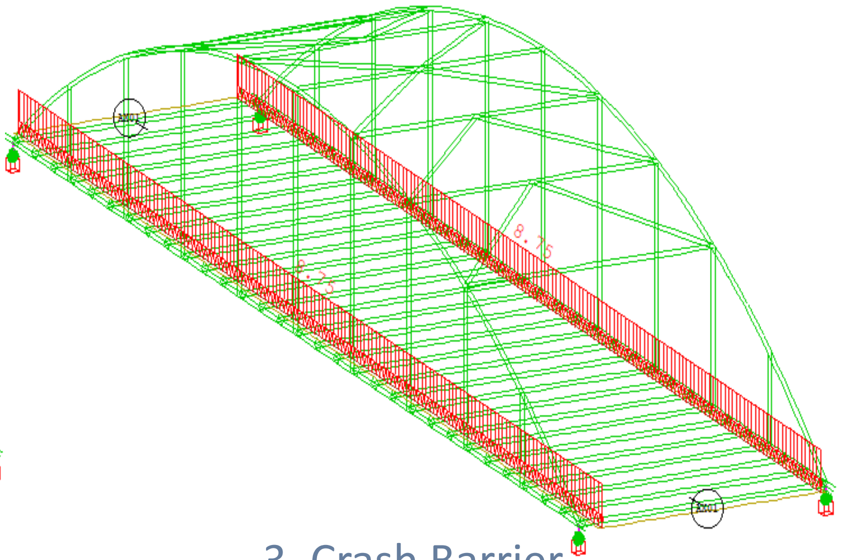
Loading: DL



1. Self Weight

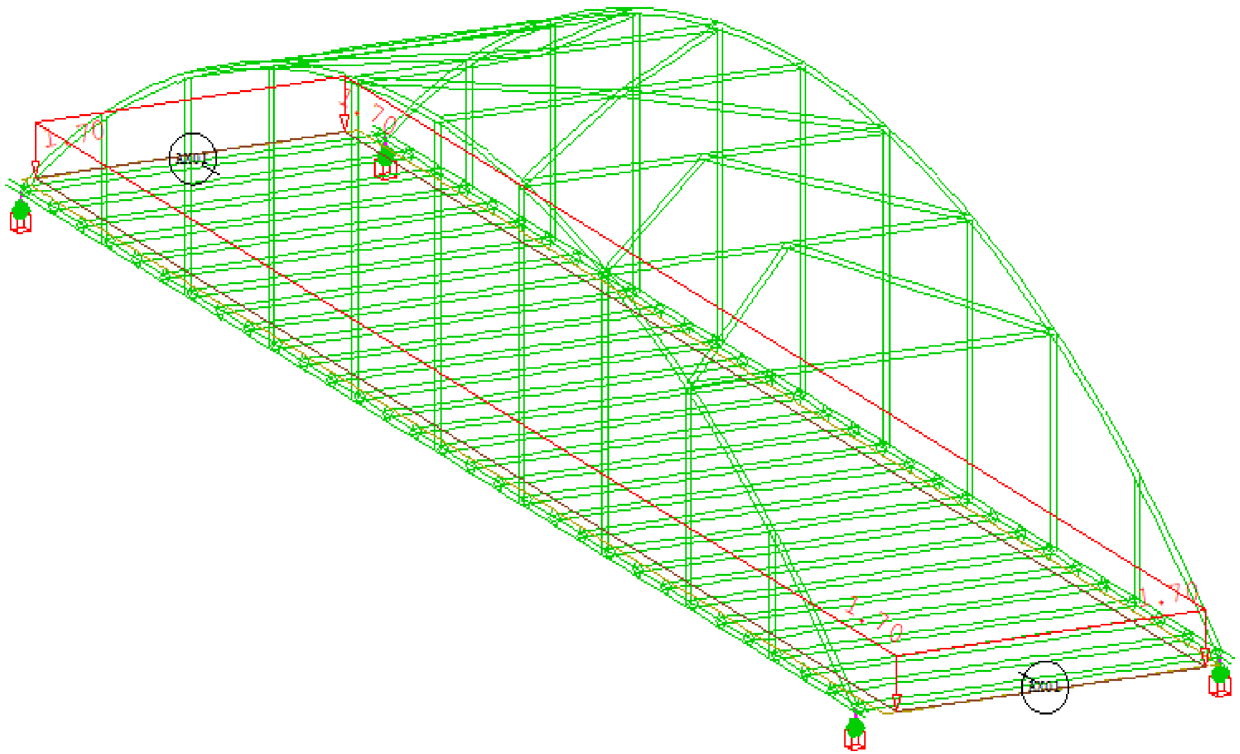


2. Deck (270 mm)
*(**6.75** kN/m^2 Loading)*

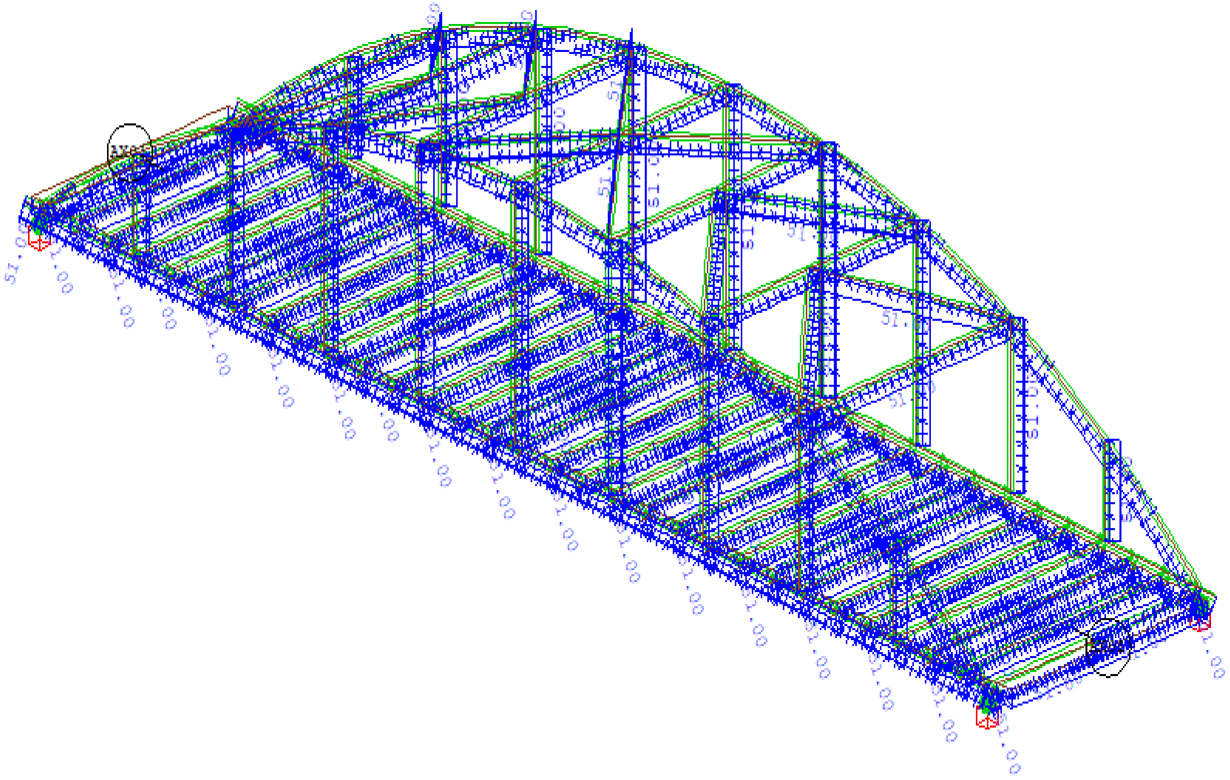


3. Crash Barrier
*(**8.75** kN/m)*

Bowstring Girder Bridge - Design Challenges



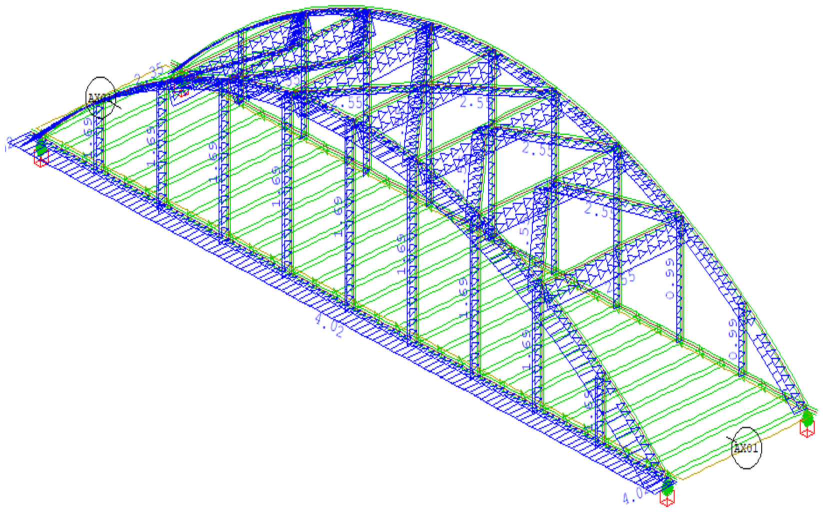
4. Wearing Coat (65 mm)
*(**1.7** kN/m^2 Loading)*



5. Temperature ($\pm 51^{o}$C)

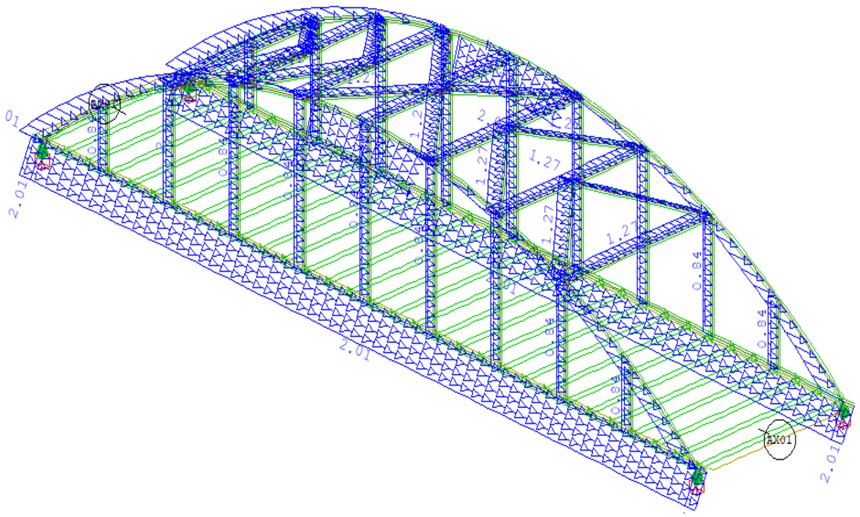
Bowstring Girder Bridge - Design Challenges

Wind Loading



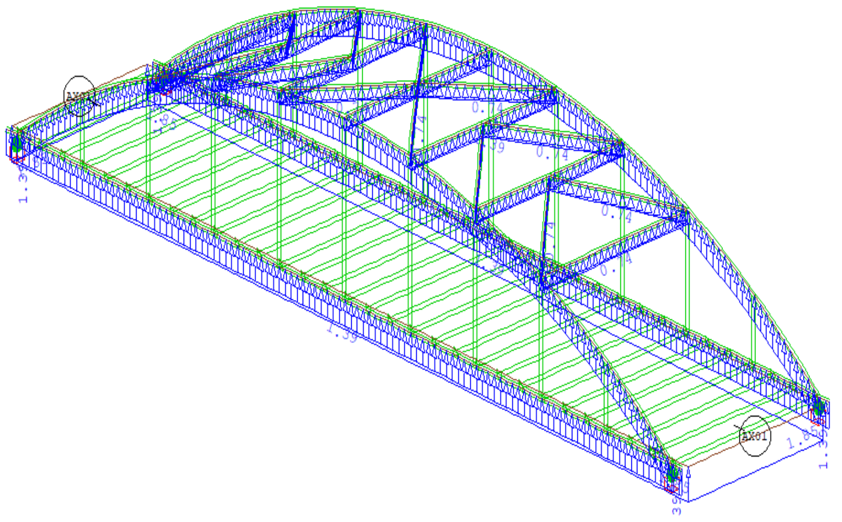
Wind Transverse

$$4.02\,\frac{kN}{m^2}$$



Wind Long

$$2.01\,\frac{kN}{m^2}$$



Wind Vertical

$$1.848\,\frac{kN}{m^2}$$

Bowstring Girder Bridge - Design Challenges

Live loads: Class 70R and Class A

1) Impact Factor = **1.154**

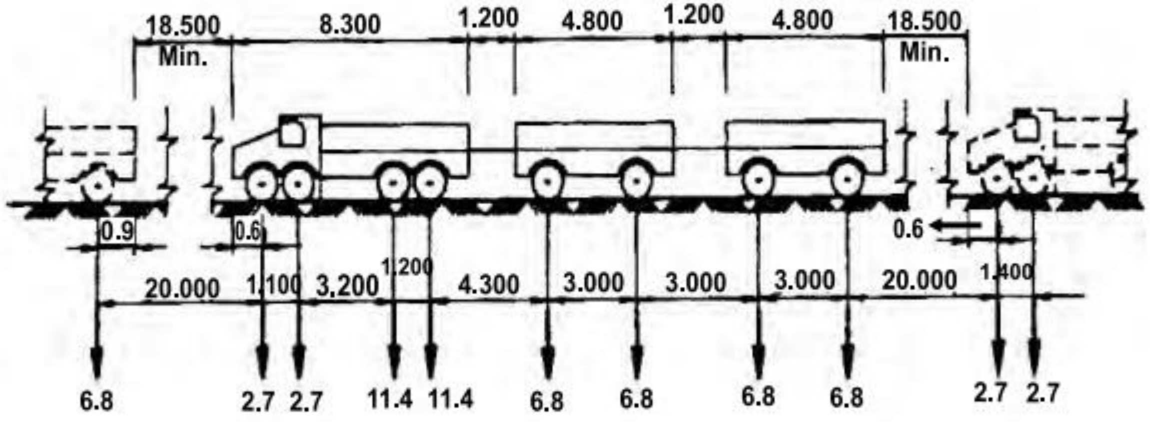
2) Congestion Factor

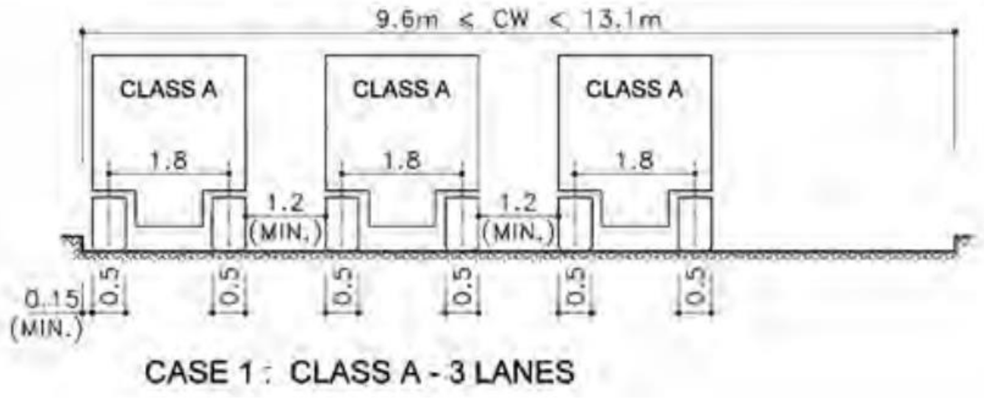
For 62.01 m Span the Congestion Factor = **1.62**
(From Table-7 of IRC-6-2017)

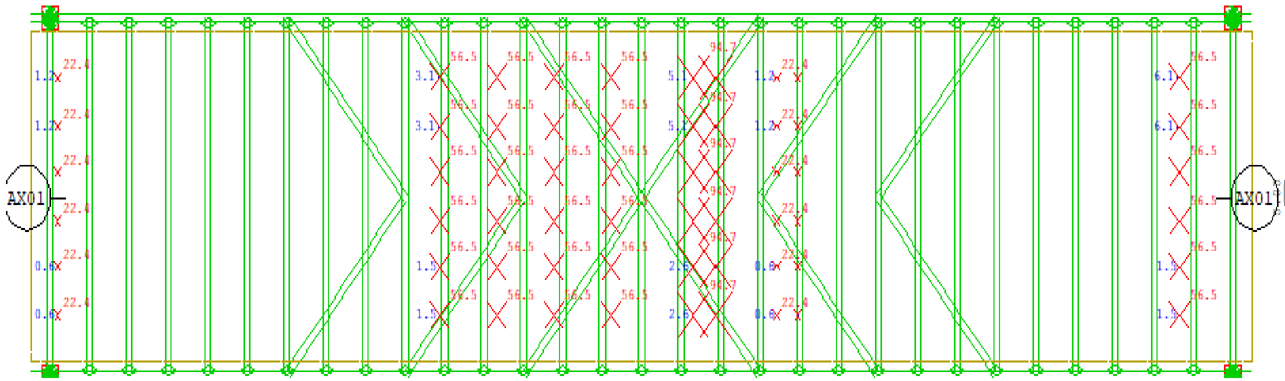
3) Lane Reduction Factor

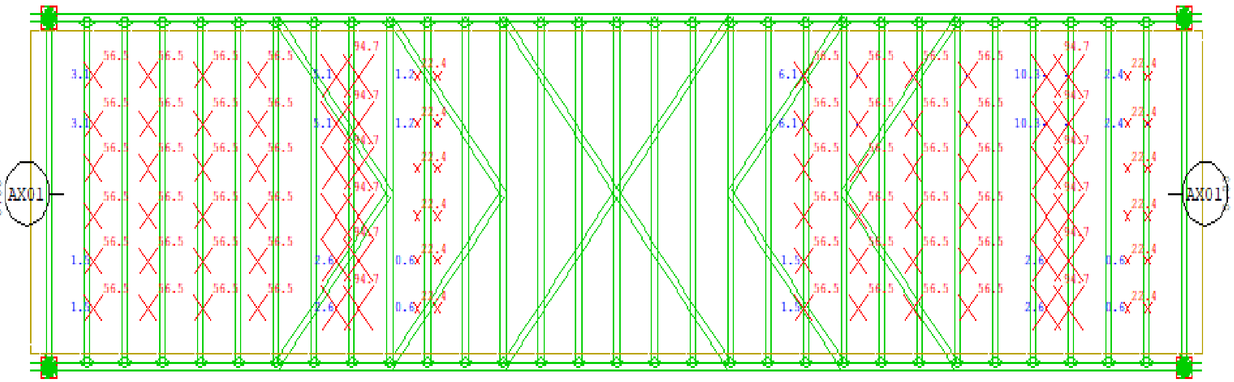
For 3 Lane Carriageway, Lane reduction is **10%**, thus Lane Reduction Factor = **0.9** *(From Table-8 of IRC-6-2017)*

Bowstring Girder Bridge - Design Challenges



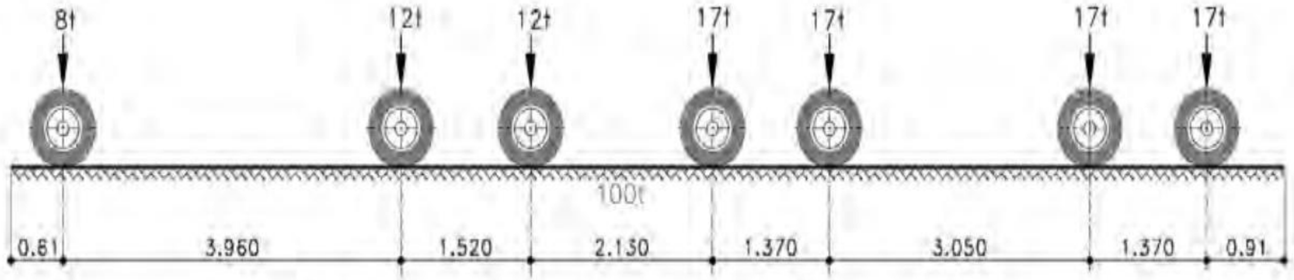




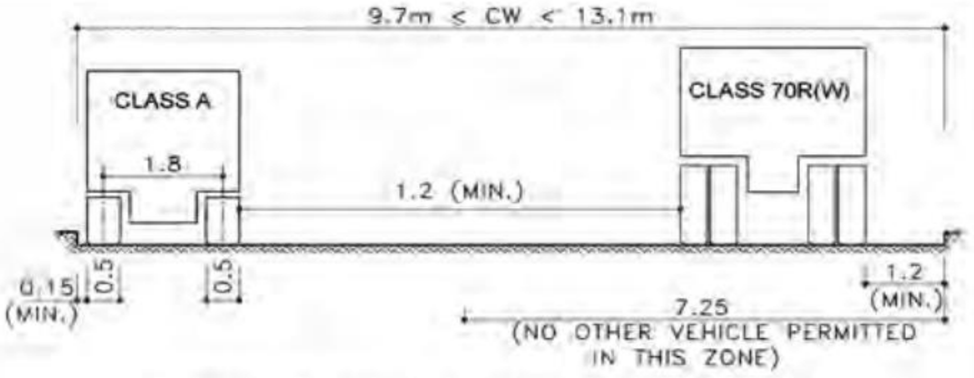


3 Class A Vehicles

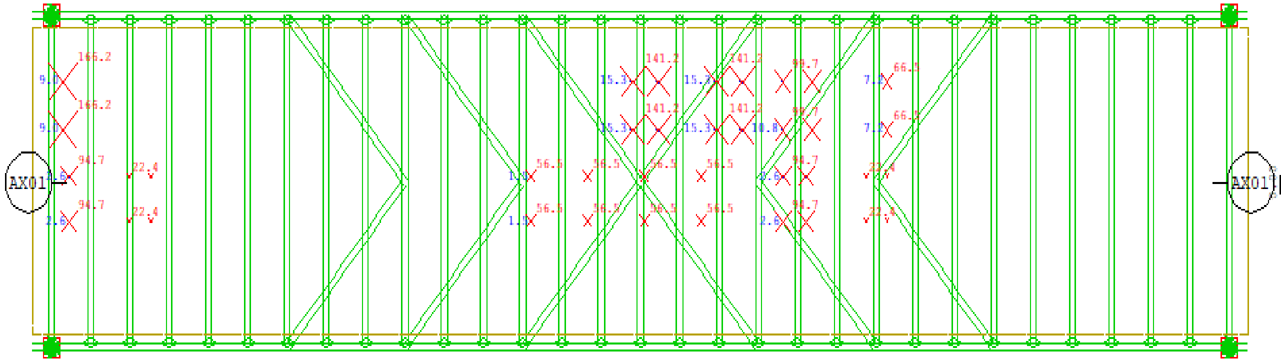
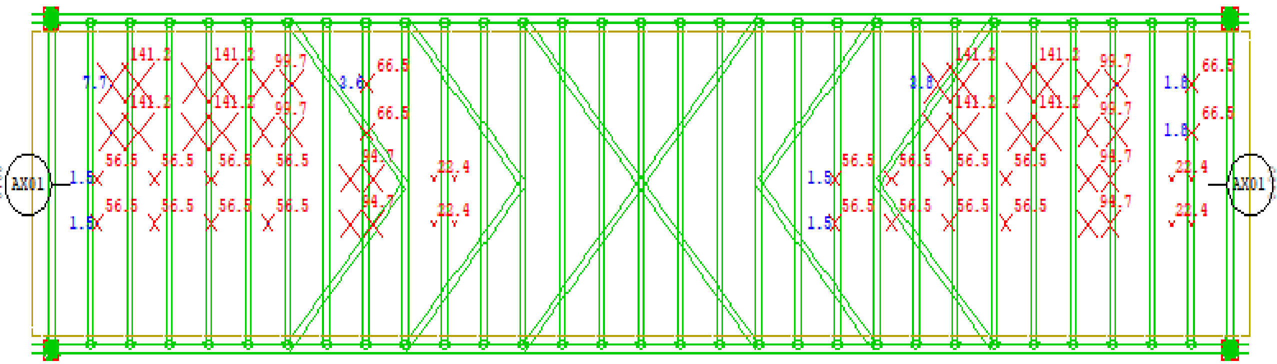
Bowstring Girder Bridge - Design Challenges



