

# Cross section and geometry optimization of steel truss arch bridges based on internal forces

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**Abstract.** The purpose of this study is to obtain the optimum geometric design and cross section member element of steel arch bridges. It is necessary because the geometric design of the steel truss arch bridges have the direct impact to the steel section used in the structures. Therefore, steel section have the impact to the economic value of the bridge design due to the structure weight. There are many important variables have to be considered in the bridge design. Rise to span ratio variable is the major variable in the arch bridge geometric design. Arch bridge structures rely on the axial force capacity of the main arch, whereas shear forces and bending moments as secondary consideration. The optimization process is done by collecting the axial force, shear force and bending moment data of each steel arch bridge numeric model, and scaling its value from 0 to 1 to compare the data of every span in the same field, in order to achieve the optimum rise to span ratio. Rise to span ratio data of steel arch bridges in China and Japan used as the comparison with the result of this study, due to their brief history and rich experiences on arch bridge engineering innovation, and also have the large of amount of steel arch bridges. The results of this study give the optimum value of rise to span ratio between 1/4 to 1/7. It has good correlation with the rise to span ratio data of steel arch bridges in China and Japan i.e. 1/4 - 1/6 and 1/5 - 1/7 respectively.

## 1 Introduction

There are many variables to be considered in choosing geometric design of steel truss arch bridges. Rise to span ratio is an important variable of geometric design which has direct impact to the structural behavior, structure total weight, support reaction and element member cross section.

For greater value of rise to span ratio, the arch structures will behave such as columns, whereas for smaller value will behave such as beams.

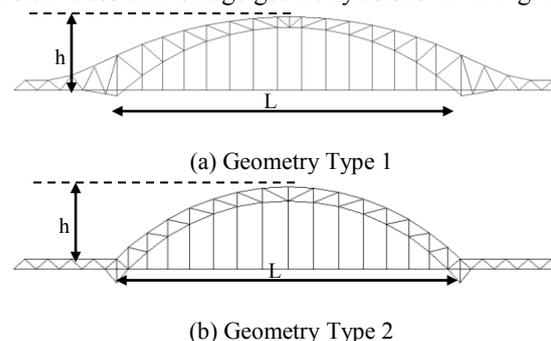
It affects the internal forces that occur along to main arch structure. Internal forces which was mentioned earlier are axial forces, shear forces and bending moments. Therefore, based on that preliminary explanation this optimization is done by reviewing the internal forces that occurs along to main arch structure of the bridges.

Bridges with a rise to span ratio value, either large or small, have their respective advantages and disadvantages. In this study will be discussed the relation of rise to span ratio variable to the total weight of the bridges. Therefore, it is required a value of rise to span ratio in which the steel truss arch bridge can be considered as the optimum design.

## 2 Steel Arch Bridge Geometry

A steel truss arch bridges is a type of bridge that rely on the axial capacity of its main structure in the form of an arch structure. The main structure of this arch bridge as the name implies, is a truss composed of short to longer members of axial structures that support and transfer an axial load to the foundation, and only carry a little bending moment [1].

This optimization intended for commonly used type of steel truss arch bridge geometry as shown in Fig. 2.1.



**Fig. 1.** Commonly used type of steel truss arch bridge geometry

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Steel truss arch bridges with geometry Type 1 are more widely used because of their superiority on its aesthetic aspect. Bridges with arches as in geometry Type 2 are more often used on bridge types with the arch structure located below the deck.

Chen, et al (2013) describes the rise to span ratio is one of the important parameters in the design consideration of steel truss arch bridges. The steel truss arch bridges in China has a rise to span ratio value distributions between 1: 2 to 1: 8, but mostly from 1: 4 to 1: 6. While the ratio of existing steel arch bridges in Japan has the rise to span ratio value distribution range from 1: 3 to 1: 9, mostly from 1: 5 to 1: 7. Very steep or very sloping ration values (close to 1: 8 or 1: 3) are usually applied to arch bridges with short span [2].

Steel truss arch bridges with geometry Type 1 are applied to some arch bridges, as shown from Fig. 2 and Table 1.



