

UNIVERSITY OF BAHRAIN

College of Engineering



Department of Civil
Engineering

Optimum Design of Geometrically Nonlinear Suspended and Curved Pedestrian Bridges Using Swarm Intelligence Techniques

A Thesis Submitted in Partial Fulfillment of the Requirements for the M.Sc.
Degree in Civil Engineering

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- ☐ Without making any changes to the thesis.
- ☒ After making the modifications attached with this decision.

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Abstract

This study aims to achieve the optimum design of a curved footbridge hanging by a curved arch. For this purpose, the design of the I-4 Maitland pedestrian bridge located in the Florida was considered, and the structural of the footbridge was modeled using SAP2000. Once it is designed, the structure members are classified into seven groups per their functionality and modality for carrying the design loads; however, these groups are designated as standard W-section, hollow structural sections (HSS), cables and pipe sections.

The optimization uses the cross-sectional area of the classified sections as variables due to their effect on the overall weight of the footbridge structure and their criteria are evaluated by AASHTO / AISC standards. Three metaheuristic algorithms are used in the optimization process which are: learning-based optimization teaching algorithm (TLBO), artificial bee colony algorithm (ABC), and differential evolution algorithm (DE). The MATLAB software is used for maintaining optimization process, along with API SM toolbox considering it as a translator between SAP2000 and MATLAB.

The results show that the DE algorithm is best optimizer for the design as the design weight was reduces up to 27.79% of its initial weight in just 11.59 days, while the ABC algorithm reaches 33.86% in 21 days and the TLBO algorithm reaches 27.79%. taking 30.5 days.

Dedication

To my parents and family

Acknowledgments

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Abbreviations

AASHTO	American Association of State Highway and Transportation Officials.
ABC	Artificial Bee Colony.
AISC	American Institute of Steel Construction.
API	Application Programming Interface.
ASCE	American Society of Civil Engineers.
CO ₂	Carbon Dioxide.
CSI	Computers and Structures Incorporation.
DE	Differential Evolution.
GA	Genetic Algorithm.
HSS	Hollow Structure Sections
LRFD	Load and Resistance Factor Design.
NSA	Navy Federal Credit Union.
NSGA	Non-Dominated Sorting Genetic Algorithm.
OAPI	Open Application Programming Interface.
TLBO	Teaching-Learning-Based-Optimization.
UFC	Unified Facilities Criteria.

CHAPTER ONE

INTRODUCTION

Chapter 1 Introduction

1.1 Background

Pedestrian bridges or footbridges are a part of road projects where it's required to overpass obstacles such as rivers, seas, railways, and valleys. In ancient times, they were made by laying a few stones in the river, or fallen trees were used for this purpose, but now they have become massive steel and concrete structures. In a contest with highway or railway bridges, footbridges serve lighter loads as they carry pedestrians, bikes, or equestrians.



Figure 1-1 The Rothay River (Wikipedia, 2022)

1.2 Types of Footbridges

Many types of footbridges are used in today's cities, and their classification is related to their structural system. The type of footbridges used in practice falls into one of the following groups. (Bigrentz, 2021)

1. Beam/Girder footbridges.
 2. Truss footbridges
 3. Cantilever footbridges
 4. Arch footbridges
 5. Suspension footbridges
 6. Cable-Stayed footbridges
1. **Beam/Girder Footbridges** are the simplest type of all bridges. It is yet the least expensive to assemble. The used structural elements could be hollow box-section steel or reinforced concrete. All that is needed to construct this type of footbridge is to provide two piers at both sides of the span and place

the girder on top of these piers. However, this type of footbridge has limitations in the span that could be reached up to 80 m as a maximum.



Figure 1-2 Somers Town Beam Bridge, London (SteelConstruction.info, n.d.)

2. **Truss Footbridges:** the footbridge deck is held by trusses which are large panels consisting of members connected by pins or hinges, creating a sequence of triangle shapes to achieve sufficient rigidity and stability for the structure.



Figure 1-3 Footbridge Tremerje (Laško), Slovenia (Ponting, n.d.)

3. **Cantilever Footbridges:** They are considered a tremendous structural engineering breakthrough. The cantilever footbridge is a large span held by one of its ends, and the other is a commonly suspended span (no support beneath).



*Figure 1-4 Puente de la Mujer, Puerto Madero, Argentina
(BA@turismo Buenos Aires, n.d.)*

4. **Arch Footbridges:** It is one of the footbridges types that depend on the compression principle. It is considered the oldest type of all footbridge since it was built in the Roman ages using stones and rocks. Recently, this concept has been evaluated to hang the bridge deck instead of carrying the bridge deck above the arch, as in Figures 1-5 and 1-6.



Figure 1-5 Riverfront Park Minto Island Bridge in Salem Oregon (gettyimages, n.d.)



Figure 1-6 Alcántara Bridge, Spain (DIPUTACION DE CACERES, n.d.)

5. **Suspension Footbridges:** These bridges consist of two main cables attached to supports placed at the footbridge's ends, as shown in Figure 1-7.