CLASS 70R (WHEELED) - LONGITUDINAL POSITION



CASE 2 : CLASS A - 1 LANE + CLASS 70R (W)

70R + Class A Vehicle

Bowstring Girder Bridge - Design Challenges

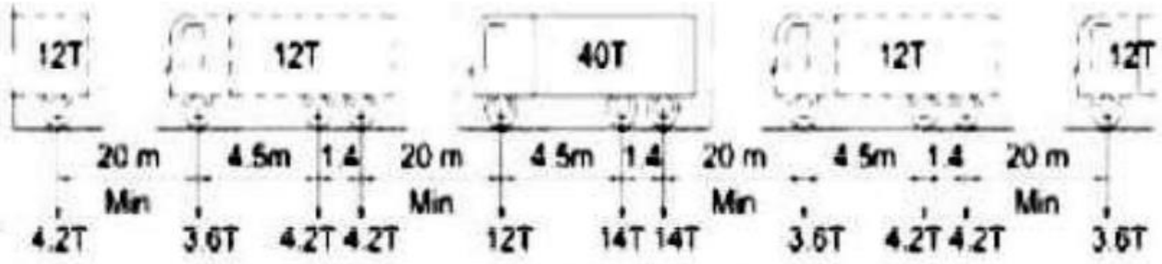
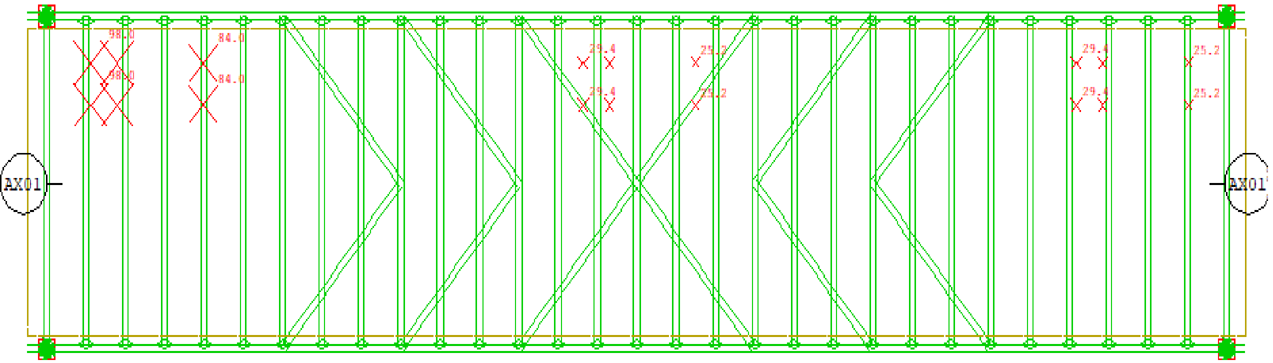


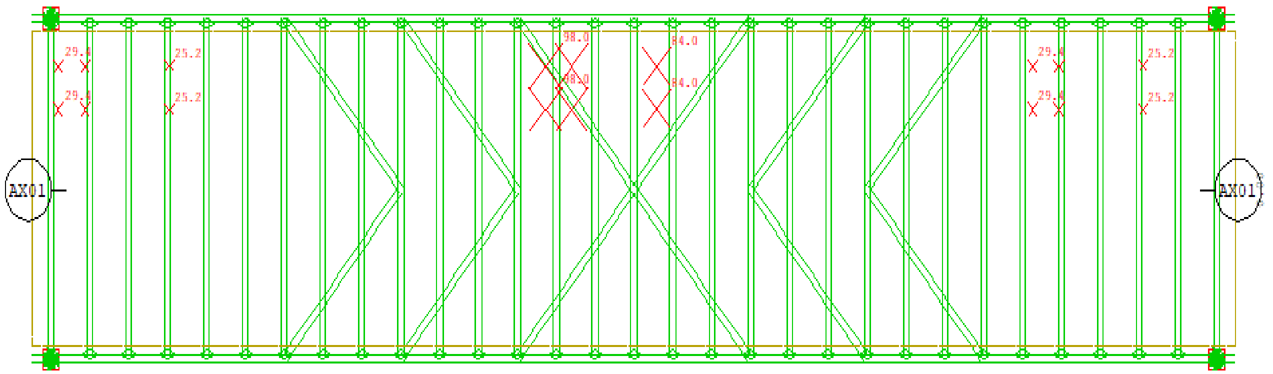
Fig 7A : Fatigue Load Train

NOTE: 1. Fatigue truck of 40 T must be included in Fatigue Load Train

2. Only such number of additional 12 T trucks shall be included in train as can be accommodated in influence line of detail under consideration

Fatigue Train from IRC-6 Amendment Notification No.54

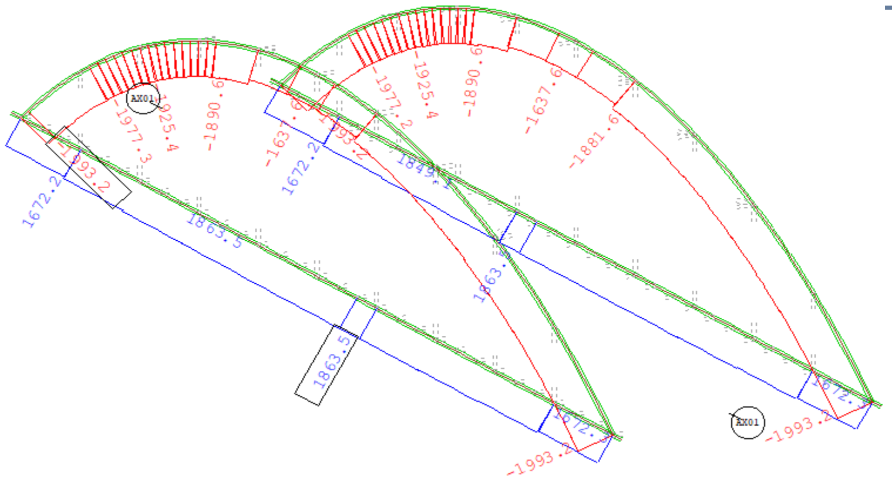




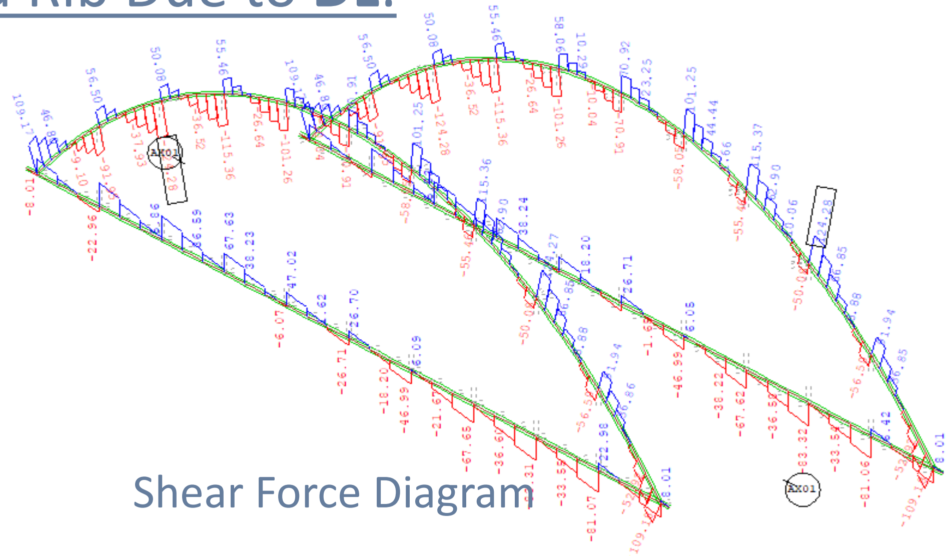
Fatigue Vehicle

Bowstring Girder Bridge - Design Challenges

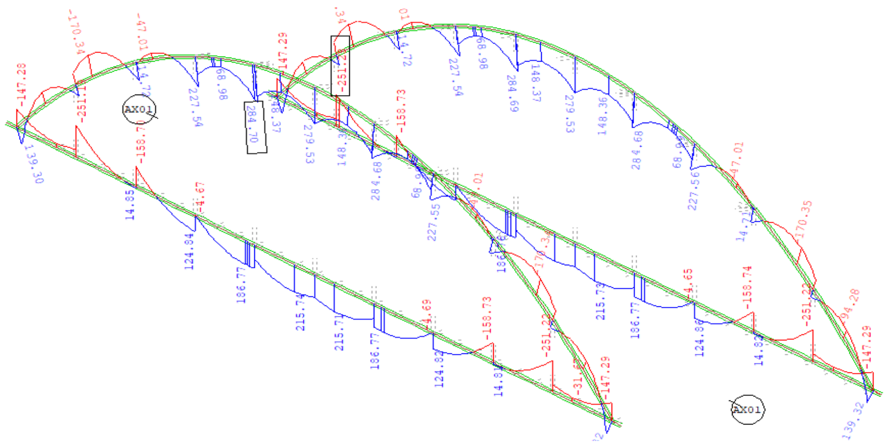
Results Forces in Arch Tie and Rib Due to **DL**:



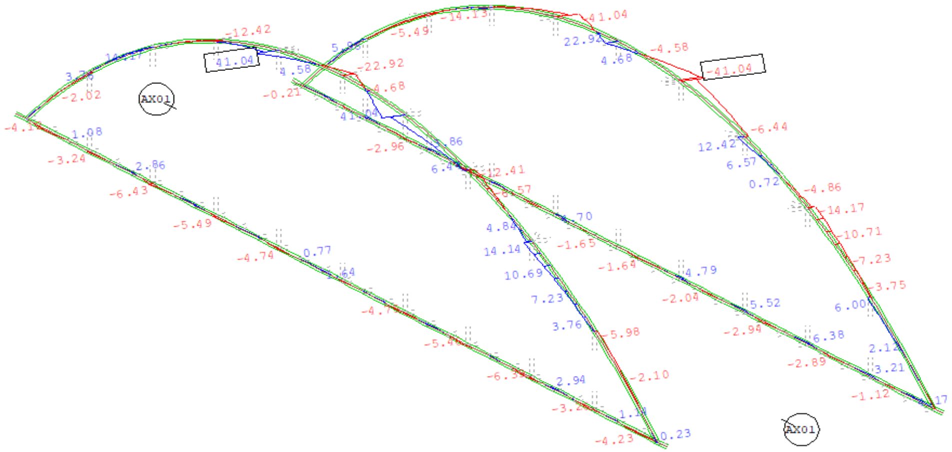
Axial Forces in Members



Shear Force Diagram



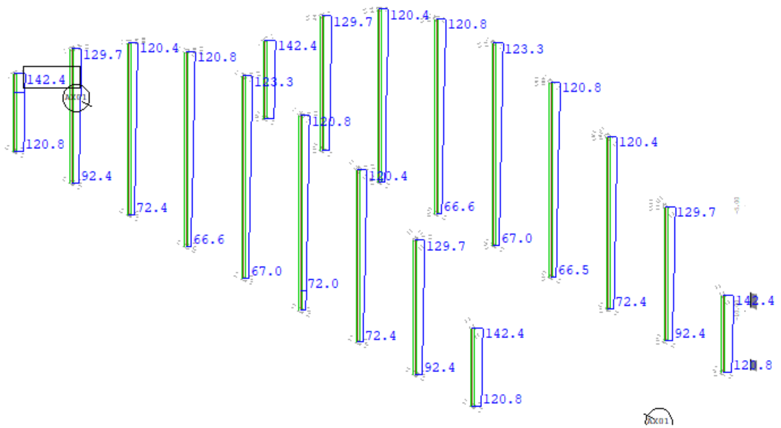
Bending Moment (My-in plane) Diagram



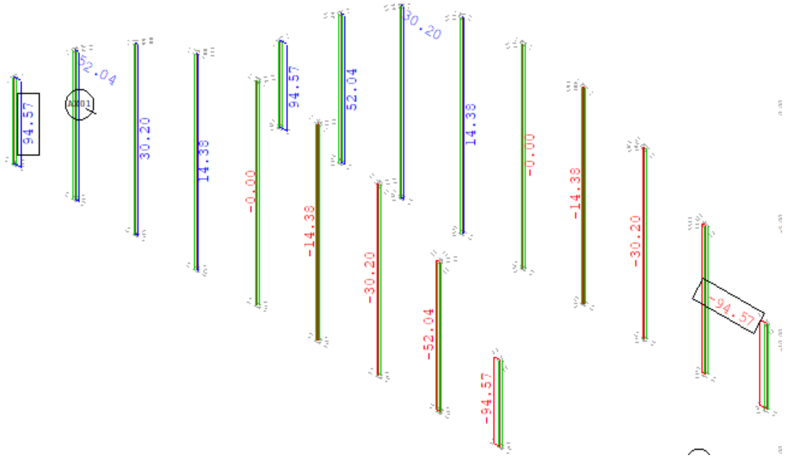
Bending Moment (Mz-out of plane)Diagram

Bowstring Girder Bridge - Design Challenges

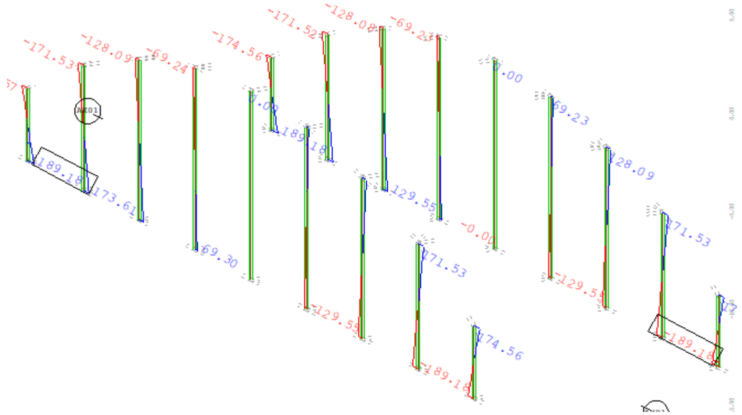
Forces in Hangers Due to DL:



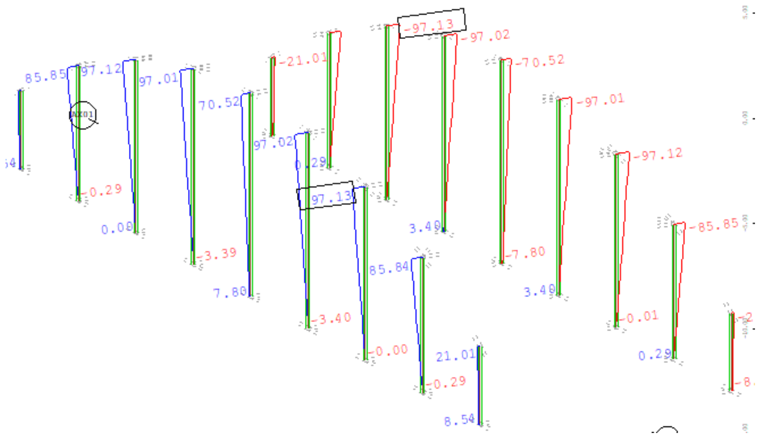
Normal Forces in Members



Shear Force Diagram



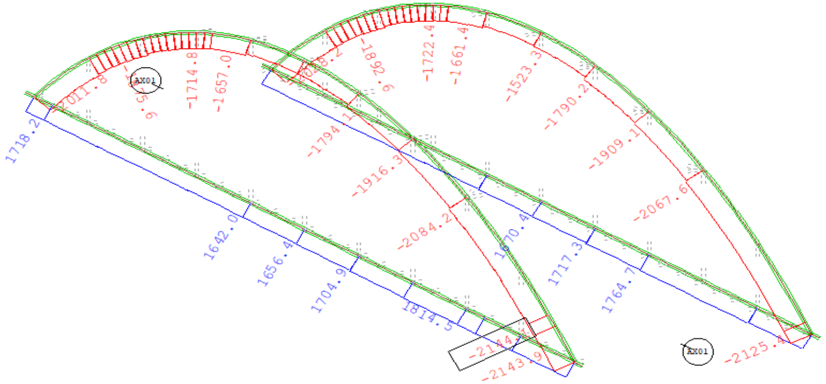
Bending Moment (My-in plane) Diagram



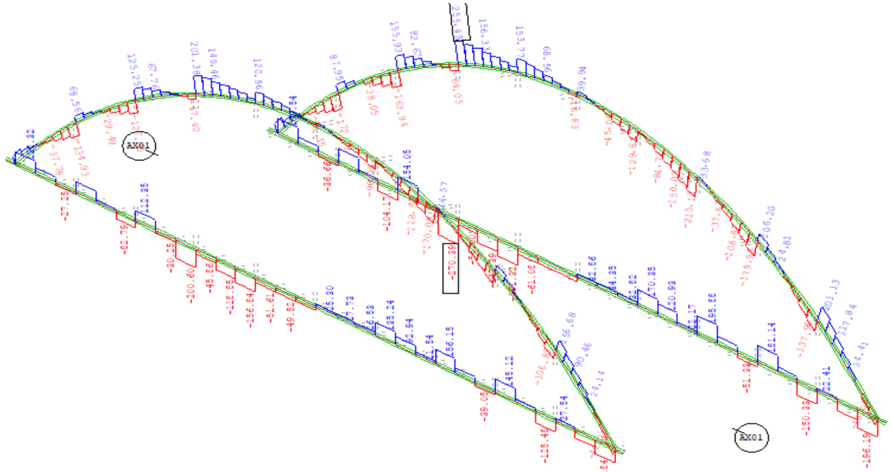
Bending Moment (Mz-out of plane)Diagram

Bowstring Girder Bridge - Design Challenges

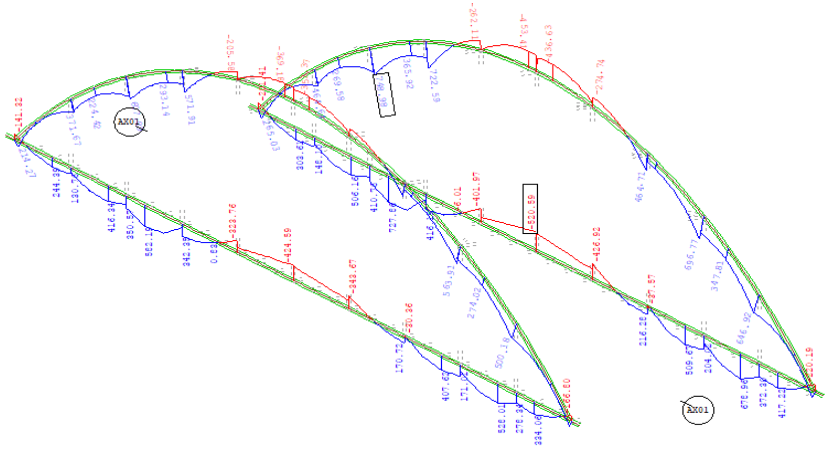
Forces in Arch Tie and Rib Due to 3 Class A vehicle:



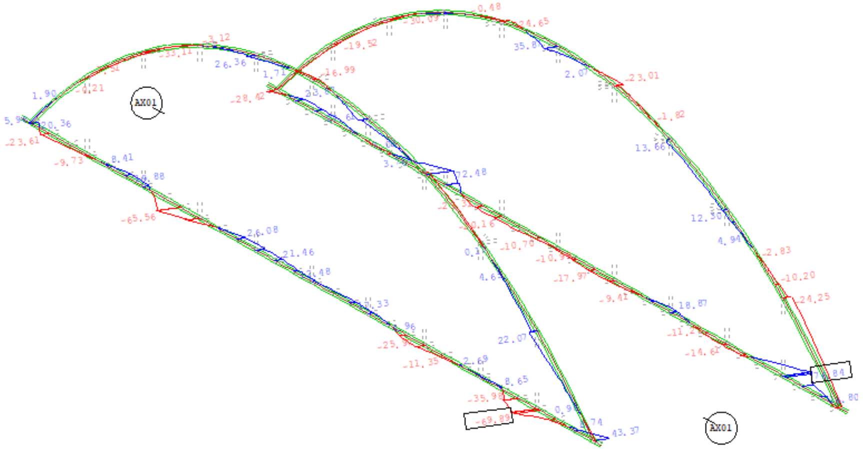
Normal Forces in Members



Shear Force Diagram



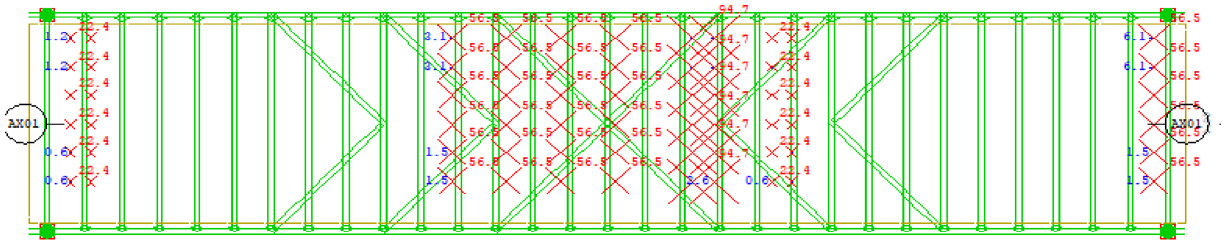
Bending Moment (My-in plane) Diagram



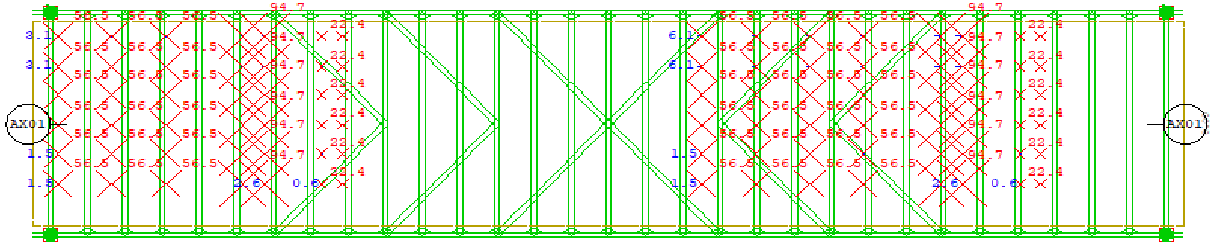
Bending Moment (Mz-out of plane)Diagram

Bowstring Girder Bridge - Design Challenges

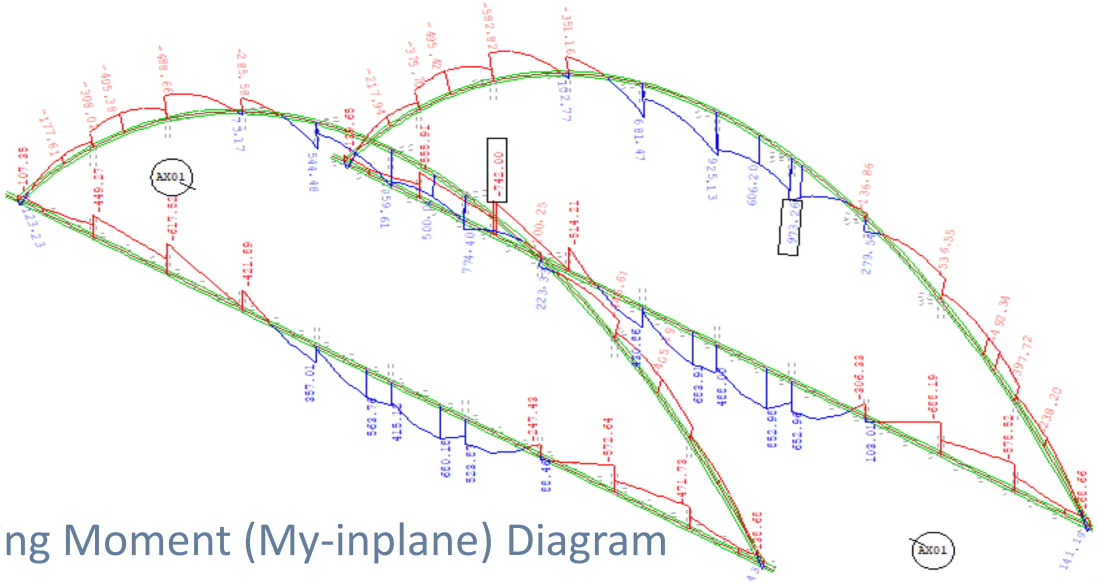
Bending Moment in Arch Tie and Rib Due to 3 Class A vehicle - 2 Locations:



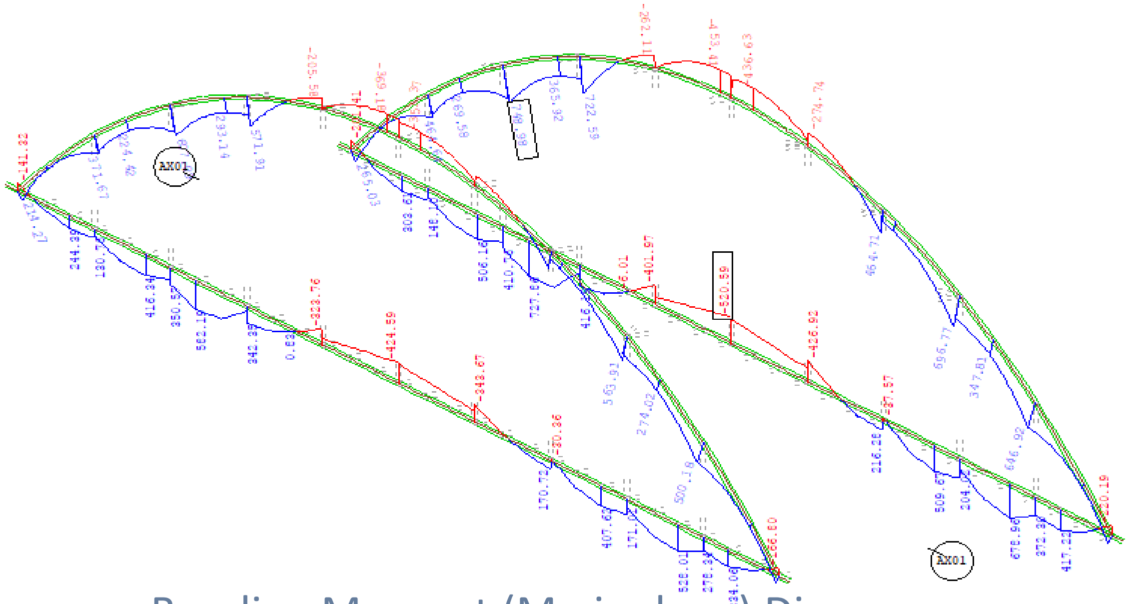
Vehicle Location 1



Vehicle Location 2



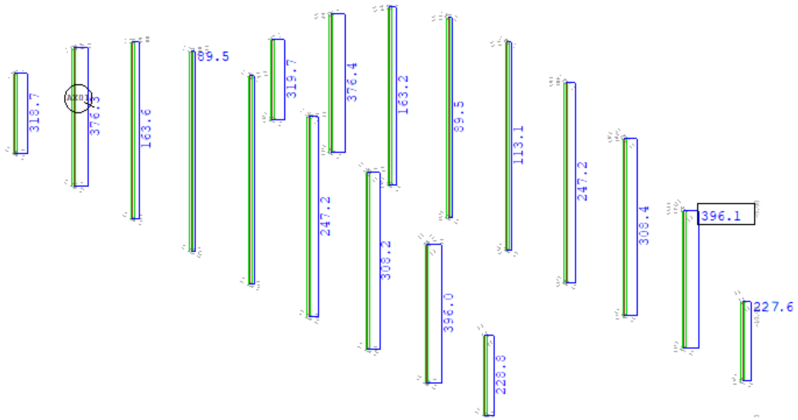
Bending Moment (My-inplane) Diagram



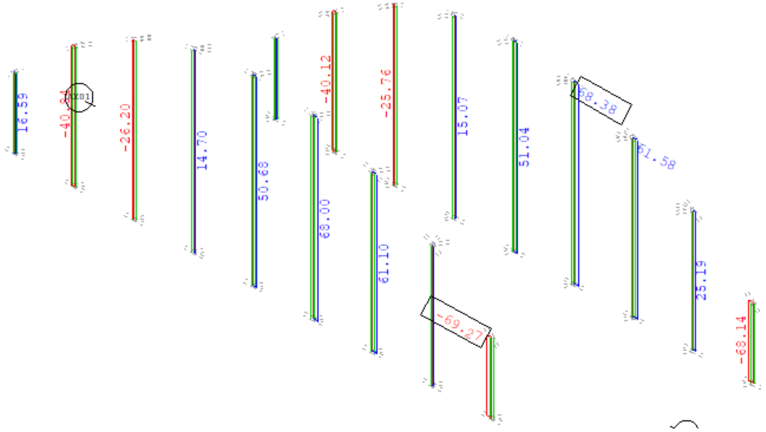
Bending Moment (My-inplane) Diagram

Bowstring Girder Bridge - Design Challenges

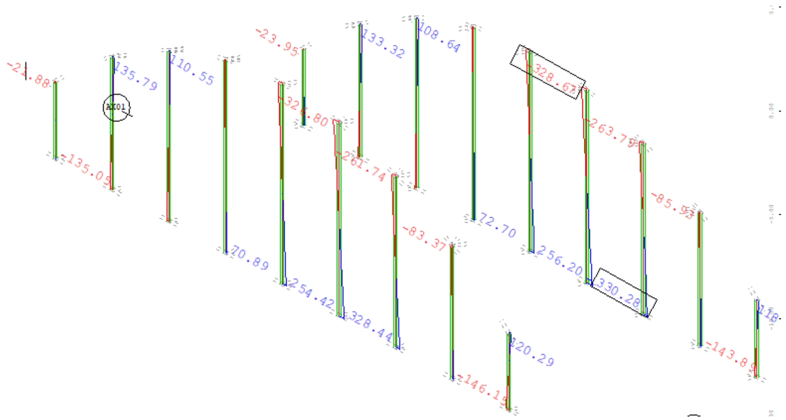
Forces in Hangers Due to 3 Class A vehicle:



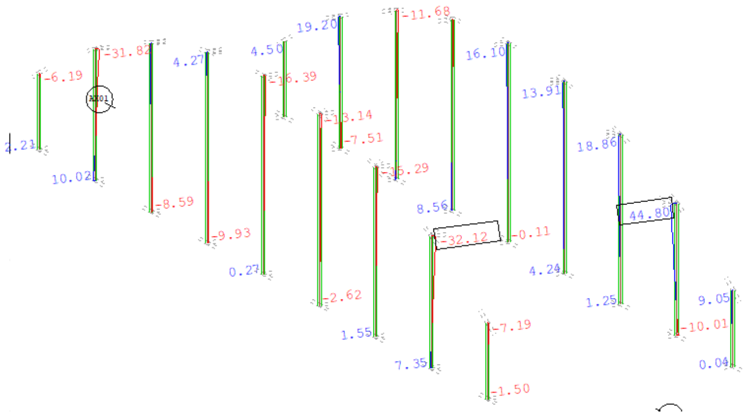
Normal Forces in Members



Shear Force Diagram



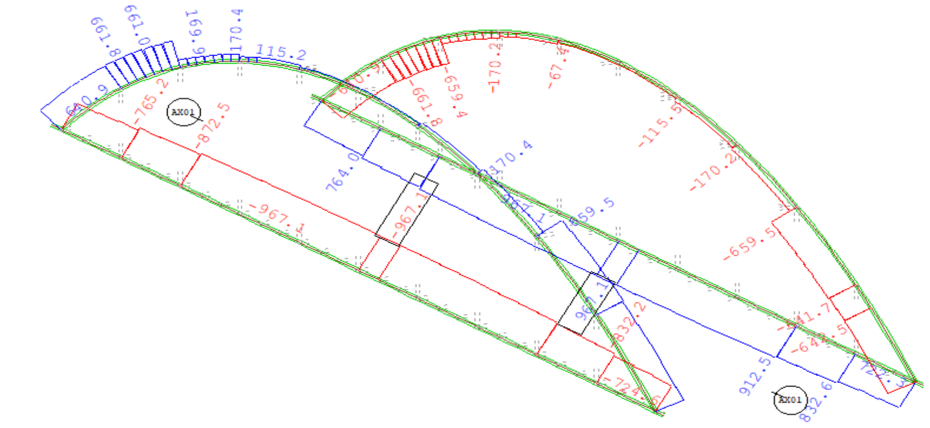
Bending Moment (My-in plane) Diagram



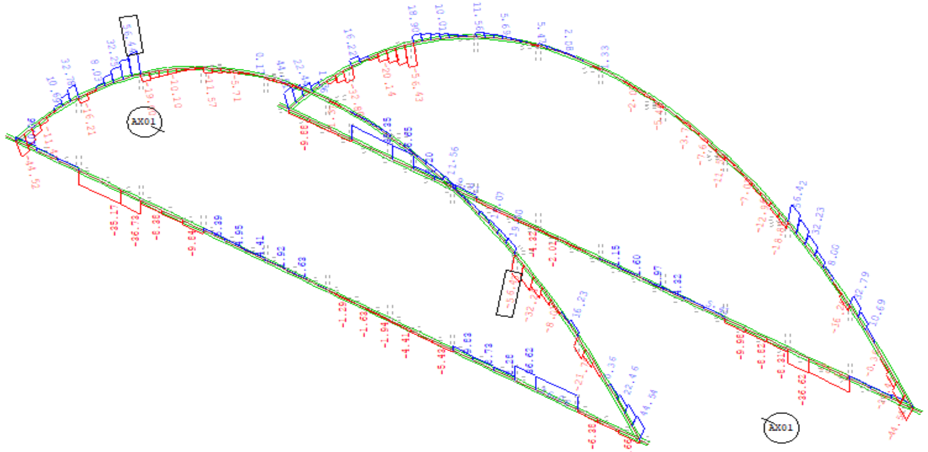
Bending Moment (Mz-out of plane)Diagram

Bowstring Girder Bridge - Design Challenges

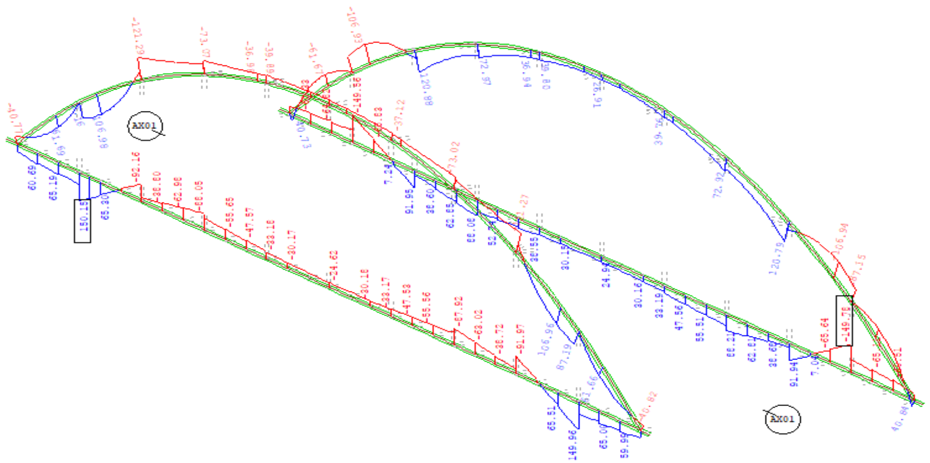
<u>Forces in Arch Tie and Rib Due to **Transverse Wind Load**:</u>



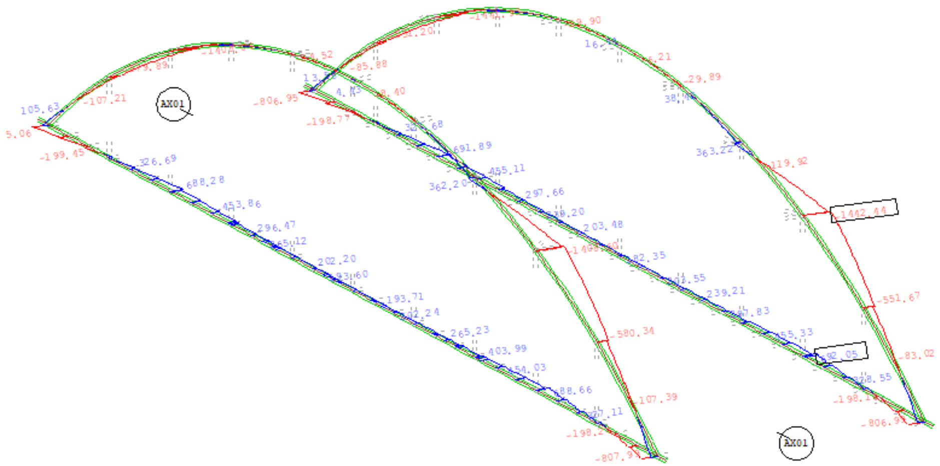
Normal Forces in Members



Shear Force Diagram



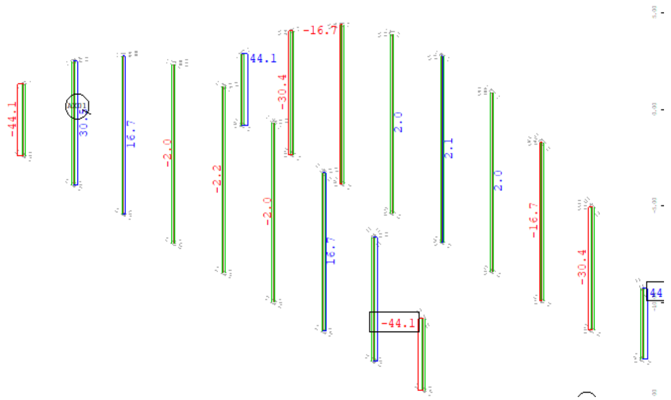
Bending Moment (My-in plane) Diagram



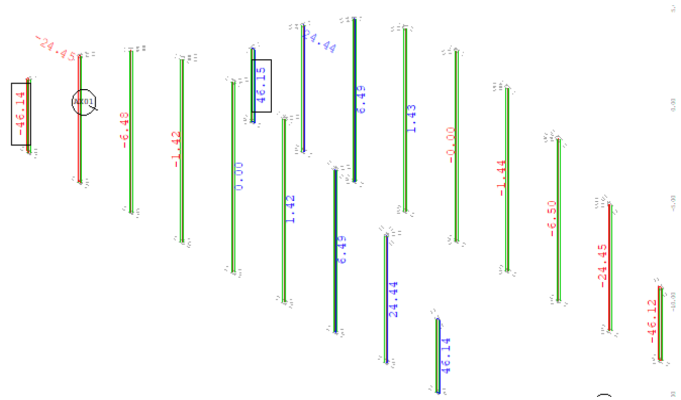
Bending Moment (Mz-out of plane)Diagram

Bowstring Girder Bridge - Design Challenges

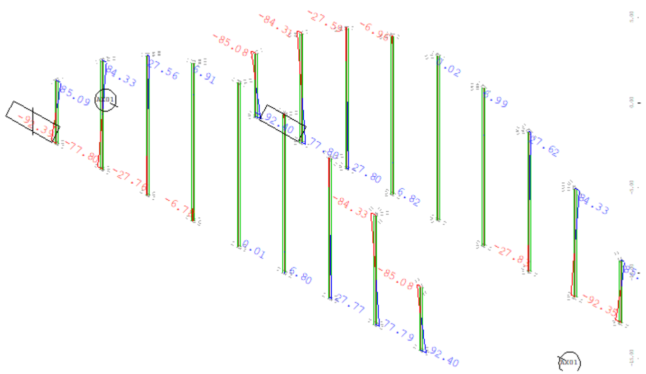
Forces in Hangers Due to **Transverse Wind Load**:



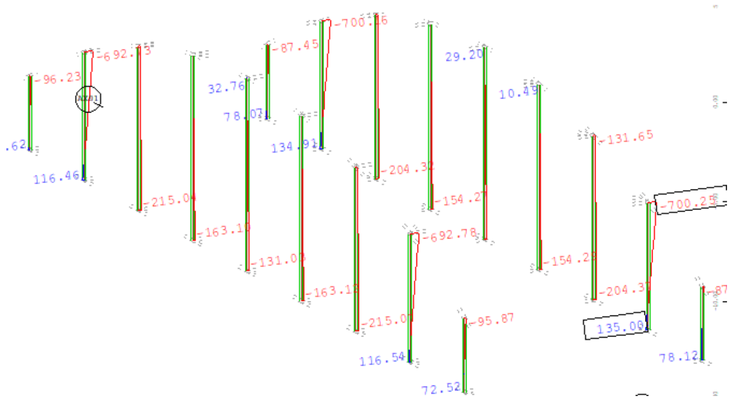
Normal Forces in Members



Shear Force Diagram



Bending Moment (My-in plane) Diagram



Bending Moment (Mz-out of plane)Diagram

Bowstring Girder Bridge - Design Challenges

With the forces obtained in various elements for different load cases –

1. Combine the forces using the load factors given in IRC6
2. Carryout sectional design
3. Design the joint/connections

Design for the Buckling

As the Ribs of the Arch Bridges are **Extremely slender**, they are susceptible to Buckling, thus, Compression members are designed accounting Global Buckling of Arch Bridge

As per IRC-24, for Compression Members, the Design Strength is calculated by:

$$Pd = A_e f_{cd}$$

Bowstring Girder Bridge - Design Challenges

Steps involved:

Calculate f_{cd}

$$f_{cd} = \frac{f_y / \gamma_{m0}}{\phi + \left[\phi^2 - \lambda^2\right]^{0.5}} = \chi f_y / \gamma_{m0}$$

Calculate reduction factor, χ

$$\chi = \frac{1}{\Phi + \sqrt{\Phi^2 + \bar{\lambda}^2}}$$

$$\Phi = 0{,}5\left(1 + \alpha\left(\bar{\lambda} - 0{,}2\right) + \bar{\lambda}^2\right)$$

Calculate slenderness, λ

$$\bar{\lambda} = \sqrt{\frac{A \cdot f_y}{N_{cr}}}$$

Calculate critical buckling force, N_{cr}

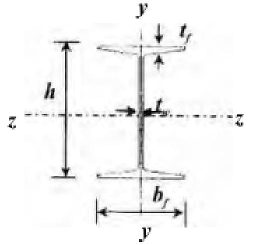
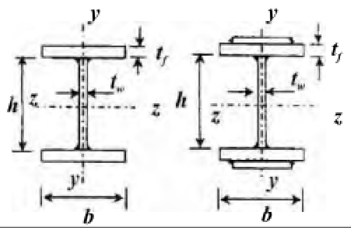
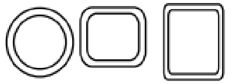
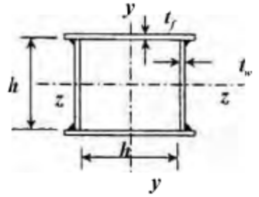
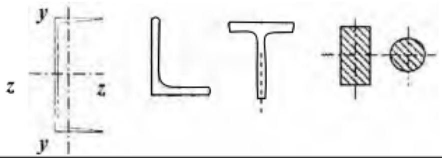
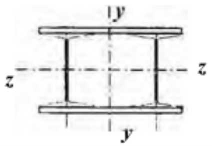
Two methods:

1) Calculations provided in **Annex- D of EN 1993-2** or
2) Carrying out **Buckling analysis using FEM Software**.