**Fig. 2.** Chaotianmen Bridge (552 m) Chongqing, Cina [3]

**Table 1.** Steel truss arch bridge with geometry Type 1 [4]

Bridge Name	Span (m)
Chaotianmen Bridge	552
Bridge of the Americas	344
Laviolette Bridge	335
Silver Jubilee Bridge	330
Wanzhou Railway Bridge	360

Arch bridges with geometry Type 2 can be used for arch bridges with the type of arch structure below the deck or above the bridge deck. The application of the geometry Type 2 arch bridge is shown in Fig. 3 and Table 2.



**Fig. 3.** Birchenough Bridge (329 m) Manicaland Province, Zimbabwe [4]

**Table 2.** Steel truss arch bridge with geometry Type 2 [4]

Bridge Name	Span (m)
New River Gorge Bridge	518
Sydney Harbour Bridge	503
Danlinghe Bridge	400
Hiroshima Airport Bridge	380
Birchenough Bridge	329
Glen Canyon Dam Bridge	313

### 3 Geometry Optimization Method

The process of geometry optimization is done with help of SAP2000 software, by changing rise to span ratio parameter to get the structural behaviour of main structure. Bridge modeling is carried out for spans of 150 m, 200 m, 250 m and 300 m in each geometry. Each span on each geometry is modeled for each rise to span ratio, starting from a ratio of 1/2.25 to 1/8.00 with intervals of 1/0.25.

The type of steel section used to model the bridge is limited to only the Wide Flange (WF) steel section as the main member elements, and the hollow pipe steel section as bracing elements. Load input in the modeling includes the service load in accordance with SNI 1725: 2016.

Permit deflection variable and P-M ratio variable are the constraint applied to bridge model, in purpose to achieve the efficient section. P-M ratio variable as strength constraint in scale 0 to 1 set between the value 0.6 to 0.9, in order to get not too wasteful but also not to risky of section capacity usage. On the other hand, permit deflection variable as service constraint set to  $L / 240$  with L as length of main span.

**Table 3.** The main span of the Type 1 arch bridge in Indonesia[5]

Bridge name	Span (m)
Kutai Kartanegara Baru	270
Teluk Masjid	250
Muara Sabak	200

**Table 4.** The main span of the Type 2 arch bridge in Indonesia[5]

Bridge name	Span (m)
Tayan	280
Rumbai Jaya	150
Batanghari II	150
Ogan Pelengkung	160
Kalahien	200
Rumpiang	200
Mahakam Ulu	200

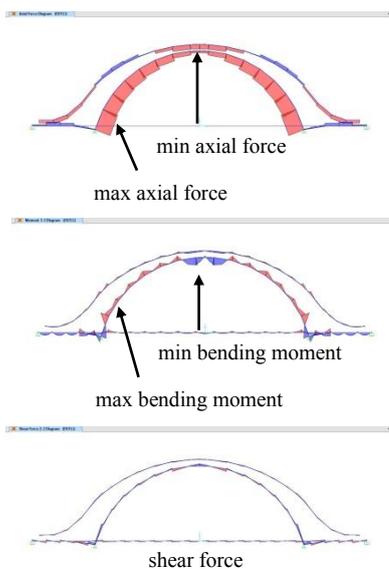
Bojonegoro	128
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Selection of span from 150 m to 300 m based on the existing bridge spans in Indonesia, as shown in Table 3 for bridges with geometry Type 1, and Table 4 for bridges with geometry Type 2.

#### 4 Geometry Design Optimization Result

There are 96 models for each geometry consisting of bridges with rise to span ratio from 1/2.25 to 1/8.00. The results of numeric model analysis are presented in chart to see occurred patterns. The internal forces that reviewed are internal forces (axial force, shear force, bending moment) occurring on main element of arch as main structure of arch bridge.

The method used for collect required data by calculating the magnitude of difference between largest and smallest internal force that occurred in main structure of the arch as shown in Fig. 4.



**Fig. 4.** Steel truss arch bridge NFD, BMD and SFD

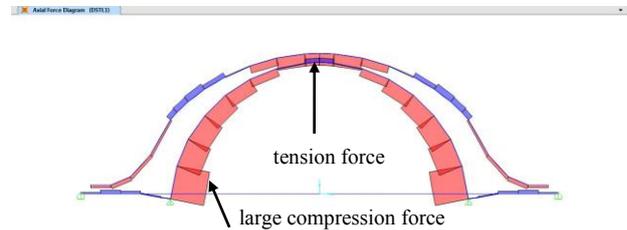
The maximum and minimum force difference values obtained for each span and each rise to span ratio value is plotted on one chart for each span by scaling the force value that occurs with the range of values 0-1. The result are charts with rise to span ratio value as abscissa and internal forces occurring on the bridge as ordinate, the arch bridge with the geometry Type 1 as shown to Fig. 7 to Fig. 10, and on bridges with geometry Type 2 as shown in Fig. 11 to Fig. 14, includes:

- Rise to span ratio value to axial force
- Rise to span ratio value to shear force
- Rise to span ratio value to bending moment

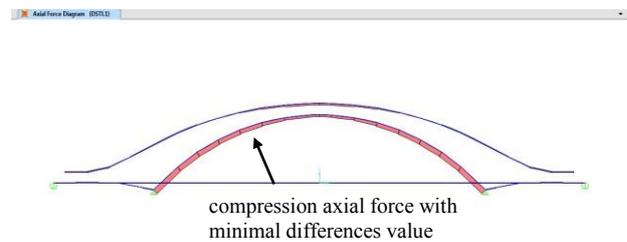
Position of the optimum point is set when NFD value starts flat (no longer having significant fluctuations). It means, differences gap between maximum value and minimum value from that point until certain point is almost constant.

For example, a curved bridge with rise to span ratio of 1 / 2.25 has NFD as shown in Fig. 5. The behavior of

the arch in main span of the bridge on upper side bears the tension axial load, while on lower side bears a very large compression axial load. So the section selection is based on the need of a very large compression axial force that occurs on the lower side of the arch. Therefore, due to structural behaviour such as those occurring on bridges with rise to span ratio of 1 / 2.25 are considered not optimum.

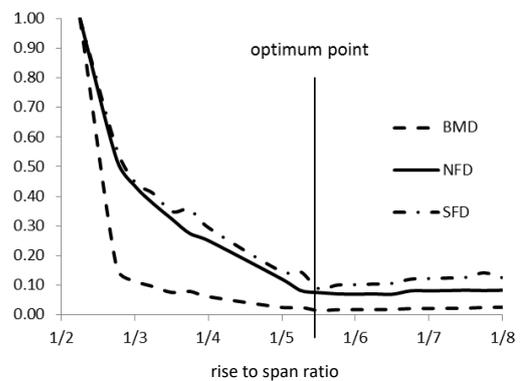


**Fig. 5.** Steel truss arch bridge NFD (rise to span ratio 1/2.25)

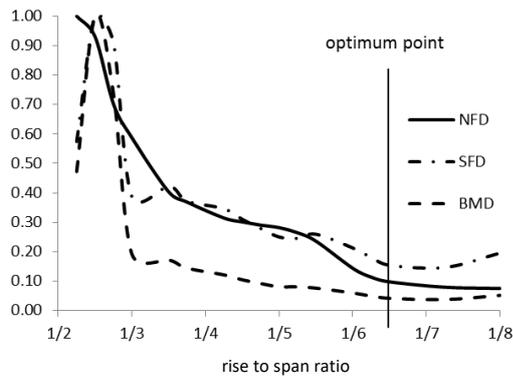


**Fig. 6.** Steel truss arch bridge NFD (rise to span ratio 1/5.50)

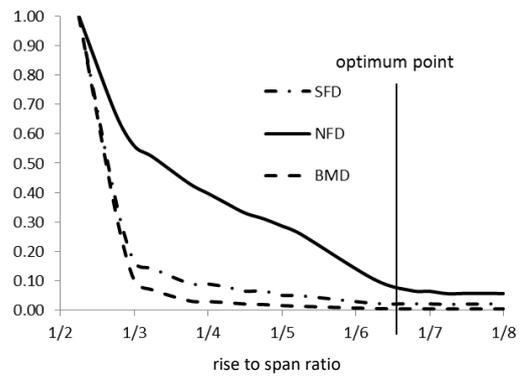
On the other hand, a bridge with rise of span ratio of 1/5.50 has NFD behavior pattern as shown in Fig. 6. The axial force that occurs entirely is compression axial force. The gap between maximum and minimum axial is a little. So the section selection based on the greatest compression axial force needs becomes efficient for all frames along the arch.