Bowstring Girder Bridge - Design Challenges

Imperfection factor α

Refer Table 4 from IRC 24-2010:

Cross Section	Limits	Buckling about axis	Buckling Class
Rolled I-Sections 	$h/b_f > 1.2$: $t_f < 40$ mm	z-z y-y	a b
	40 mm$< t_f \leq 100$ mm	z-z y-y	b c
	$h/b_f \leq 1.2$: $t_f \leq 100$ mm	z-z y-y	b c
	$t_f > 100$ mm	z-z y-y	d d
Welded I-Sections 	$t_f \leq 40$ mm	z-z y-y	b c
	$t_f > 40$ mm	z-z y-y	c d
Hollow-Sections 	Hot rolled	Any	a
	Cold formed	Any	b
Welded Box Sections 	Generally (Except as below)	Any	b
	Thick welds and $b/t_f < 30$	z-z	c
	$h/t_w < 30$	y-y	c
Channel, Angle, T and Solid Sections 		Any	c
Built-up Member 		Any	c

Section class = ‘b’

Refer Table 3 from IRC 24-2010:

(Clauses **507.1.1** and **507.1.2.1**)

Buckling Class	**a**	**b**	**c**	**d**
α	0.21	0.34	0.49	0.76

$$\boldsymbol{\alpha = 0.34}$$

Bowstring Girder Bridge - Design Challenges

Calculate critical buckling force, N_{cr}

Method 1: As per **Annex- D of EN 1993-2**

Now, given in New Guideline of IRC (B-9.4) on Arch Bridges

Bowstring Girder Bridge - Design Challenges

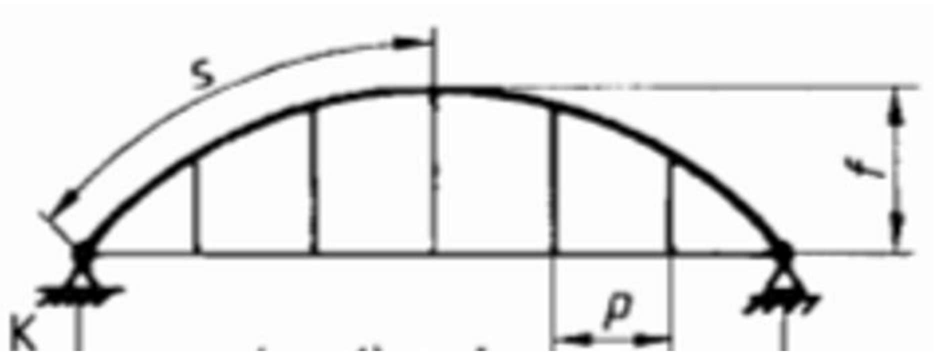
Buckling of Arch as per Annex- D of EN 1993-2

- The critical buckling force N_{cr} in the arch for **in plane buckling** is expressed by:

$$N_{cr} = \left(\frac{\pi}{\beta s}\right)^2 EI_y$$

- The critical buckling force in free standing arches for **out of plane buckling** is expressed by:

$$N_{cr} = \left(\frac{\pi}{\beta \cdot \ell}\right)^2 EI_z$$



Where,

N_{cr} relates to the force at the supports;

$\bar{s}$ is the half length of the arch;

l is the projection length of the arch;

E_{Iy} & **E_{Iz}** are the in plane & out of plane flexural stiffness of the arch;

β is the buckling length factor

Bowstring Girder Bridge - Design Challenges

In-plane Buckling Factor β as per Annex- D of EN 1993-2

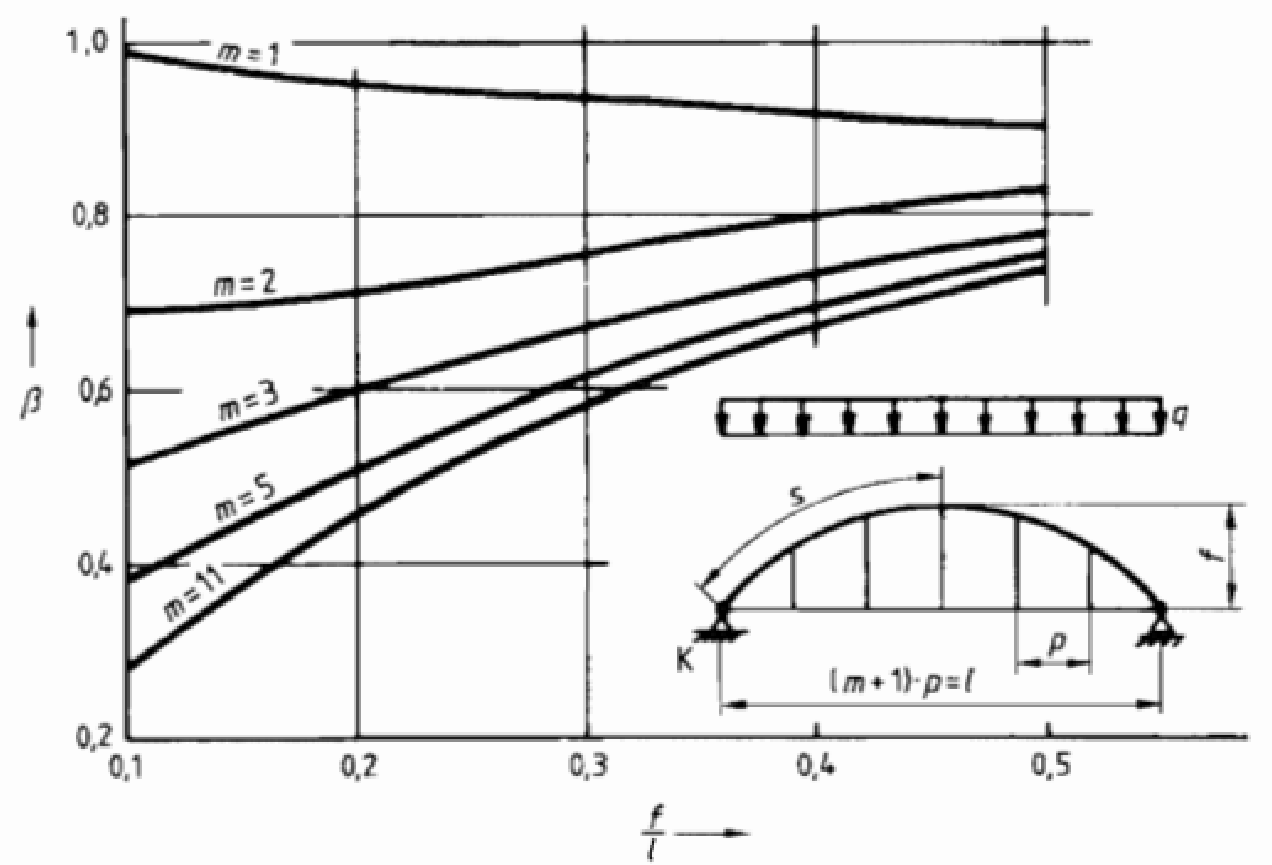


Table D.4 - Arch with vertical Hangers.

Bowstring Girder Bridge - Design Challenges

Properties of the Arch considered are as follows:

$\mathbf{I_y = 1.219 \times 10^{10}\ mm^4}$

E = 200 GPa

S = 33.11 m

$\boldsymbol{\beta \approx 0.42}$

$$N_{cr} = \left(\frac{\pi}{\beta s}\right)^2 E\,Iy$$

$$N_{cr} = \left(\frac{\pi}{0.42 \times 33110}\right)^2 200 \times 10^9 \times 1.219 \times 10^{10}$$

$$\underline{\boldsymbol{= 1.244 \times 10^5\ kN}}$$

(In-plane Critical Buckling Load)

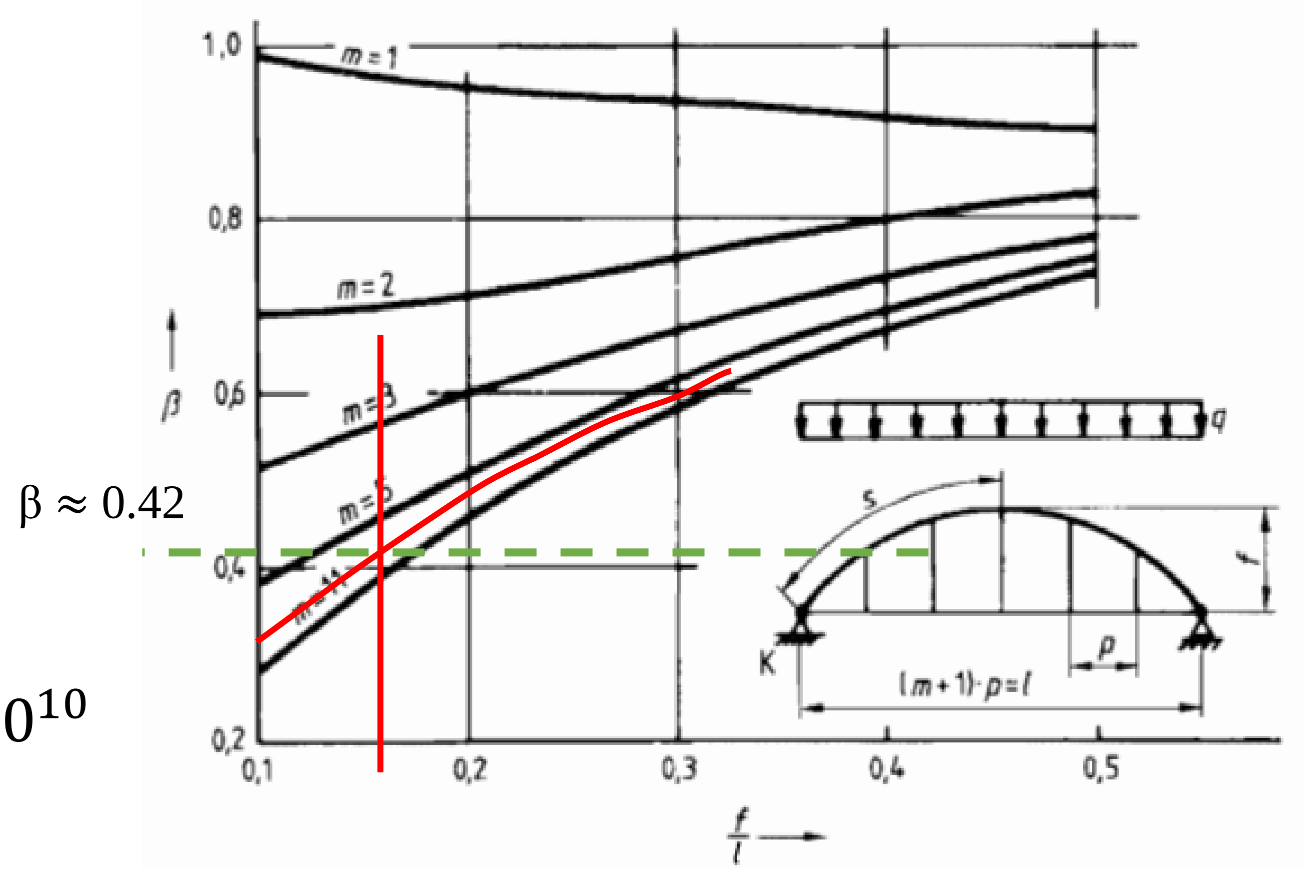
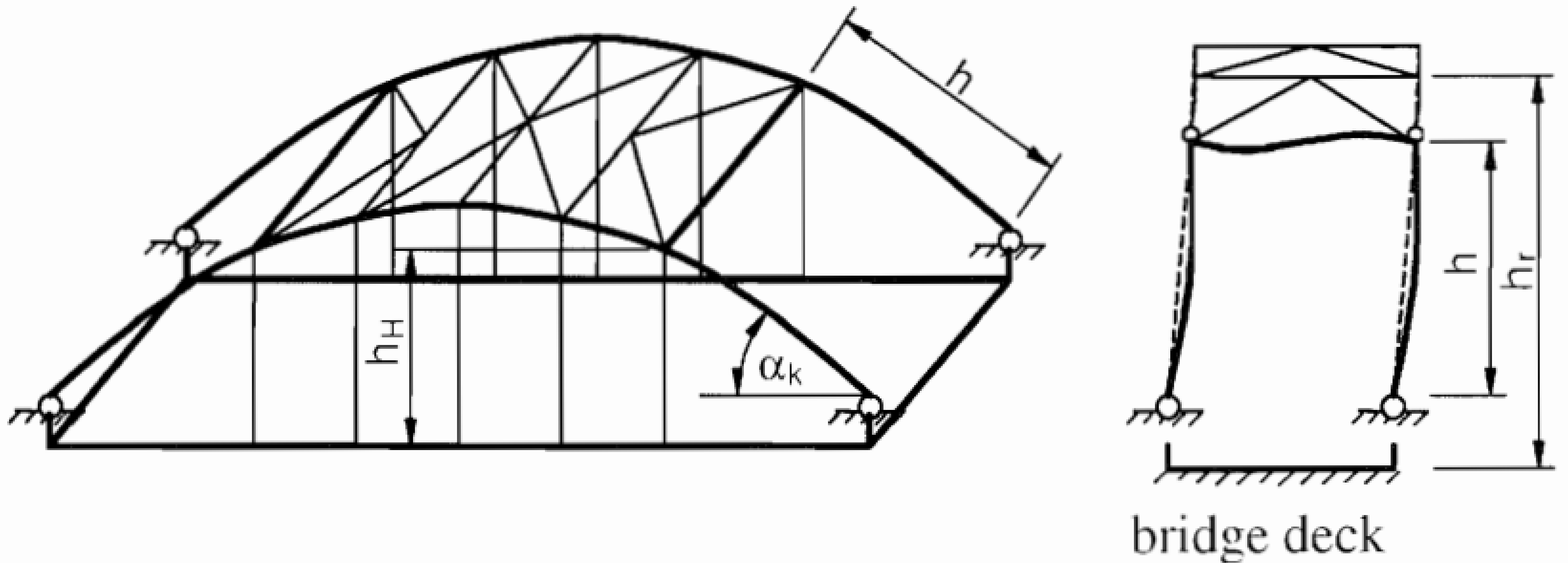


Table D.4 - Arch with vertical Hangers.

Bowstring Girder Bridge - Design Challenges

Out of plane Buckling as per Annex- D of EN 1993-2

For out of plane buckling of Arches with **wind bracing and end portals**. The buckling length factor β may be taken from Table D.1 (EN 1993-2), using the geometry in Figure below :



where, $\mathbf{h_r}$ is mean Length of all hangers divided by $\frac{1}{\sin(\alpha k)}$.

Bowstring Girder Bridge - Design Challenges

Out of plane Buckling as per Annex- D of EN 1993-2

Properties of the Arch considered are as follows:

Iz = $\mathbf{7.996 \times 10^9\ mm^4}$

E = 200 GPa

h = 7.3 m

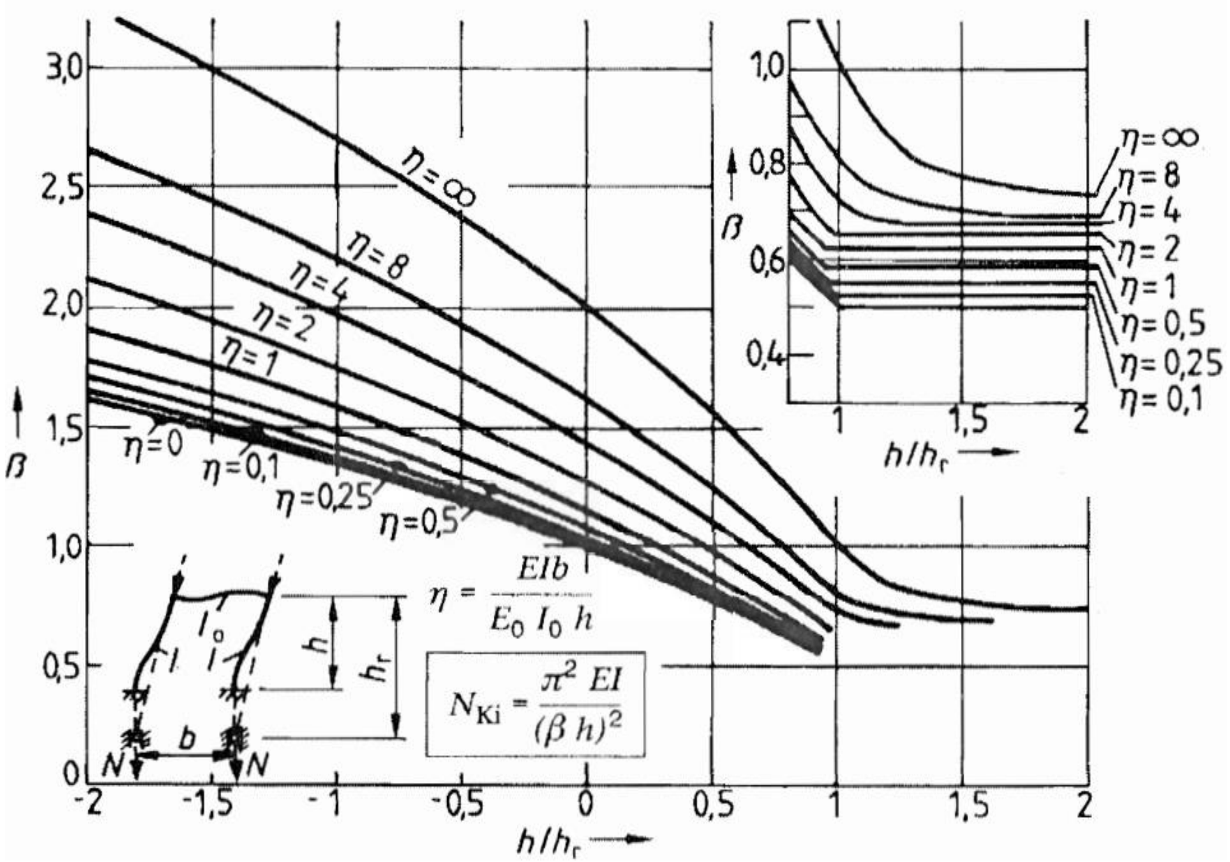
$\mathbf{h_r}$ **= 7.48m**

$$\boxed{\eta = \frac{EIb}{E_0\ I_0\ h}}$$

$$Ncr = \left(\frac{\pi}{\beta h}\right)^2 E\ Iy$$

$$Ncr = \left(\frac{\pi}{0.80 \times 7300}\right)^2 200 \times 10^9 \times 7.996 \times 10^9$$

$\underline{= \mathbf{4.623 \times 10^5\ kN}}$ *(Out of plane Critical Buckling Load)*



Bowstring Girder Bridge - Design Challenges

Calculate critical buckling force, N_{cr}

Method 2: **Buckling analysis using FEM Software**.

Bowstring Girder Bridge - Design Challenges

Method 2: **Buckling analysis using FEM Software**.

The method presented in Technical Paper of Hans De Backer published in 34th symposium of IABSE

The above method is simplified nonlinear finite element approach, where the Imperfection factors from Table D.8 (Eurocode 3) is to be considered.

Table D.8 of Eurocode 3 -1993-2

Shape and amplitudes of imperfections for in plane buckling of arches

	1	2	3			
		shape of imperfection (sinus or parabola)	e_0 according to classification of cross section to buckling curve			
			a	b	c	d
1			$\frac{s}{300}$	$\frac{s}{250}$	$\frac{s}{200}$	$\frac{s}{150}$
2			$\frac{\ell}{600}$	$\frac{\ell}{500}$	$\frac{\ell}{400}$	$\frac{\ell}{300}$

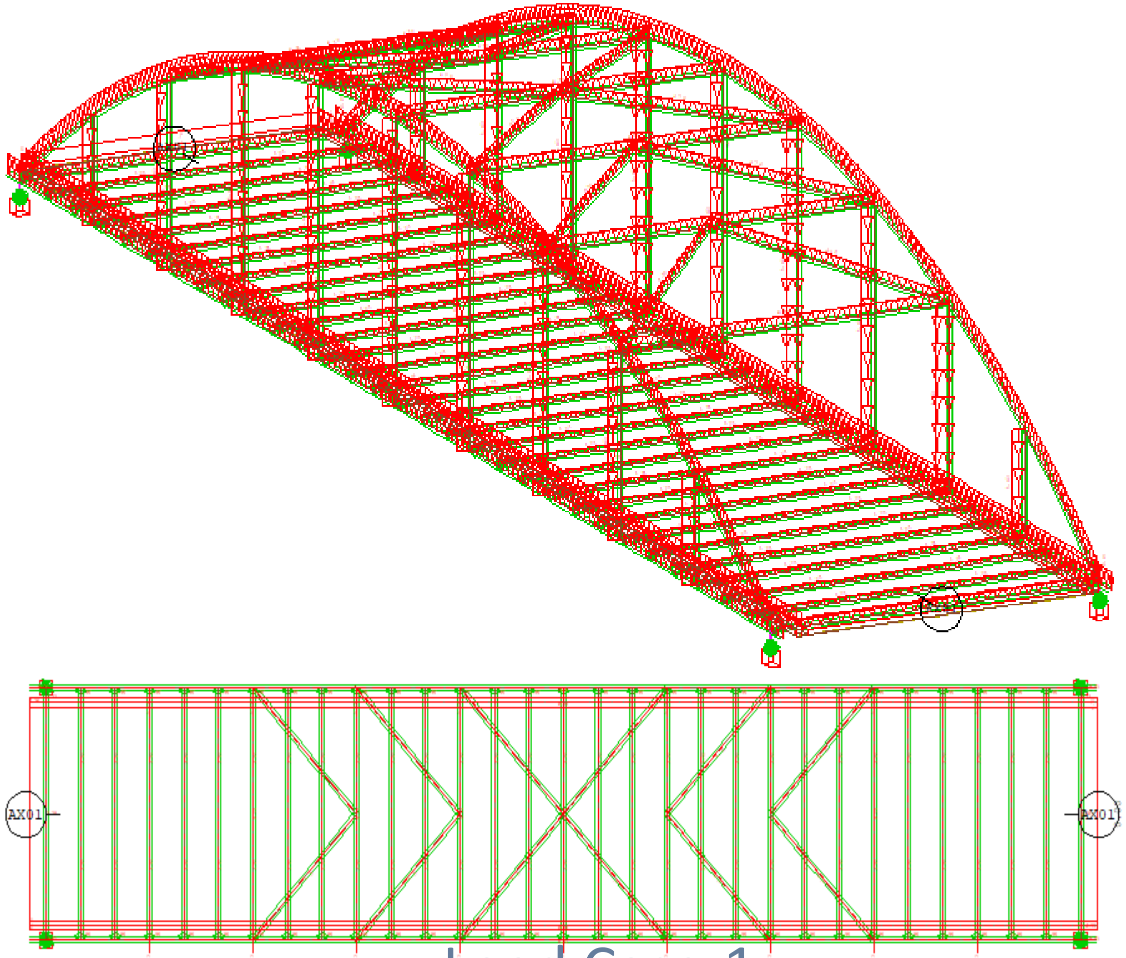
Table D.9 of Eurocode 3 -1993-2

Shape and amplitudes of imperfections for out of plane buckling of arches

	shape of imperfection (sinus or parabola)	e_0 according to classification of cross section to buckling curve				
			a	b	c	d
		$\ell \leq 20$ m	$\frac{\ell}{300}$	$\frac{\ell}{250}$	$\frac{\ell}{200}$	$\frac{\ell}{150}$
		$\ell > 20$ m $\ell_1 = \sqrt{20\,\ell[m]}$	$\frac{\ell_1}{300}$	$\frac{\ell_1}{250}$	$\frac{\ell_1}{200}$	$\frac{\ell_1}{150}$

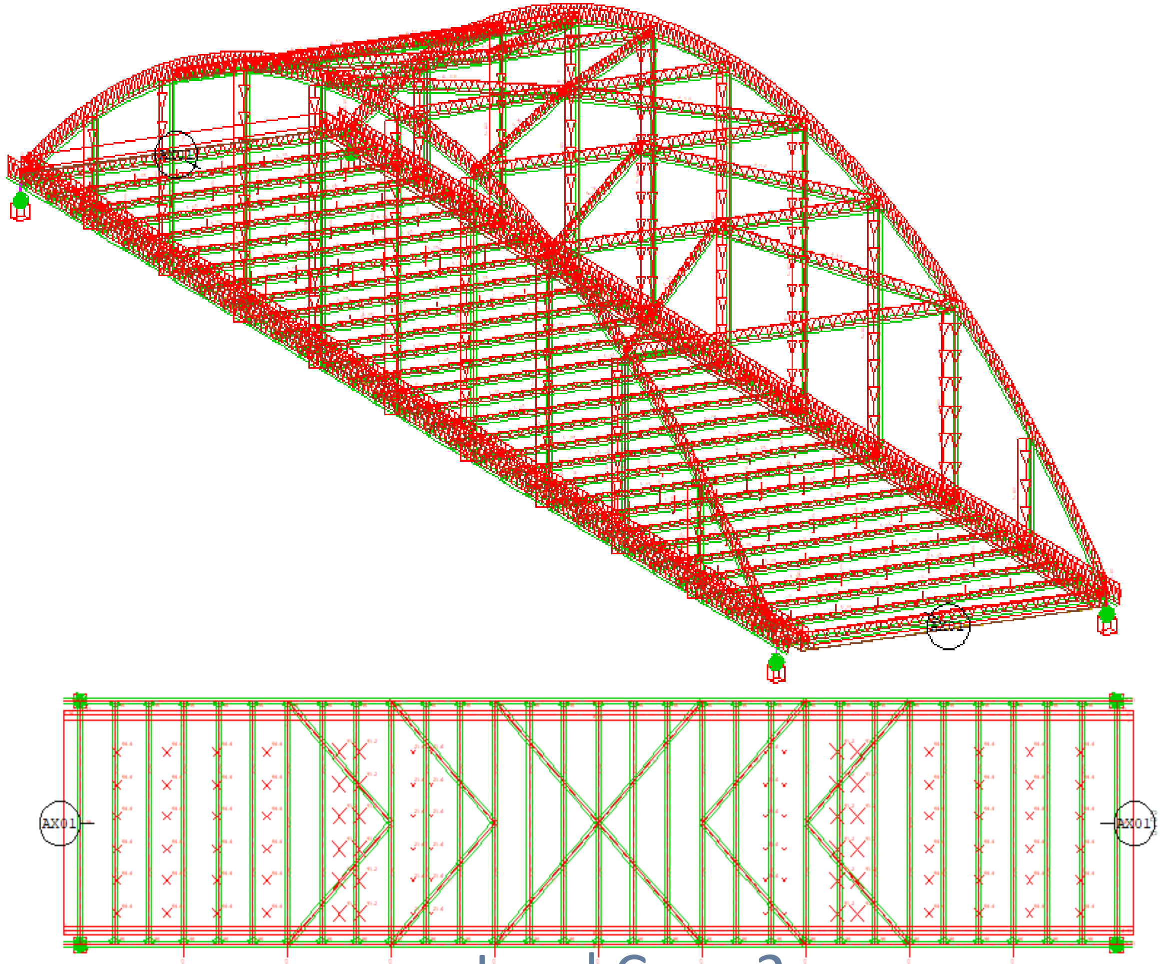
Bowstring Girder Bridge - Design Challenges

- Two Cases of Loading for the Buckling analysis of the Arch are considered.