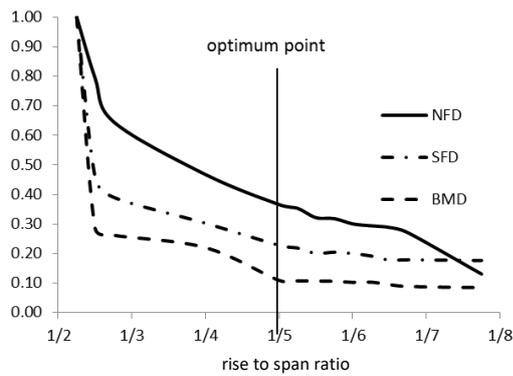
**Fig. 7.** Maximum and minimum force differences value of spans 150 m geometry Type 1



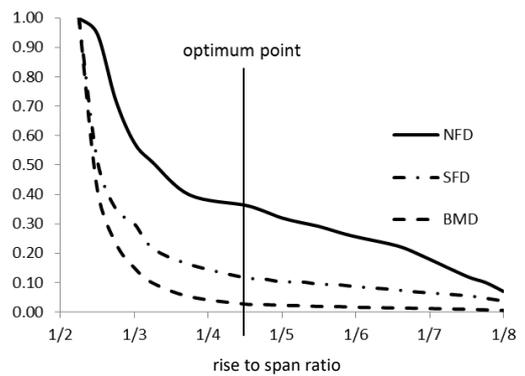
**Fig. 8.** Maximum and minimum force differences value of spans 200 m geometry Type 1



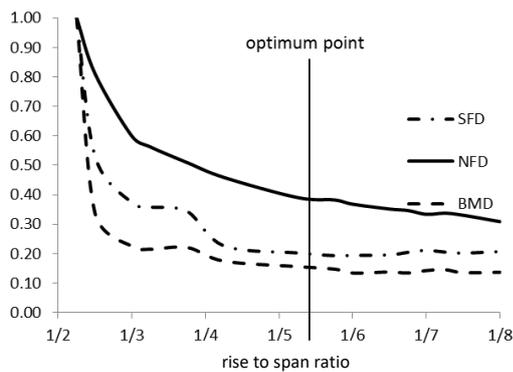
**Fig. 12.** Maximum and minimum force differences value of spans 200 m geometry Type 2



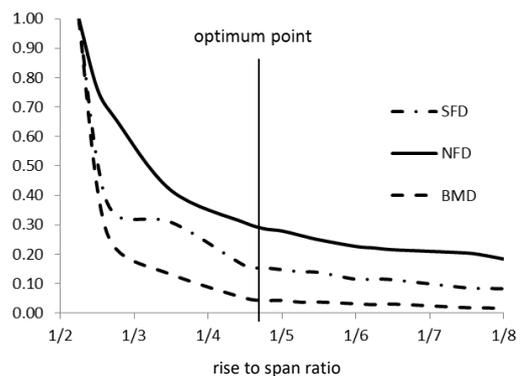
**Fig. 9.** Maximum and minimum force differences value of spans 250 m geometry Type 1



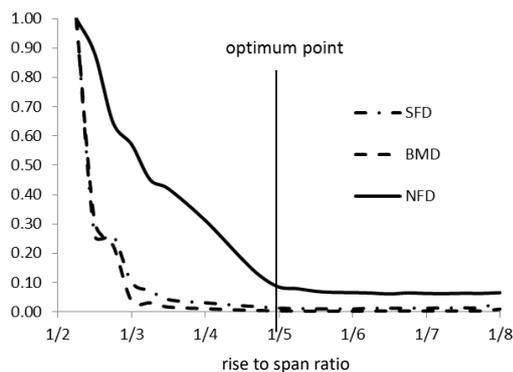
**Fig. 13.** Maximum and minimum force differences value of spans 250 m geometry Type 2



**Fig. 10.** Maximum and minimum force differences value of spans 300 m geometry Type 1



**Fig. 14.** Maximum and minimum force differences value of spans 300 m geometry Type 2



**Fig. 11.** Maximum and minimum force differences value of spans 150 m geometry Type 2

**Table 5.** Summary of geometry 1 analysis results

No	Span	Optimum rise to span ratio
1	150 m	1 : 5,50
2	200 m	1 : 6,50
3	250 m	1 : 5,00
4	300 m	1 : 5,50

Based on chart in Fig. 5 until Fig. 8 can be obtained the position of optimum rise to span ratio based on internal force values. As presented in Table 5 the

optimum rise to span ratio for bridge geometry Type 1 is between 1 / 5.00 until 1 / 6.00.

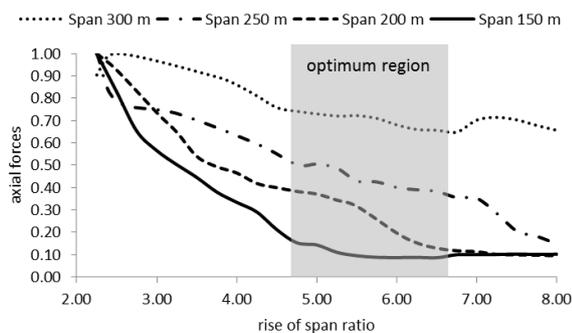
**Table 6.** Summary of geometry Type 2 analysis results

No	Span	Optimum rise to span ratio
1	150 m	1 : 5,00
2	200 m	1 : 6,50
3	250 m	1 : 4,50
4	300 m	1 : 4,75

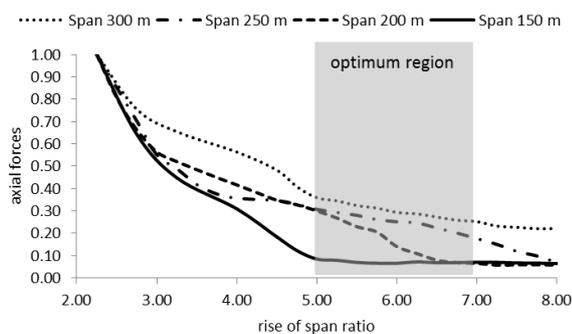
Based on chart in Fig. 11 until Fig. 14 can be obtained the position of optimum rise to span ratio based on internal force values. As presented in Table 6 the value of optimum rise to span ratio for bridge geometry Type 2 is between 1/4.50 until 1/6.50.

Refer to summary discussed in Table 5 and Table 6 can be concluded that the geometry design of optimum steel truss arch bridge is achieved with rise to span ratio in range from 1/4.00 to 1/7.00.

The next method by calculating the standard deviation of axial force values that occurred on each main structure of the bridge. Results are as shown in Fig. 15 and Fig. 16. The results obtained from this method are similar to the previous method, i.e. rise to span ratio value between 1/4.50 to 1/6.50 for geometry Type 1 and 1/5.00 to 1/7.00 for geometry Type 2.



**Fig. 15.** Rise to span ratio to standard deviation of axial force for geometry Type 1



**Fig. 16.** Rise to span ratio to standard deviation of axial force for geometry Type 2

The results has good correlation with the existing steel arch bridge data as shown in Table 7 for steel arch

bridges in Japan and Table 8 for steel arch bridges in China. Chen, et al (2013) describes the rise to span ratio of steel arch bridges, most of the bridges in Japan using value between 1/5 to 1/7 and between 1/4 to 1/6 for China.

**Table 7.** Rise to span data of steel arch bridges on Japan [2]

Rise ratio	Number
1/10-1/9	8
1/9-1/8	30
1/8-1/7	85
1/7-1/6	401
1/6-1/5	217
1/5-1/4	72
1/4-1/3	13
1/3-1/2	5

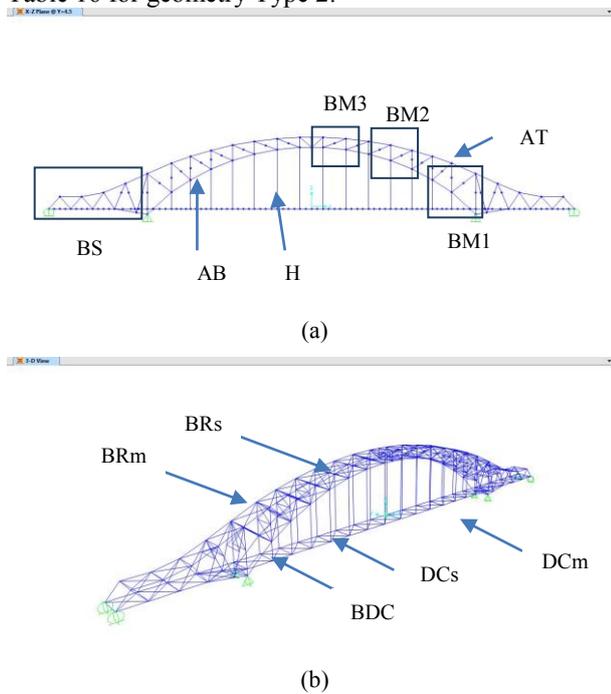
**Table 8.** Rise to span data of steel arch bridges on China [2]

Rise ratio	Number
1/8-1/6	5
1/6-1/5	10
1/5-1/4	18
1/4-1/3	11

## 5 Cross Section Optimization Results

The cross section optimization is performed by issuing P-M ratio between 6.00 to 9.00 and L/ 240 as maximum permit deflection. Optimization performed by accommodating the environmental load i.e. earthquake load, load temperature and wind load.