Load Case-1

(Self Weight + Wearing Coat + SIDL)

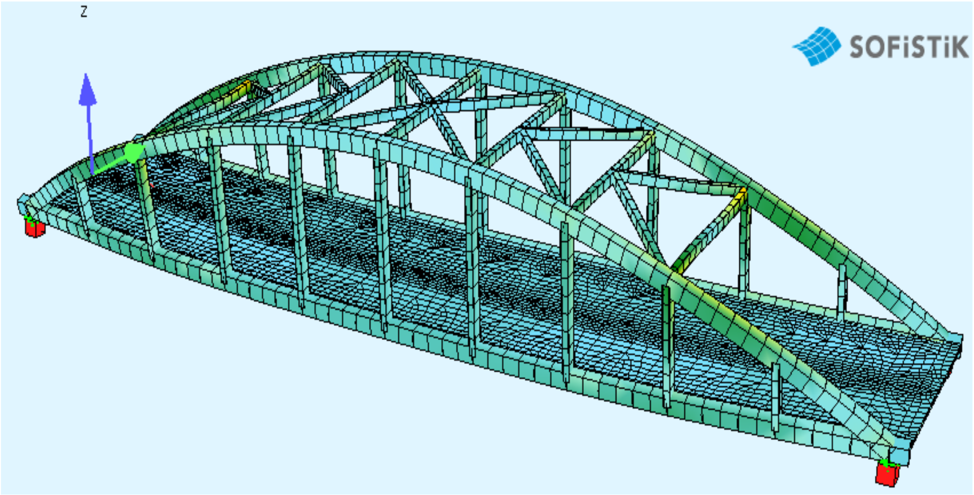


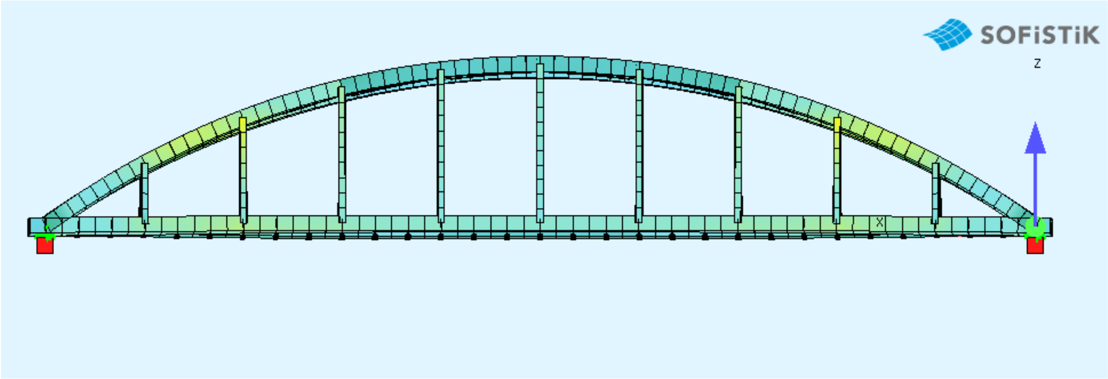
Load Case-2

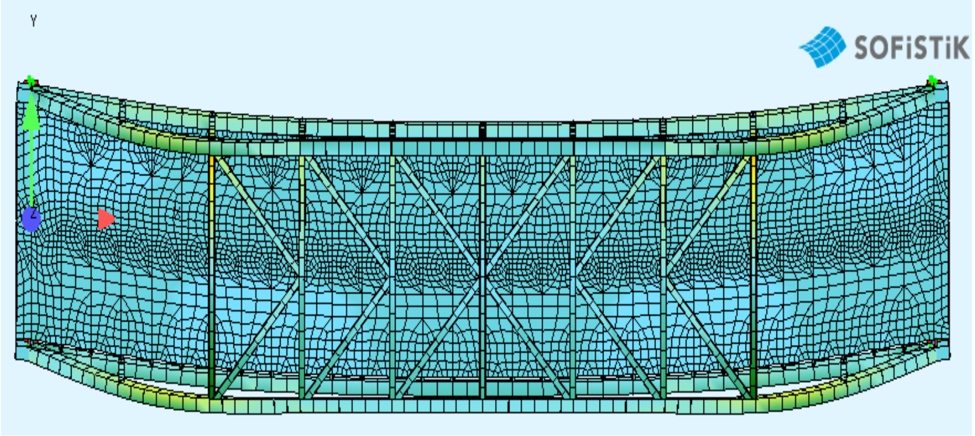
(Load Case-1 + 3 Class A Vehicle Loading)

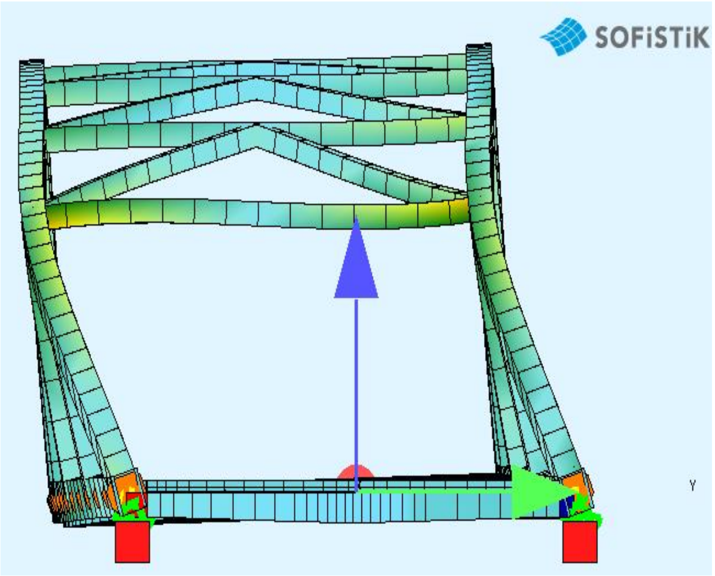
Bowstring Girder Bridge - Design Challenges

First mode shape of buckling of the Arch for Load Case-1 (Buckling Factor is **15.96**).







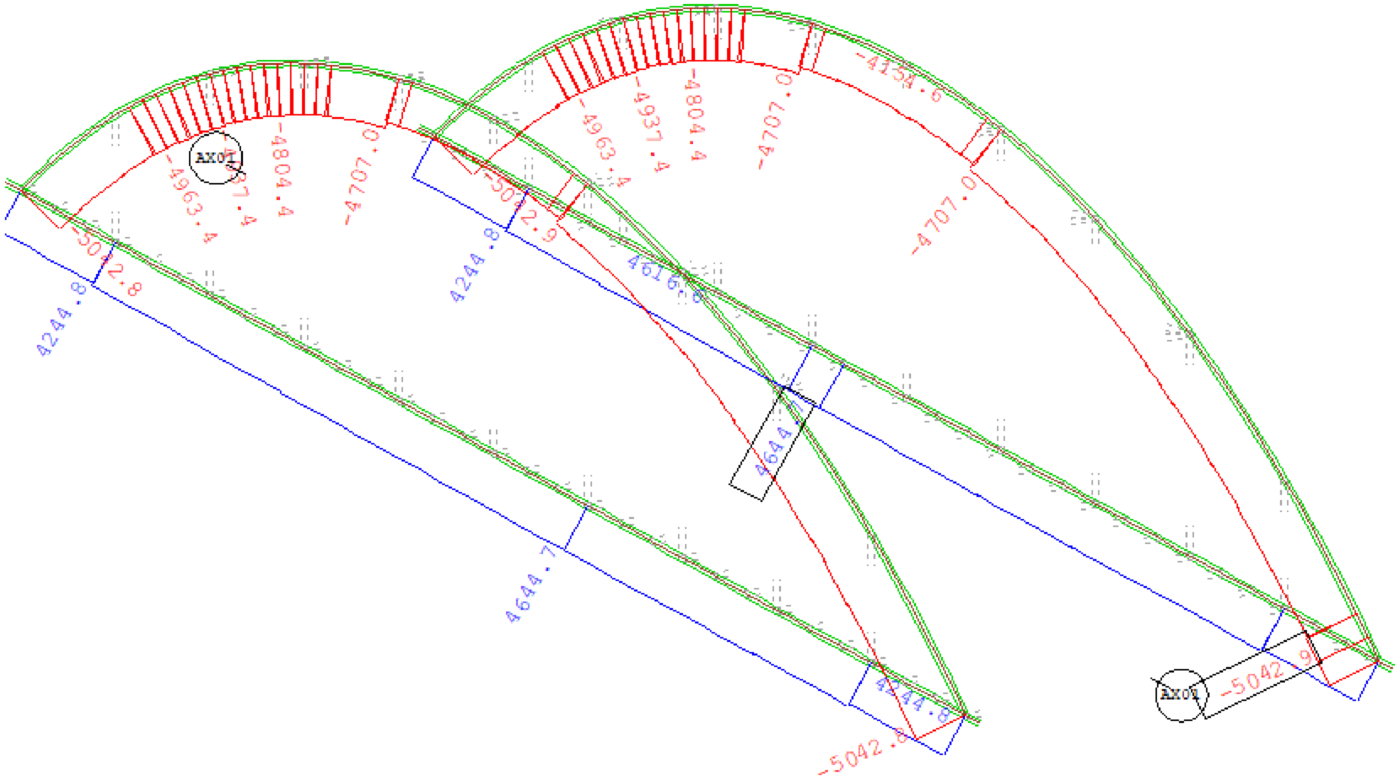


Loadcases	Load Distributi
101 Buckling 1 fact 15.96	
102 Buckling 2 fact 17.07	
103 Buckling 3 fact 38.57	
104 Buckling 4 fact 38.57	
105 Buckling 5 fact 39.33	
106 Buckling 6 fact 40.30	
107 Buckling 7 fact 73.38	
108 Buckling 8 fact 73.53	
109 Buckling 9 fact 74.56	
110 Buckling 10 fact 74.72	

Bowstring Girder Bridge - Design Challenges

- Normal Forces from Buckling Analysis of the Arch for Load Case-1.

(Max Compressive Force= **5042.9 kN** for Static Loading for the Load Case Considered)

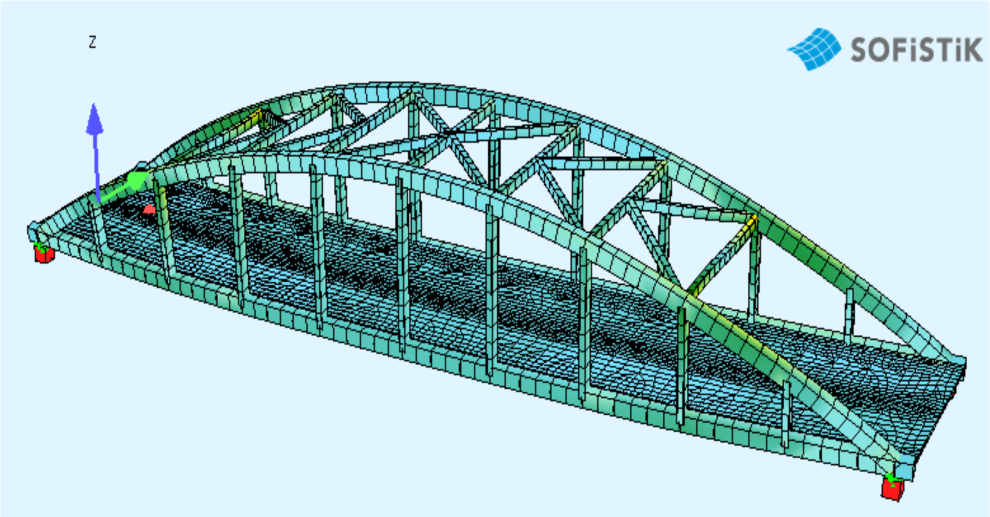


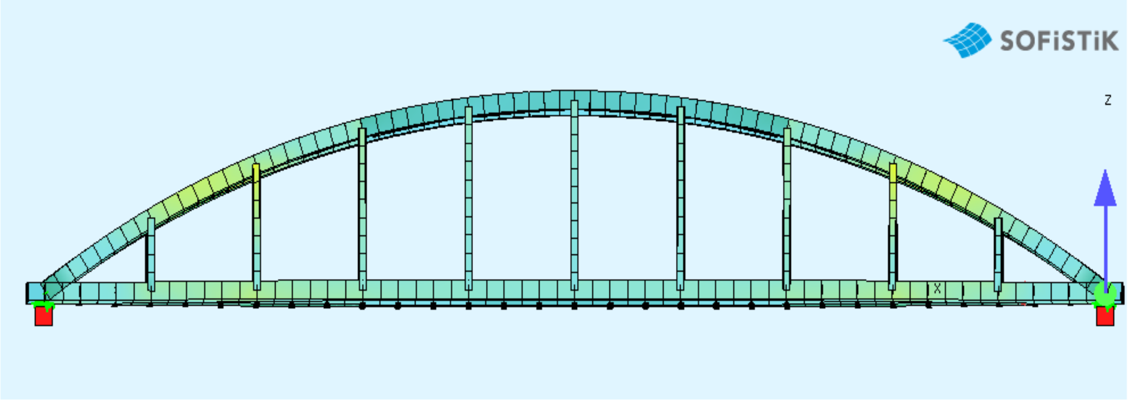
Critical Buckling Force, Ncr = $\mathit{Compressive\ Force\ due\ to\ Static\ Loading} \times \mathit{Buckling\ Factor}$

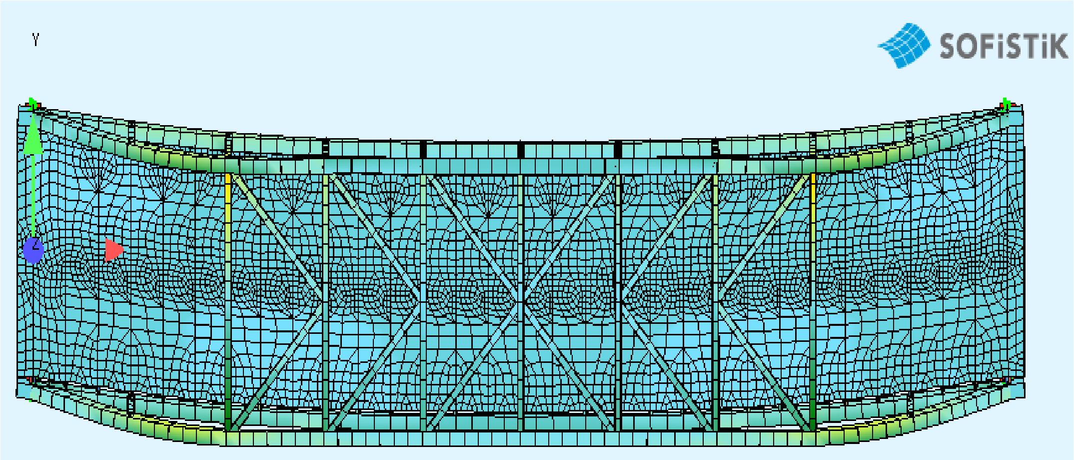
$$= 5042.9 \times 15.96 = \mathbf{80485}\ \boldsymbol{kN}$$

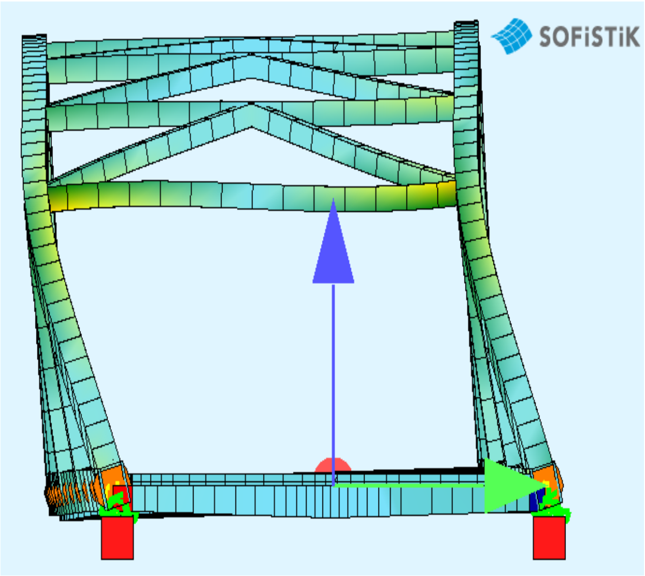
Bowstring Girder Bridge - Design Challenges

- First mode shape of buckling of the Arch for Load Case-2 (Buckling Factor is **11.6**).





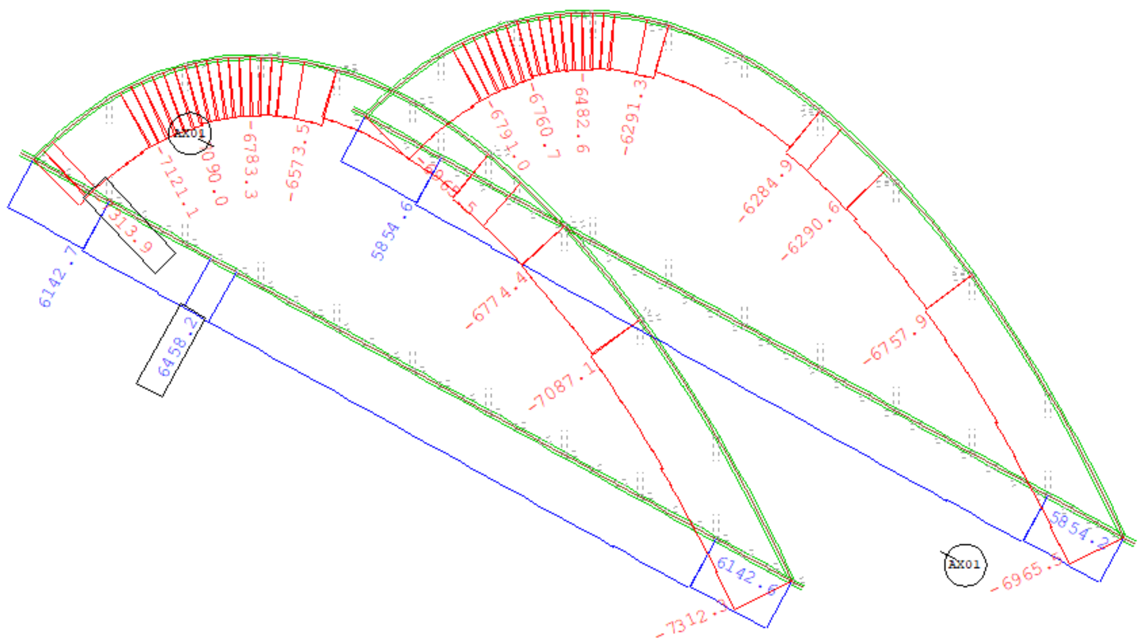




Loadcases	Load Distributio
151 Buckling 1 fact	11.60
152 Buckling 2 fact	12.57
153 Buckling 3 fact	27.21
154 Buckling 4 fact	27.37
155 Buckling 5 fact	28.59
156 Buckling 6 fact	29.16
157 Buckling 7 fact	51.49
158 Buckling 8 fact	51.55
159 Buckling 9 fact	54.14
160 Buckling 10 fact	54.20

Bowstring Girder Bridge - Design Challenges

- Normal Forces from Buckling Analysis of the Arch for Load Case-2.
  (Max Compressive Force= **6965.5 kN** for Static Loading for the Load Case Considered)



Critical Buckling Force, Ncr = $\textit{Compressive Force due to Static Loading} \times \textit{Buckling Factor}$

$$= 6965.5 \times 11.6 = \mathbf{80800\ kN}$$

Bowstring Girder Bridge - Design Challenges

N_{cr} for the Arch Rib = *min (Ncr Case-1, Ncr Case-2)= min (80485,80800)* = ***80485 kN***

A = 85000 mm^2

fy = 390 MPa

α = 0.34

Sr. No	Parameters	Formula	Value
1	Slenderness Ratio	$\bar{\lambda} = \sqrt{\frac{A \cdot f_y}{N_{cr}}}$	0.642
2	φ Factor	$\Phi = 0{,}5\left(1 + \alpha\left(\bar{\lambda} - 0{,}2\right) + \bar{\lambda}^2\right)$	0.781
3	Reduction Factor	$\chi = \frac{1}{\Phi + \sqrt{\Phi^2 + \bar{\lambda}^2}}$	0.558