The dominant load on the arch bridge is the axial compression load, therefore the buckling factor becomes important thing to be considered in the design of the main arch structures. With pre-defined design limits, obtained the optimum steel cross section as shown in Table 9 to Table 12 for geometry Type 1 and Table 13 to Table 16 for geometry Type 2.



**Fig. 17.** Grouping of geometry Type 1 bridge element

The result of cross section optimization is defined by group of element as shown in Fig. 17.

**Table 9.** Steel cross section of arch bridge span 150 m geometry Type 1

No	Element group	Steel Section
1	Arch Bottom (AB)	WF 1800.400.20.40+2.20 *)
2	Arch Top (AT)	WF 1000.500.14.25
3	Deck Main Girder (DCm)	WF 1000.500.14.20
4	Deck Secondary Girder (DCs)	WF 392.400.10.16
5	Deck Bracing (BDC)	Pipe 323,9x6
6	Hanger (H)	Pipe 406,4x6
7	Arch Bracing Side (BS)	WF 450.400.10.20
8	Arch Bracing 1 (BM1)	WF 1000.500.16.30
9	Arch Bracing 2 (BM2)	WF 350.300.7.10
10	Arch Bracing 3 (BM3)	WF 304.300.7.10
11	Lateral Arch Bracing (BRm)	WF 304.300.7.10
12	Diagonal Arch Bracing (BRs)	Pipe 355,6x6

Note:  
\*) The steel section is customized from steel section  
WF 1200.400.20.40

**Table 10.** Steel cross section of arch bridge span 200 m geometry Type 1

No	Element group	Steel Section
1	Arch Bottom (AB)	WF 1800.600.16.36+2.16 *)
2	Arch Top (AT)	WF 1200.600.14.25
3	Deck Main Girder (DCm)	WF 1000.500.14.25
4	Deck Secondary Girder (DCs)	WF 400.400.8.14
5	Deck Bracing (BDC)	Pipe 377x6
6	Hanger (H)	Pipe 457x6
7	Arch Bracing Side (BS)	WF 600.400.10.25
8	Arch Bracing 1 (BM1)	WF 1000.500.14.25
9	Arch Bracing 2 (BM2)	WF 350.350.8.12
10	Arch Bracing 3 (BM3)	WF 400.250.6.10
11	Lateral Arch Bracing (BRm)	WF 304.300.7.10
12	Diagonal Arch Bracing 1 (BRs1)	Pipe 406,4x6
13	Diagonal Arch Bracing 2 (BRs2)	Pipe 244,5x5
14	Diagonal Arch Bracing 3 (BRs3)	Pipe 355,6x6

Note:  
\*) The steel section is customized from steel section  
WF 1200.600.16.36

**Table 11.** Steel cross section of arch bridge span 250 m geometry Type 1 m

No	Element group	Steel Section
1	Arch Bottom (AB)	WF 1800.600.16.36+2.16 *)
2	Arch Top (AT)	WF 1200.600.16.36
3	Deck Main Girder (DCm)	WF 1200.600.14.25
4	Deck Secondary Girder (DCs)	WF 392.400.10.16
5	Deck Bracing (BDC)	Pipe 406,4x6
6	Hanger (H)	Pipe 610x6
7	Arch Bracing Side (BS)	WF 1000.500.14.25
8	Arch Bracing 1 (BM1)	WF 1000.500.16.30
9	Arch Bracing 2 (BM2)	WF 300.250.8.12
10	Arch Bracing 3 (BM3)	WF 304.300.7.10
11	Lateral Arch Bracing (BRm)	WF 300.300.8.12
12	Diagonal Arch Bracing 1 (BRs1)	Pipe 508x6
13	Diagonal Arch Bracing 2 (BRs2)	Pipe 508x6
14	Diagonal Arch Bracing 3 (BRs3)	Pipe 508x6

Note:  
\*) The steel section is customized from steel section  
WF 1200.600.16.36

**Table 12.** Steel cross section of arch bridge span 300 m geometry Type 1

No	Element group	Steel Section
1	Arch Bottom (AB)	WF 1800.600.16.36+2.16 *
2	Arch Top (AT)	WF 1800.600.16.36+2.16 *
3	Deck Main Girder (DCm)	WF 1800.600.16.36+2.16 *
4	Deck Secondary Girder (DCs)	WF 400.400.8.14
5	Deck Bracing (BDC)	Pipe 377x6
6	Hanger (H)	Pipe 1120x10
7	Arch Bracing Side (BS)	WF 1750.500.20.36
8	Arch Bracing 1 (BM1)	WF 1800.400.20.40+2.20 **)
9	Arch Bracing 2 (BM2)	WF 350.350.8.12
10	Arch Bracing 3 (BM3)	WF 1500.400.16.36 ***)
11	Lateral Arch Bracing (BRm)	WF 300.300.8.12
12	Diagonal Arch Bracing 1 (BRs1)	Pipe 478x6
13	Diagonal Arch Bracing 2 (BRs2)	Pipe 478x6
14	Diagonal Arch Bracing 3 (BRs3)	Pipe 478x6

Note:  
 \*) The steel section is customized from steel section WF 1200.600.16.36  
 \*\*) The steel section is customized from steel section WF 1200.400.20.40  
 \*\*\*) The steel section is customized from steel section WF 1000.400.16.36

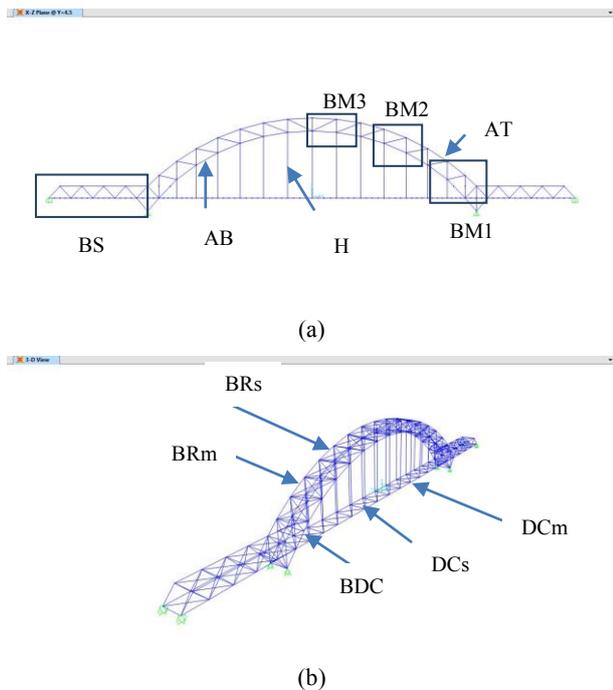
**Table 13.** Steel cross section of arch bridge span 150 m geometry Type 2

No	Element group	Steel Section
1	Arch Bottom (AB)	WF 1200.600.16.36
2	Arch Top (AT)	WF 1200.600.14.25
3	Deck Main Girder (DCm)	WF 400.400.8.14
4	Deck Secondary Girder (DCs)	WF 350.350.8.12
5	Deck Bracing (BDC)	Pipe 630x15
6	Hanger (H)	Pipe 478x6
7	Arch Bracing Side (BS)	WF 450.400.10.20
8	Arch Bracing 1 (BM1)	WF 392.400.10.16
9	Arch Bracing 2 (BM2)	WF 350.300.7.10
10	Arch Bracing 3 (BM3)	WF 400.400.8.14
11	Lateral Arch Bracing (BRm)	WF 304.300.7.10
12	Diagonal Arch Bracing (BRs)	Pipe 377x6
13	Top Chord Truss (TT)	WF 1000.500.14.25