Bowstring Girder Bridge - Design Challenges

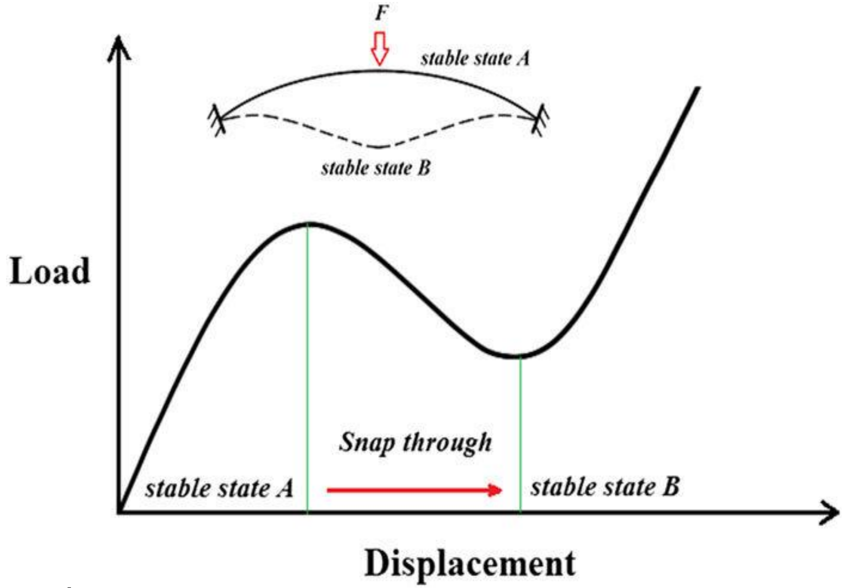
Snap through Buckling

Bowstring Girder Bridge - Design Challenges

Snap through Buckling:

Snap through of arches may be assumed to be prevented, if the following criterion is satisfied:

$$\boxed{\ell\sqrt{\frac{EA}{12EI_y}} > K}$$



Value of Factor **K** can be found using **Table D.5** (Eurocode-3 -1993-2):

Table D.5: Factor *K*

$\frac{\ell}{2}$ $\frac{\ell}{2}$ f	f/ℓ	0,05	0,075	0,10	0,15	0,20
Arch with pinned supports	K	35	23	17	10	8
Arch with fixed supports	K	319	97	42	13	6

Bowstring Girder Bridge - Design Challenges

Snap through Buckling:

The Section properties of the arch considered are as follows:

f=10 m

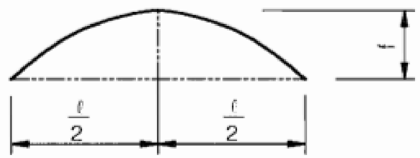
l = 62.01 m

A = 85000 mm^2

Iy =1.219 × 10^{10} mm^4

E = 200 GPa

Table D.5: Factor K *{for $f/l = \frac{10}{62.01} = \mathbf{0.16}$}*

	f/ℓ	0,05	0,075	0,10	0,15	0,20
	K	35	23	17	10	8
		319	97	42	13	6

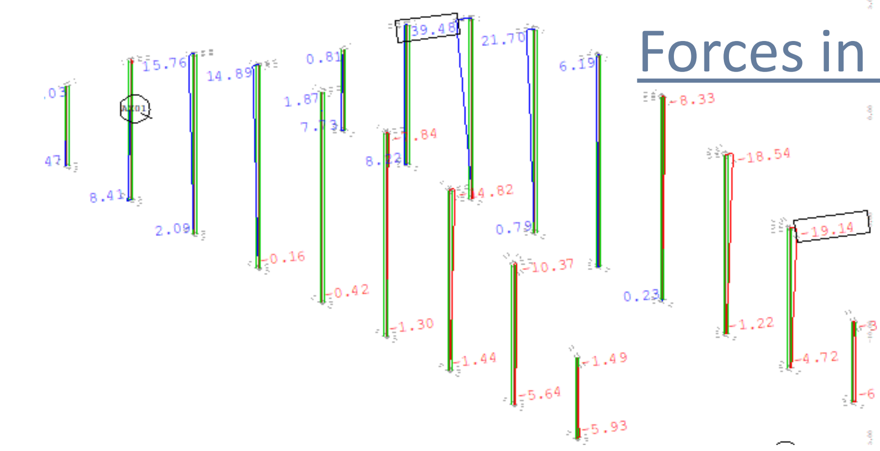
$$l\sqrt{\frac{EA}{12EIy}} = 62.01 \times 10^3 \times \sqrt{\frac{200\times10^9\times85000}{12\times200\times10^9\times1.219\times10^{10}}} = \mathbf{45.74} > \boldsymbol{K}\ (\approx \mathbf{10}) \qquad (\boldsymbol{OK})$$

Check for Fatigue

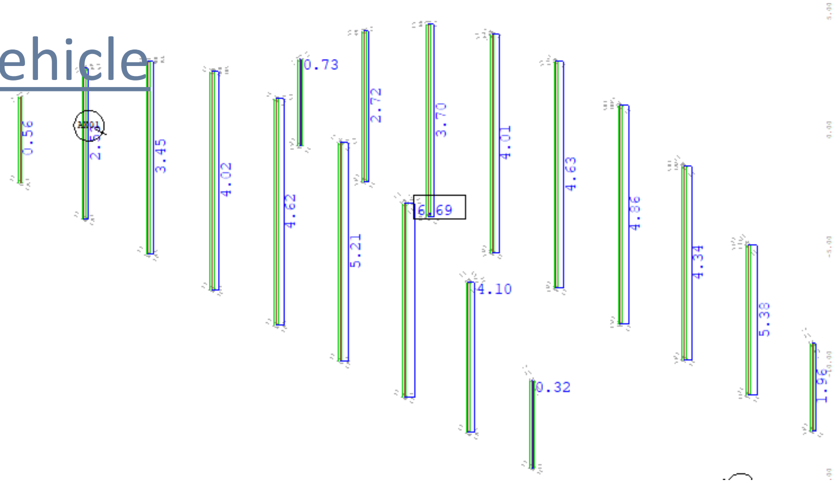
Bowstring Girder Bridge - Design Challenges

Fatigue Check of Hangers

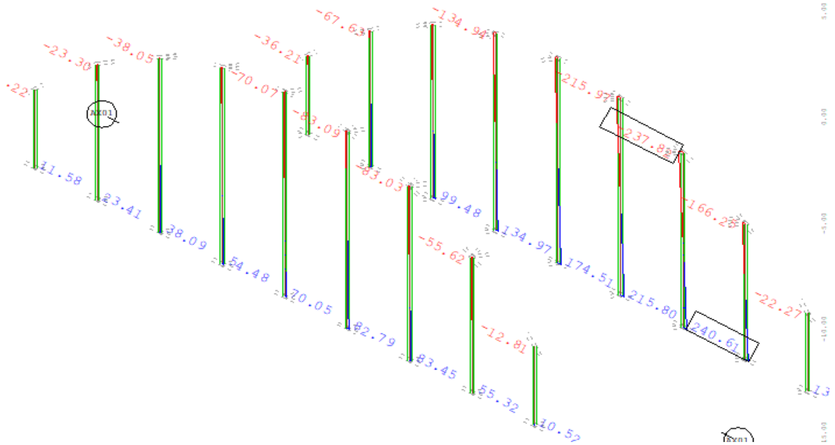
Forces in member due to Fatigue vehicle load



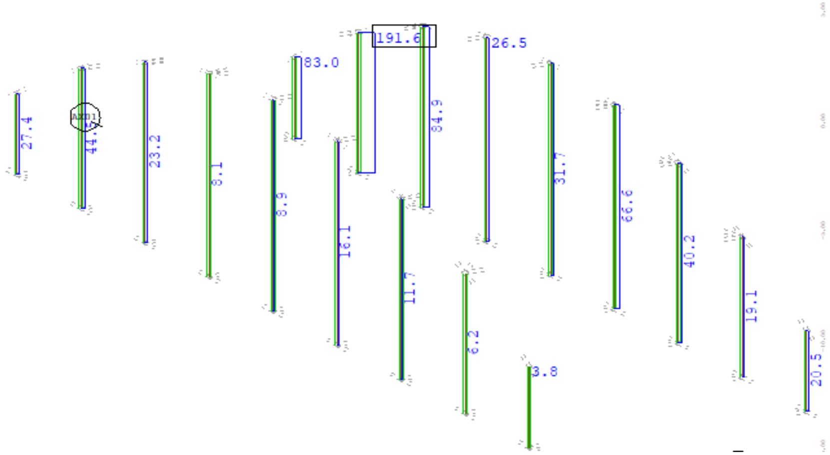
Bending Moment (My-in plane) Diagram



Torque (Tn) Diagram



Bending Moment (Mz-out of plane) Diagram



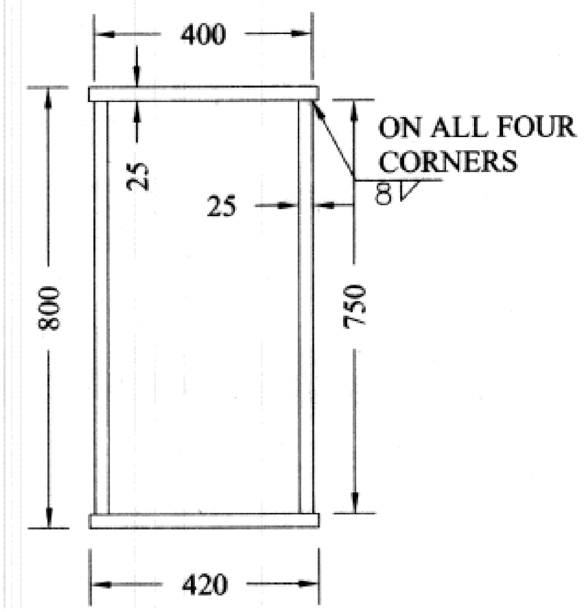
Axial Force (Nx) Diagram

Bowstring Girder Bridge - Design Challenges

- Section Properties:

  $W\ el,_y$ =**1.163E+07** mm^3
  $W\ el,_z$ =**7.790E+06** mm^3
  A =**5.683E+04** mm^2
  W_T =**3.750E+09** mm^3
  No. of Cycles = **5 million.**

Forces in Hanger, Bending Forces,	My	kN.m	40
Bending Forces,	Mz	kN.m	241.0
Torsion,	Tn	kN.m	7.0
Axial Force,	Nx	kN	192.0
Stress in Hanger, Bending Stress,	σMy	MPa	**3.44**
Bending Stress,	σMz	MPa	**30.94**
Torsional Stress,	σTn	MPa	**0.53**
Axial Stress,	σNx	MPa	**3.38**



Hanger Section

Fatigue Stress in Section:

σtotal, Axial	Mpa	**37.77**
τTn, Shear Stress	Mpa	**0.53**

(σMy+ σMz+ σNx)

Bowstring Girder Bridge - Design Challenges

a) Limiting stress range for low fatigue,

$$f \leq 27/\gamma_{mft}$$

= **21.6** MPa (< f = 37.77 MPa)

Where,

$\gamma_{mft} = 1.25$

b) Limiting no of cycles for low fatigue,

$$N_{SC} < 5 \text{ X } 10^6 \left(\frac{27/\gamma_{mft}}{\gamma_{fft} f} \right)^3$$

= 0.**818x10^6** Cycles (< 5 million assumed cycles)

Where,

$\gamma_{fft} = 1.0$

IRC-24 2010: Table 18

Partial Safety Factors for Fatigue Strength (γ_{mft})

Inspection and Access	Consequence of failure	
	Fail-safe	Non-fail-safe
Periodic inspection, maintenance and accessibility to detail is good	1.00	1.25
Periodic inspection, maintenance and accessibility to detail is poor	1.15	1.35

Low fatigue - Fatigue assessment is not required for a member, connection or detail, if normal and shear design stress ranges, *f*, satisfy the above two conditions.
As, above conditions are not satisfied (as per IRC-24 2010: Clause 511.2.2.3), **Fatigue check is Required**.

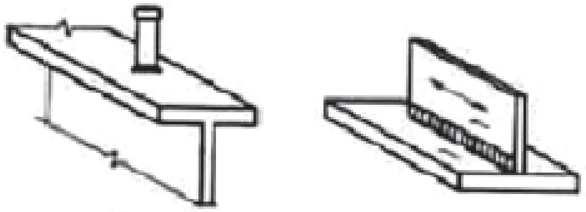
Bowstring Girder Bridge - Design Challenges

Fatigue Strength Calculations:

Design normal and shear fatigue stress for 5 million stress cycles:

f_{fn}	MPa	92.00
τ_{fn}	MPa	67.00

IRC-24 2010: Table 19

iii)	92	(7) 	**Material with machine gas-cut edges with draglines or manual gas-cut material** (7) : Corners and visible signs of edge discontinuities to be removed by grinding in the direction of the applied stress.
xx)	67	 (40) (39)	**Welds loaded in shear** (39) : Fillet welds transmitting shear. Stress range to be calculated on weld throat area. (40) : Stud welded shear connectors (failure in the weld) loaded in shear (the shear stress range to be calculated on the nominal section of the stud).

Bowstring Girder Bridge - Design Challenges

(IRC-24 2010: Clause 511.4)

Normal Stress Range:

when $5 \times 10^6 \le N_{SC} \le 10^8$	when $N_{SC} \le 5 \times 10^6$
$f_f = f_{fn} \sqrt[5]{5x10^6 / N_{SC}}$	$f_f = f_{fn} \sqrt[3]{5x10^6 / N_{SC}}$

Shear Stress:

$$\tau_f = \tau_{fn} \sqrt[5]{5x10^6 / N_{SC}}$$

f_f	Mpa	92.00
τ_f	Mpa	67.00

(IRC-24 2010: Clause 511.2.1)

$$\mu_r = (25/t_p)^{0.25} \le 1.0$$

$\mu_{r,flange}$=(25/tp)^0.25	1.00
$\mu_{r,web}$=(25/tp)^0.25	1.00

Fatigue Strength of Section:

$f_{fd,flange}=\mu_r * f_f/\gamma_{mft}$	Mpa	68.15
$\tau_{fd,web}=\mu_r * \tau f/\gamma_{mft}$	Mpa	49.63

>

Fatigue Stress in Section:

σtotal, Axial	Mpa	37.77
τTn, Shear Stress	Mpa	0.53

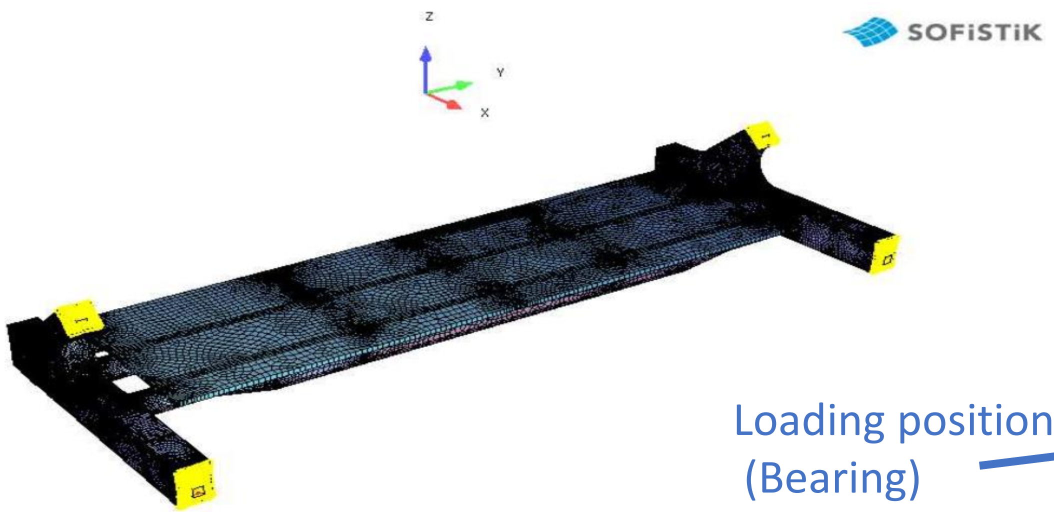
(OK)

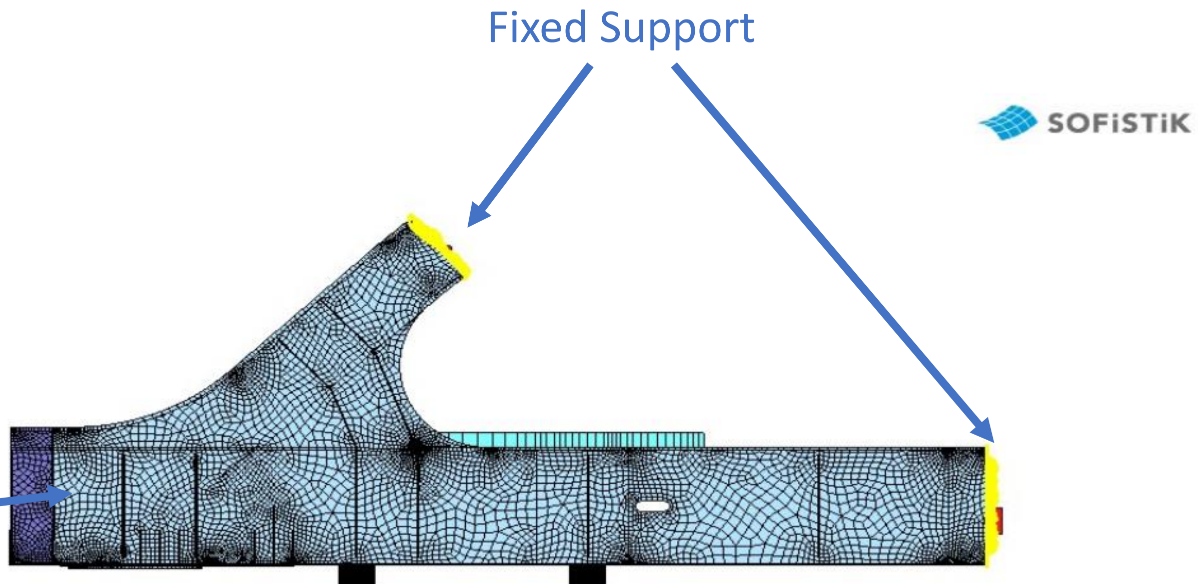
Design of End Segment of the Arch

Bowstring Girder Bridge - Design Challenges

The part of Segment connected to Tie Girder & Arch Rib is provided with Rigid Support. To avoid concentration of Load at support Extra part of Arch Rib and Tie Girder is Modeled. The SLS Forces with Maximum Vertical Force is considered and applied at Actual Support Location (at Bearing Location).

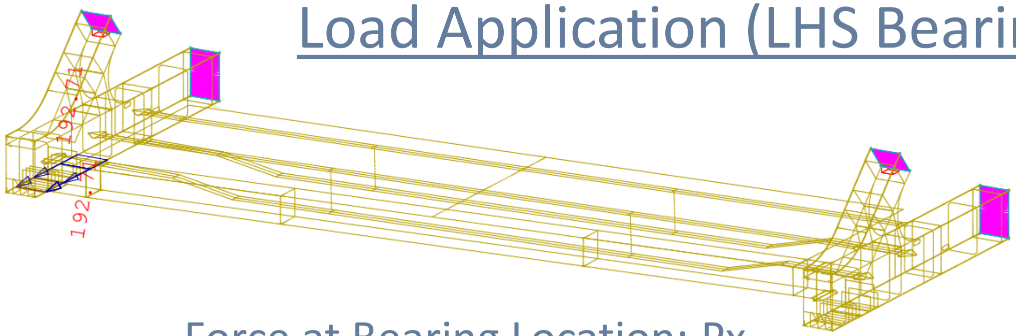
- Maximum Bearing force is applied at the Bearing Location on both the sides (LHS & RHS) of the Span. Load is Applied in the Form of Area Load at Bearing Location.
- The FEM analysis on **Plate Model** is carried out which gives Stress at different locations which are later compared with **maximum Stress Limit**.



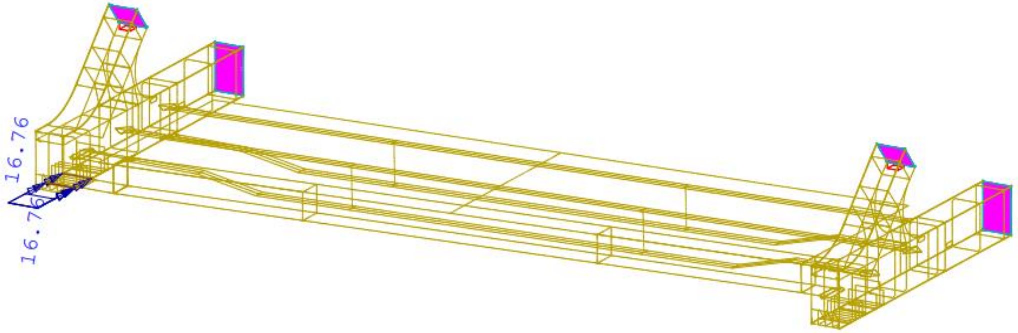


Bowstring Girder Bridge - Design Challenges

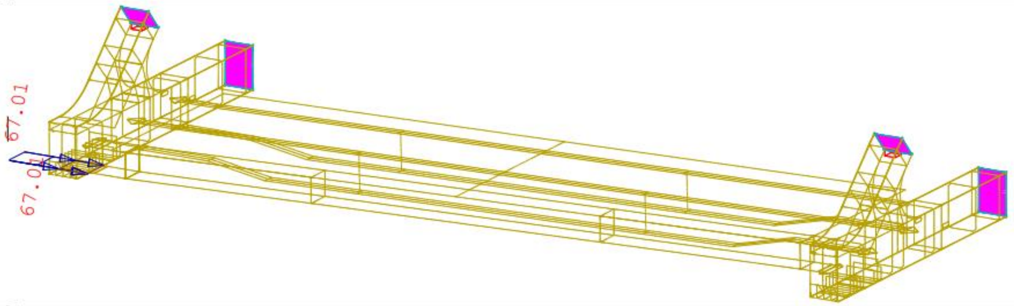
Load Application (LHS Bearing):



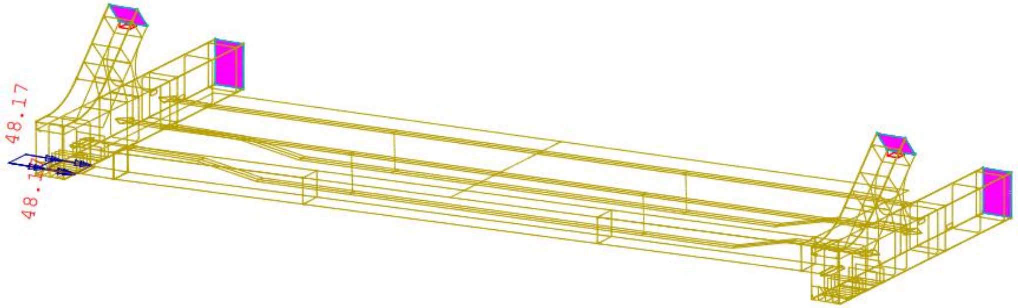
Force at Bearing Location: Px



Force at Bearing Location: Mxx



Force at Bearing Location: Py



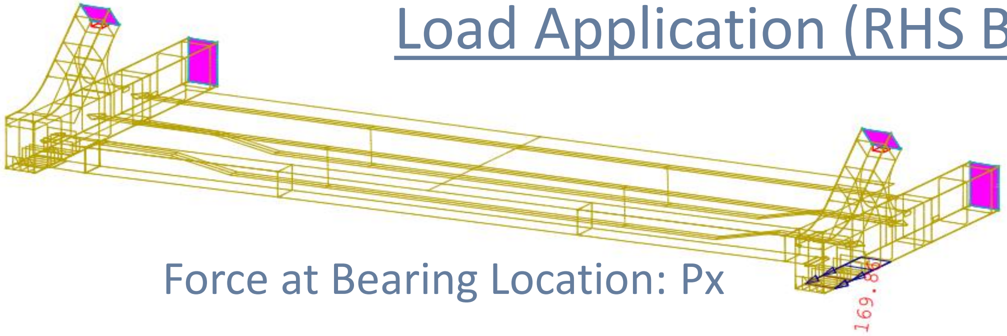
Force at Bearing Location: Myy

** (Mzz value is ignored as it is relatively small.)*

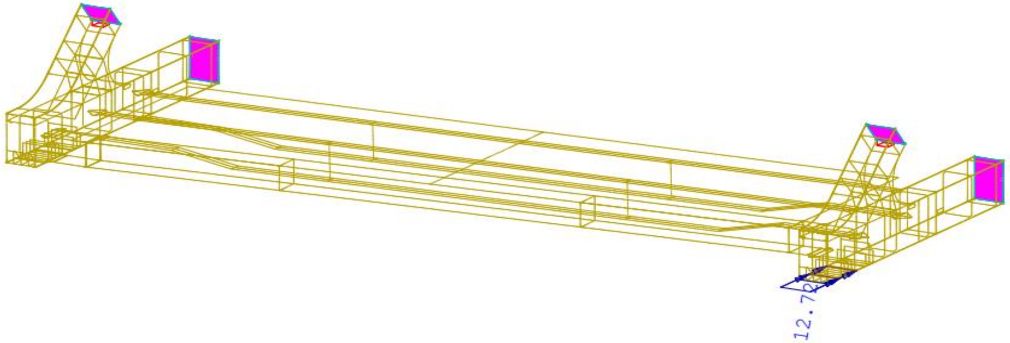
Force at Bearing Location: Pz

Bowstring Girder Bridge - Design Challenges

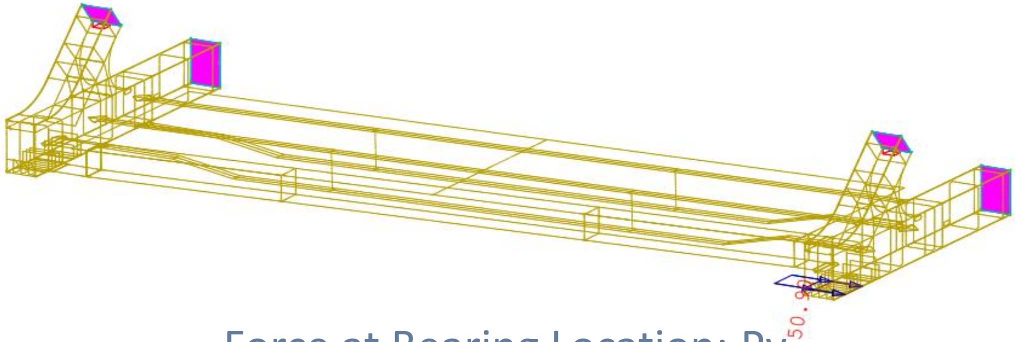
Load Application (RHS Bearing):



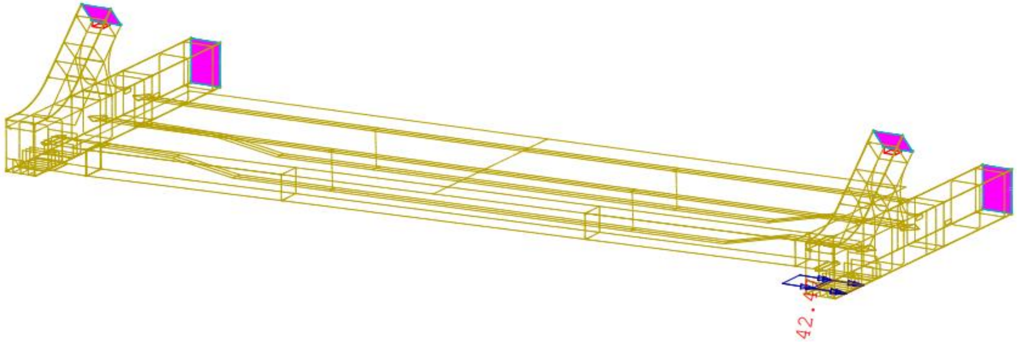
Force at Bearing Location: Px



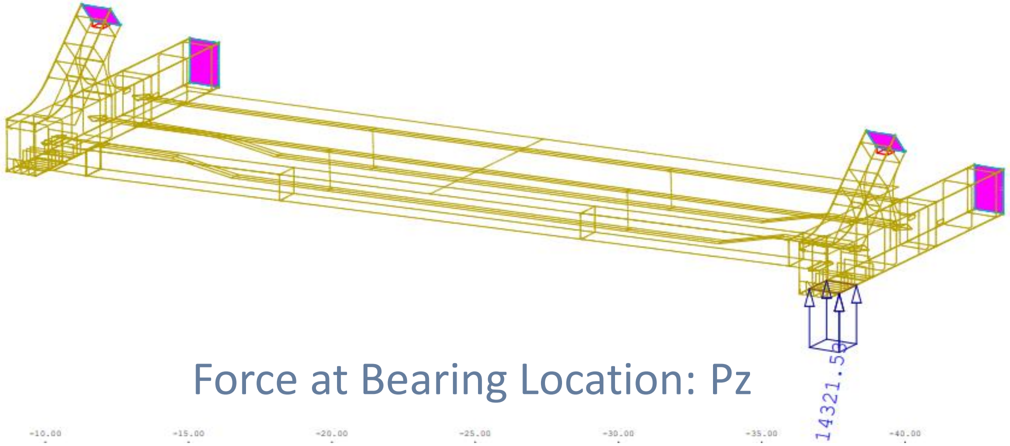
Force at Bearing Location: Mxx



Force at Bearing Location: Py



Force at Bearing Location: Myy

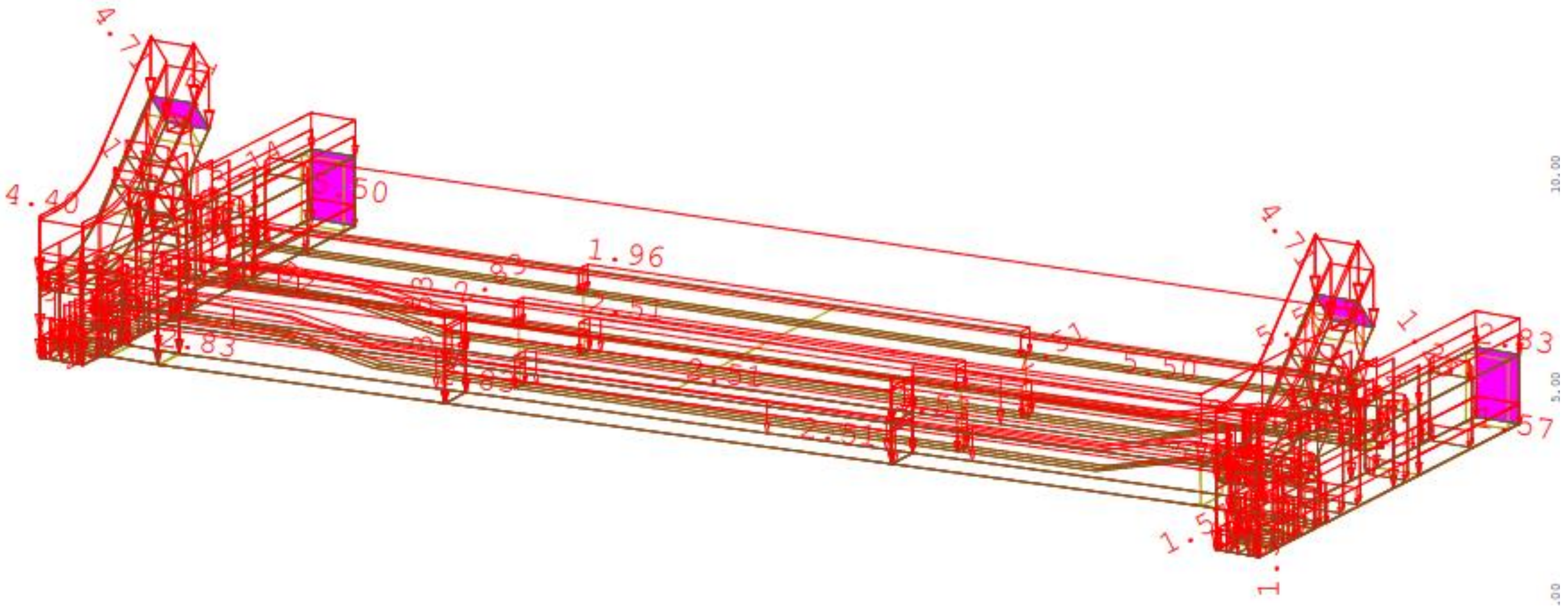


Force at Bearing Location: Pz

** (Mzz value is ignored as it is relatively small.)*

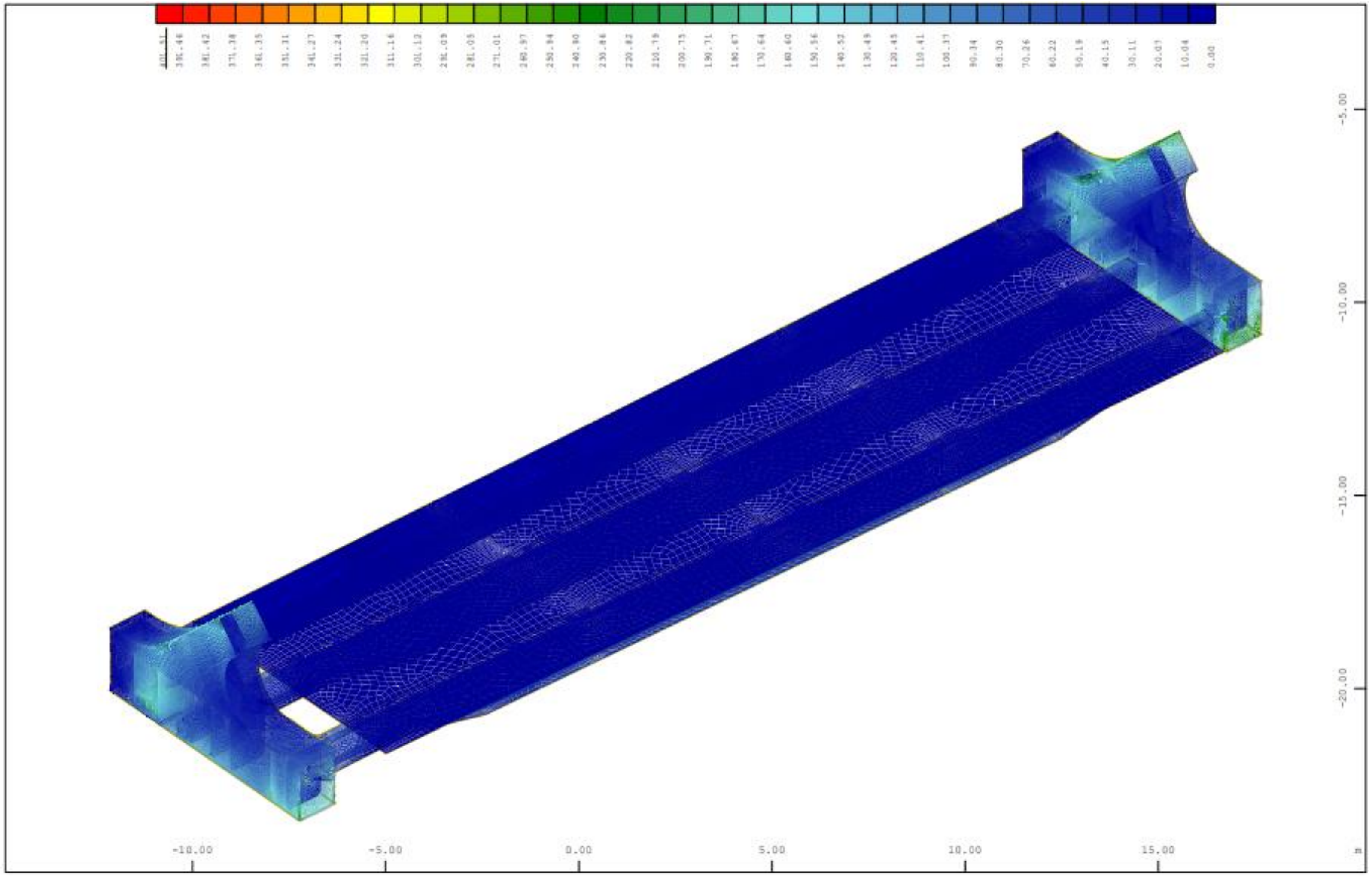
Bowstring Girder Bridge - Design Challenges

Self Weight of Modeled Structure:



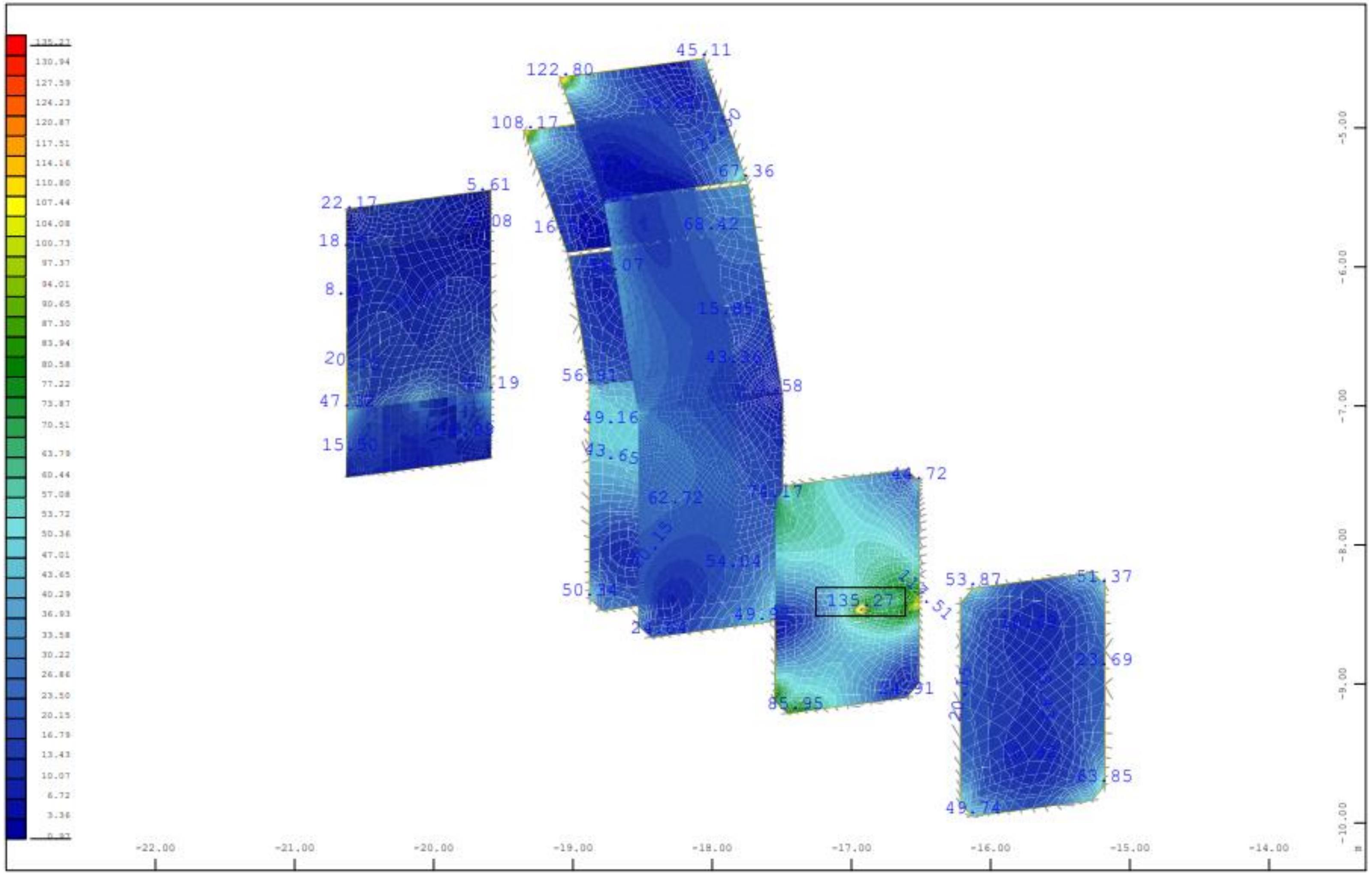
- Self Weight of modeled part is Activated.
- All the Individually applied loads are combined during Analysis and values of maximum Stress at different components/locations are obtained.