**Table 14.** Steel cross section of arch bridge span 200 m geometry Type 2

No	Element group	Steel Section
1	Arch Bottom (AB)	WF 1800.600.16.36*)
2	Arch Top (AT)	WF 1200.600.16.36
3	Deck Main Girder (DCm)	WF 500.300.8.16
4	Deck Secondary Girder (DCs)	WF 500.300.8.16
5	Deck Bracing (BDC)	Pipe 478x6
6	Hanger (H)	Pipe 660x6
7	Arch Bracing Side (BS)	WF 600.400.10.25
8	Arch Bracing 1 (BM1)	WF 400.400.20.32
9	Arch Bracing 2 (BM2)	WF 304.300.7.10
10	Arch Bracing 3 (BM3)	WF 400.400.8.14
11	Lateral Arch Bracing (BRm)	WF 304.300.7.10
12	Diagonal Arch Bracing (BRs)	Pipe 406,4x6
13	Top Chord Truss (TT)	WF 1200.600.16.36

Note:  
 \*) The steel section is customized from steel section WF 1200.600.16.36



**Fig. 18.** Grouping of geometry Type 2 bridge element

The result of cross section optimization is defined by group of elemen as shown in Fig. 18.

**Table 15.** Steel cross section of arch bridge span 250 m geometry Type 2

No	Element group	Steel Section
1	Arch Bottom (AB)	WF 1500.500.16.36+2.16 *)
2	Arch Top (AT)	WF 1800.500.20.40
3	Deck Main Girder (DCm)	WF 700.400.12.30
4	Deck Secondary Girder (DCs)	WF 400.400.8.14
5	Deck Bracing (BDC)	Pipe 406,4x6
6	Hanger (H)	Pipe 1120x10
7	Arch Bracing Side (BS)	WF 1000.500.16.30
8	Arch Bracing 1 (BM1)	WF 1750.500.20.36**)
9	Arch Bracing 2 (BM2)	WF 450.400.10.20
10	Arch Bracing 3 (BM3)	WF 600.400.10.25
11	Lateral Arch Bracing (BRm)	WF 350.350.8.12
12	Diagonal Arch Bracing (BRs)	Pipe 478x6
13	Top Chord Truss (TT)	WF 1750.500.20.36+2.20 **)

Note:  
 \*) The steel section is customized from steel section WF 1000.500.16.36  
 \*\*) The steel section is customized from steel section WF 1100.500.20.36

**Table 16.** Steel cross section of arch bridge span 300 m geometry Type 2

No	Element group	Steel Section
1	Arch Bottom (AB)	WF 1800.600.16.36+2.16 *)
2	Arch Top (AT)	WF 1000.500.16.30
3	Deck Main Girder (DCm)	WF 1000.500.14.20
4	Deck Secondary Girder (DCs)	WF 400.400.8.14
5	Deck Bracing (BDC)	Pipe 40,4x6
6	Hanger (H)	Pipe 1420x11
7	Arch Bracing Side (BS)	WF 1200.600.14.30
8	Arch Bracing 1 (BM1)	WF 1800.500.20.40**)
9	Arch Bracing 2 (BM2)	WF 600.400.10.25
10	Arch Bracing 3 (BM3)	WF 600.400.12.30
11	Lateral Arch Bracing (BRm)	WF 350.350.8.12
12	Diagonal Arch Bracing (BRs)	Pipe 610x6
13	Top Chord Truss (TT)	WF 1800.600.16.36+2.16 *)

Note:  
 \*) The steel section is customized from steel section WF 1200.600.16.36  
 \*\*) The steel section is customized from steel section WF 1200.500.20.40

While the deflections that occurred on the bridges are limited to the value of permitted deflection as shown in Table 17.

**Table 17.** Deflection that occurs on each bridge

Bridge Type	Maximum deflection	Permitted deflection
150 m geometry 1	0,167173 m	0,625 m
200 m geometry 1	0,305088 m	0,833 m
250 m geometry 1	0,437252 m	1,041 m
300 m geometry 1	0,578353 m	1,250 m
150 m geometry 2	0,233771 m	0,625 m
200 m geometry 2	0,325484 m	0,833 m
250 m geometry 2	0,357741 m	1,041 m
300 m geometry 2	0,594752 m	1,250 m

## 6 Conclusions

- The method used for geometry optimization can be used as one of the methods for optimizing bridge rise to span ratio since optimization results show a value that is quite relevant to existing bridge.
- Steel truss arch bridge with geometry Type 1 has an optimum rise to span ratio between 1/5.00 to 1/6.00.
- Steel truss arch bridge with geometry Type 2 has an optimum rise to span ratio between 1/4.50 to 1/6.50.

This research can be continued to span bridges longer than 300 m using same method to obtain a more precise pattern, that can be used for steel truss arch bridges with spans longer than 300 m.

## 7 References

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