Bowstring Girder Bridge - Design Challenges



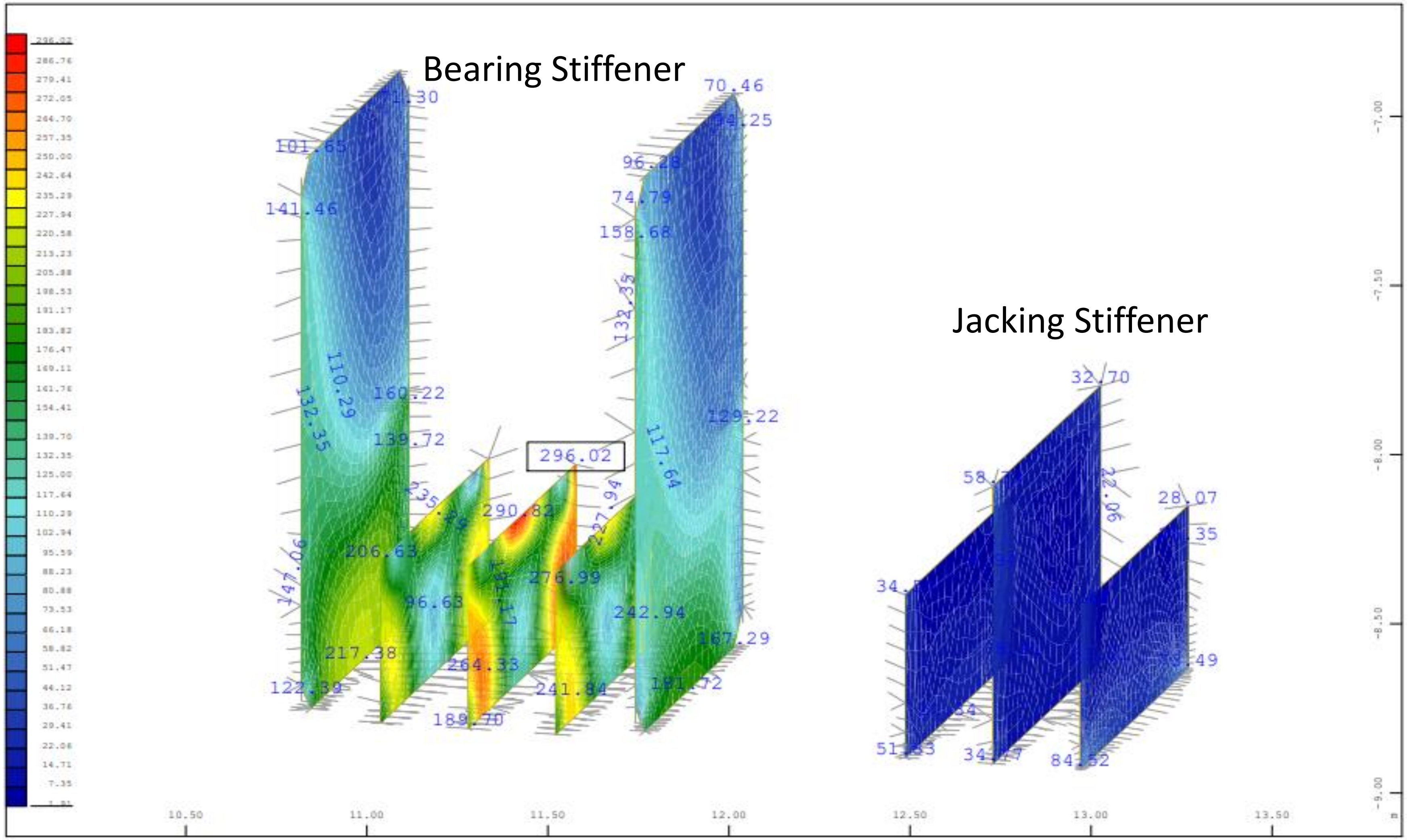
Overall Stress in Model

Bowstring Girder Bridge - Design Challenges



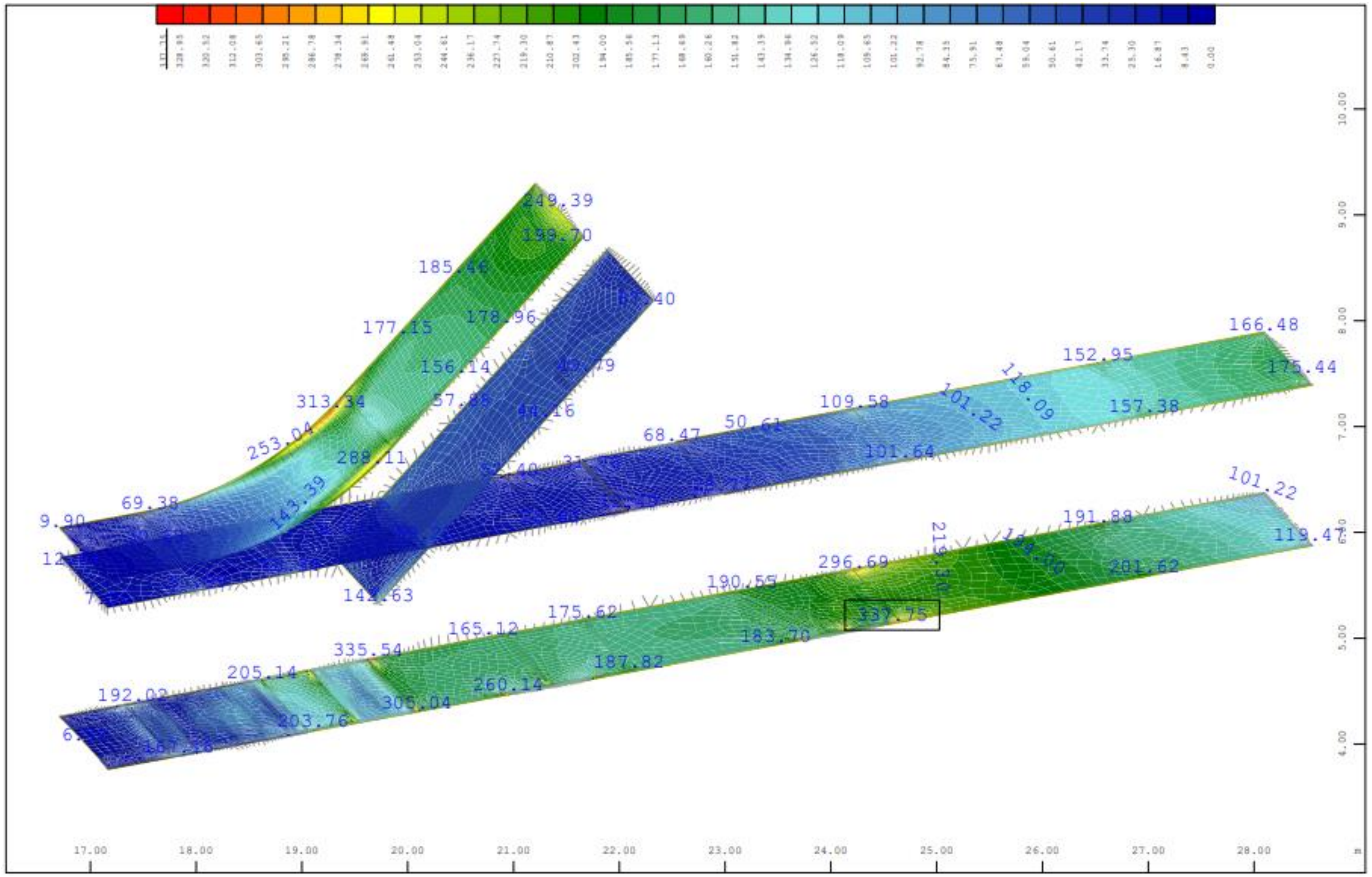
Stress in Diaphragm Stiffeners

Bowstring Girder Bridge - Design Challenges



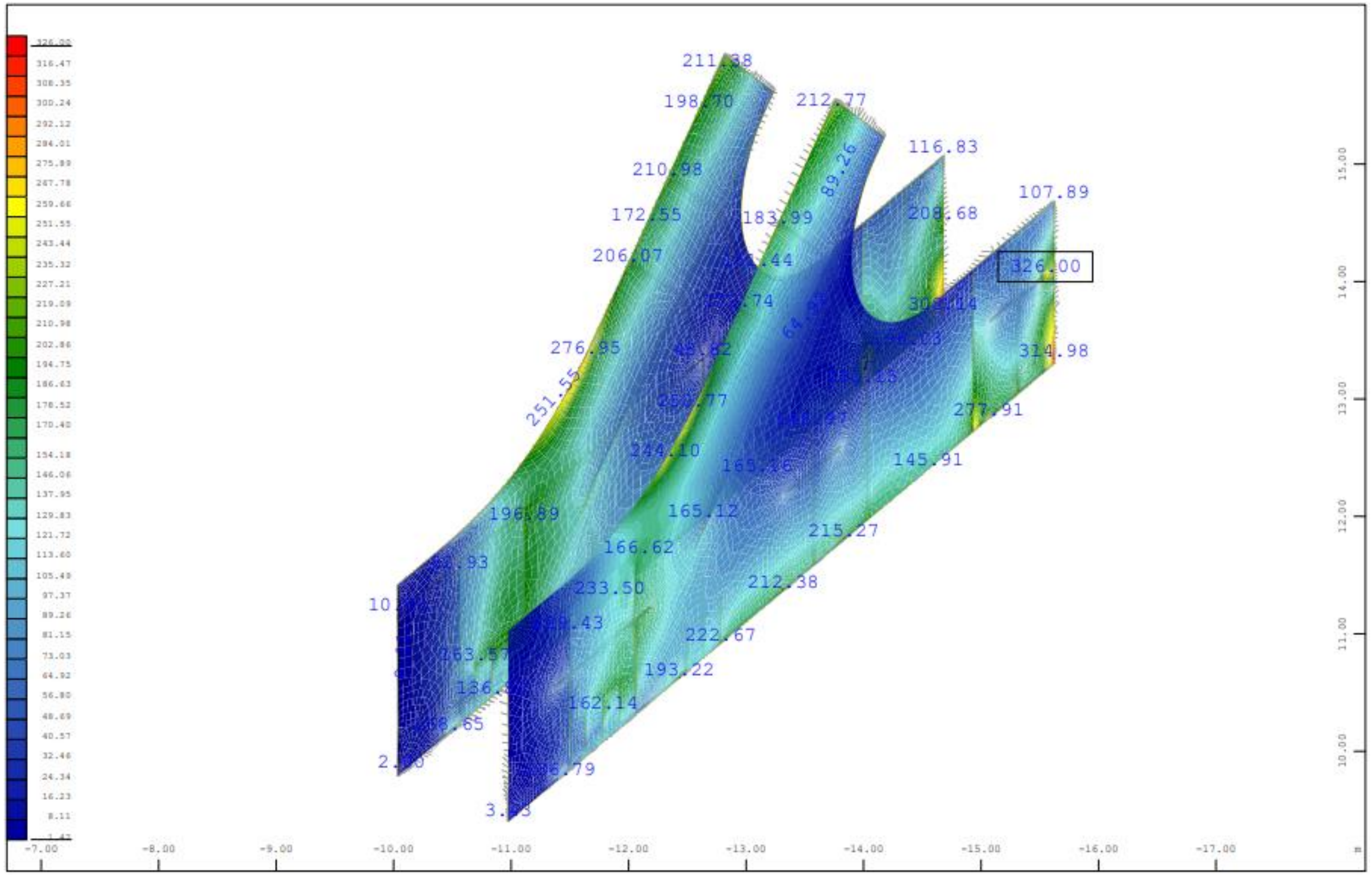
Stress in Bearing and Jacking Stiffeners

Bowstring Girder Bridge - Design Challenges



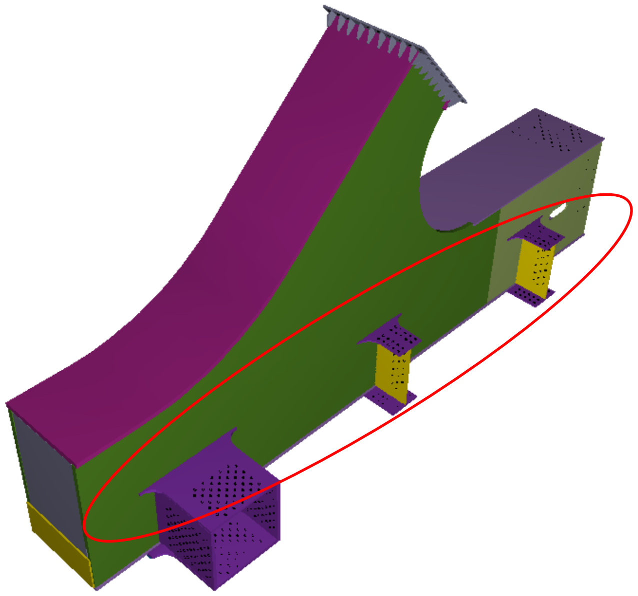
Stress in Top & Bottom Flanges

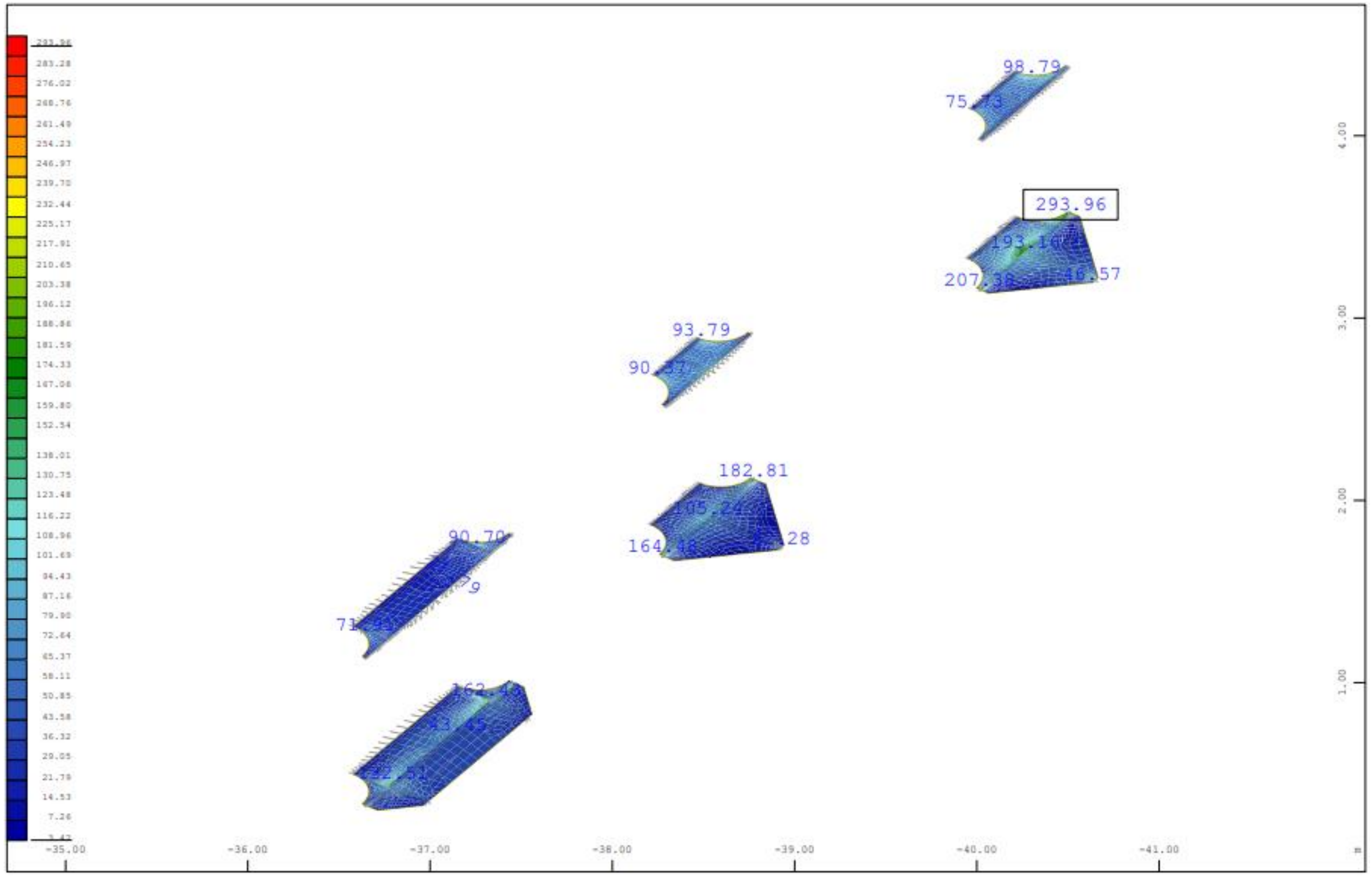
Bowstring Girder Bridge - Design Challenges



Stress in Webs

Bowstring Girder Bridge - Design Challenges





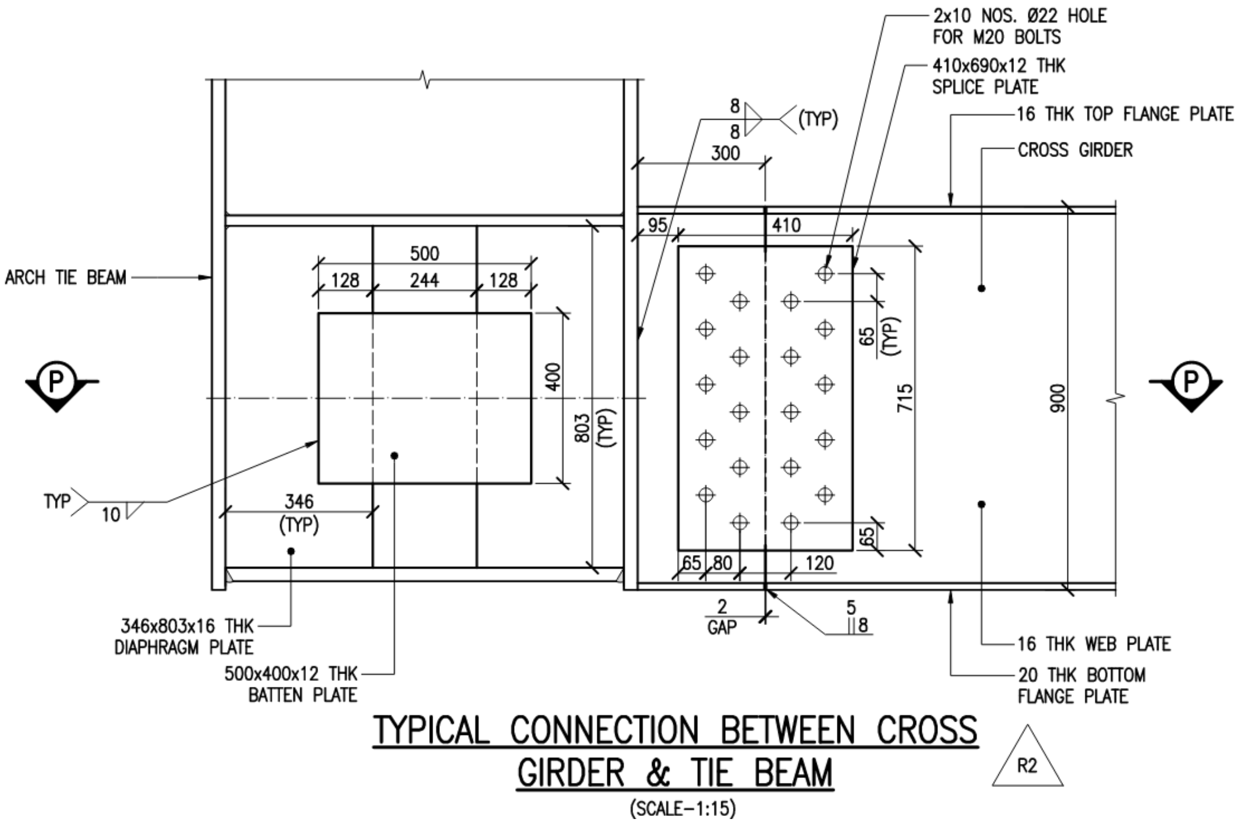
Stress in Connection plates between End Segment and Bottom Cross Girder

Bowstring Girder Bridge - Design Challenges

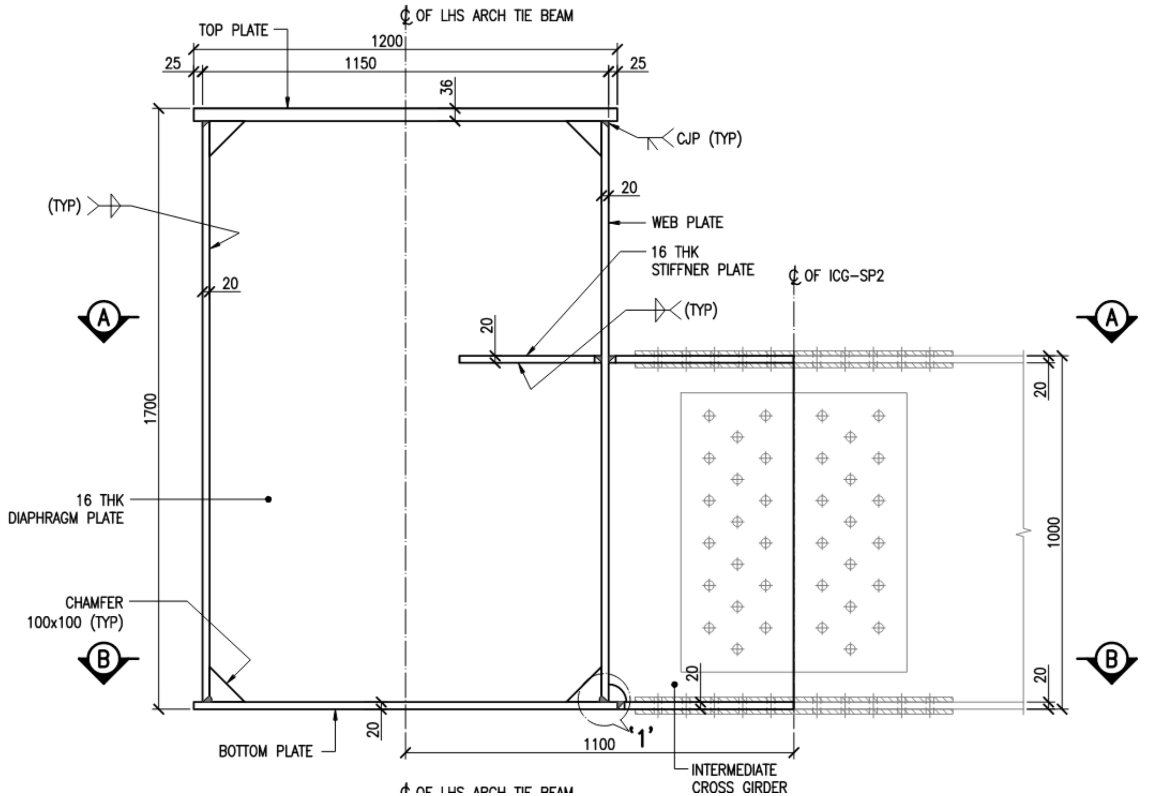
Proper Connection Details

Bowstring Girder Bridge - Design Challenges

Cross girder to Tie Beam connections

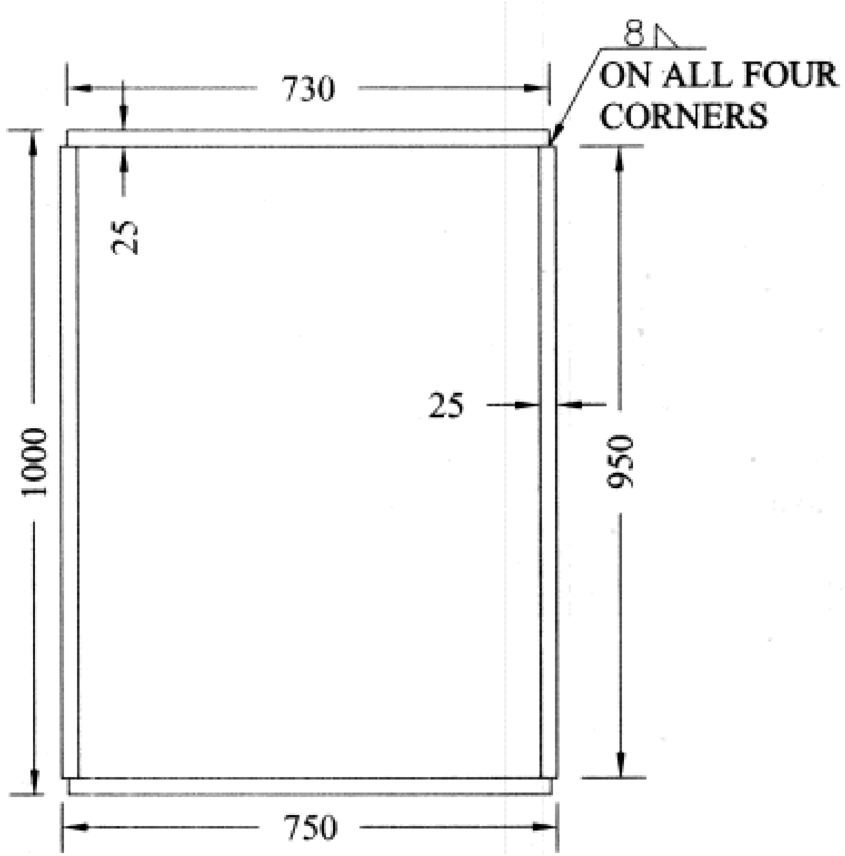


SHEAR CONNECTION

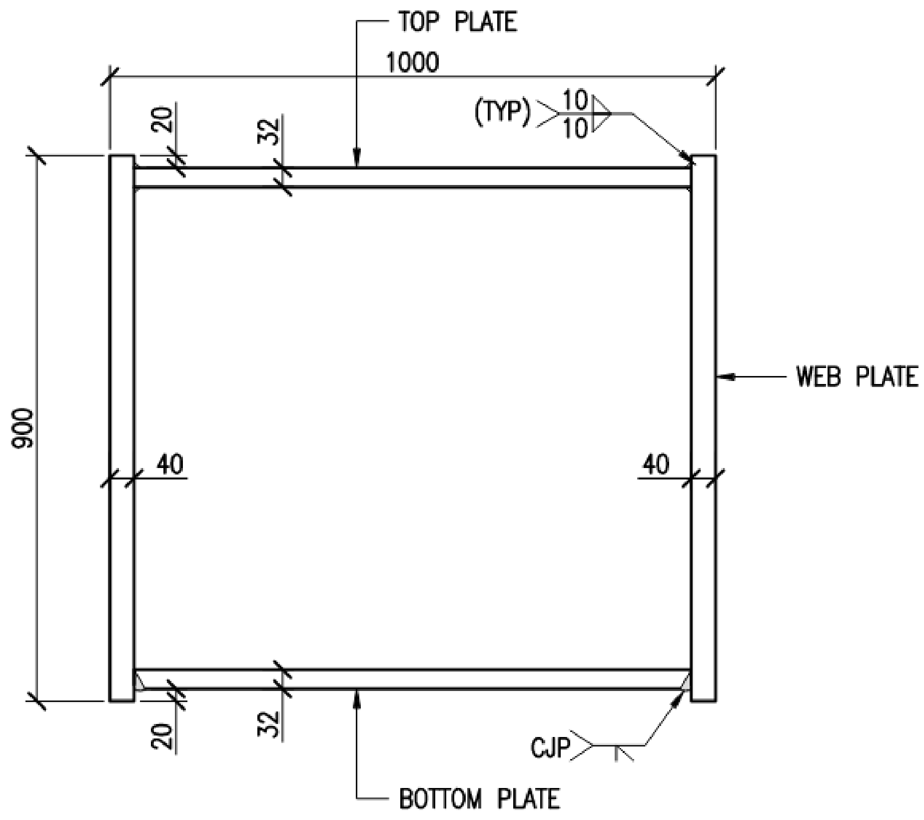


MOMENT CONNECTION

Bowstring Girder Bridge - Design Challenges



NOT GOOD DETAILING W.R.T WELDING



BETTER DETAILING W.R.T WELDING

Bowstring Girder Bridge - Design Challenges

Hanger to Tie beam Connection Failure

FAILURE OF HANGER CONNECTION DUE TO DELAMINATION OF WELD OWING TO IMPROPER DETAILING

Thank You