Figure 1-7 Eagle Canyon, Canada (Eagle Canyon Adventures, n.d.)

6. **Cable-Stayed Footbridges:** These bridges consist of two main cables attached to supports placed at the footbridge's ends, as shown in Figure 1-7..



Figure 1-8 Christina and John Markey Memorial Pedestrian Bridge, Revere, Massachusetts (Duncan Galvanizing, 2018)

Besides these mentioned types, there are other kinds of footbridges, whether fixed, temporary, or movable, as shown in Figure 1-9.



Figure 1-9 Million-Eye bridge Gateshead, United Kingdom (Gateshead Council, n.d.)

1.3 Footbridges Design

“AASHTO LRFD Guide Specifications For Design Of Pedestrian Bridges” is a standard provided by AASHTO to serve pedestrian bridge design requirements. The design code specifies the constraints of limit states,

serviceability, vibration, and constructability to fulfill safety, durability, user comfort, and aesthetics requirements

The design code takes a realism of the load's considerations, resistance components, connections, failure system based on previous cases, and inelastic behavior despite determination under elastic analysis; the following equation is used for obtaining the load values for designing footbridges.

$$\sum \eta_i \gamma_i Q_i \leq \phi R_n \quad (1-1)$$

in which:

$$\eta_i = \eta_D \eta_R \eta_I \geq 0.95 \text{ for } \gamma_i \text{ maximum} \quad (1-2)$$

$$\eta_i = \frac{1}{\eta_D \eta_R \eta_I} \leq 1.0 \text{ for } \gamma_i \text{ minimum} \quad (1-3)$$

where:

η_i is the load modifier according to the η_D ductility, η_R redundancy, η_I functional classification, γ_i is a load factor multiplied by the force effects, Q_i is the force effect, ϕ is a resistance factor based on the nominal resistance and R_n is the slight resistance.

LRFD provides a guide for pedestrian bridges where lighter loads are carried (compared to highway bridges). So, the desired loads that shall be assigned,

- ✓ Dead load, such as self-weight of the structure and non-structure (safety rail, fence, etc...)
- ✓ Live load same as bicycles, pedestrians, and equestrians.
- ✓ Wind load considering its speed, all critical directions, and surrounding topography.

Over and above, these design loads are evaluated by combinations, defined in AASHTO standards as per all statuses that can probably be influenced in the desired structure, and in this thesis is used the following combinations are:

- Strength I: The essential load combination can be excited due to bridge normal users (live loads).

$$\gamma * D.L + \gamma * L.L \quad (1-4)$$

- Strength III: The load combination can be happened due to wind load influence.

$$\gamma * D.L + \gamma * W.L \quad (1-9)$$

Gamma is a factor defined in Table 3.4.1-1 in AASHTO LRFD.

1.4 Optimization

Optimization aims to obtain the best product, whether minimizing the cost or maximizing production efficiency while satisfying certain constraints. The general mathematical formulation of structural optimization problems is as follows.

$$\text{Minimize } (W) = \sum f(x_i) \quad i=1, 2, 3, \dots, n. \quad (1-10)$$

Under inequality constraints:

$$g_j(x_i) \leq 0 \quad j=1, 2, 3, \dots, m. \quad (1-11)$$

Where W is the objective function that shall be minimized, and $g_j(x_i)$ are the constraints. x_i is the design variable, almost taken as the steel cross-section areas, and they are limited by the interval $[x_i^l, x_i^u]$. The design variables may be discrete or continuous in another meaning; they could be integer values (discrete) or actual values (continuous). The continuous values are obtained if the sections are built up or manufactured locally (no standard measurements or dimensions). In contrast, the discrete values are determined from the standard international

sections catalog, where the steel profiles are listed by serial name or number. The design variable boundaries are set to limit the used sections or values in the optimization to save time and decrease the available probability of possible combinations.

The algorithms that determine the solution to optimization problems available in the literature are divided into a couple of distinct types:

- a) **Deterministic Algorithms**: they are suitable for engineering design problems since a specific formula obtains the solutions.
- b) **Stochastic Algorithms**: they are a kind of probabilistic translation rule that led to gain popularity due to specific properties.

The design variables are generally the cross-sectional properties of steel profiles in the optimum design of steel structures. Any structural design should satisfy the design code provisions. The provisions are included in the mathematical formulation of the optimum design problem as constraints. The constraints are classified into two types; inequality and equality constraints. The inequality constraints are stated due to greater or smaller than limitation values. In contrast, equality constraints are related to the values of a resource value that is usually hard to achieve. The mathematical formulation of the optimum design of steel structures according to a steel design code generally yields a discrete programming problem. Because the steel profiles for the members of the steel structure must be selected from a catalog. Metaheuristic algorithms are shown to efficiently resolve such combinatorial optimization problems in the literature (Mona, 2019).

1.5 Metaheuristic Algorithms

Meta and heuristic are a couple of Greek words and mean higher level to find, to know beyond (Lazar, 2013). Every metaheuristic algorithm uses a local search upon a global search tradeoff in some way. Moreover, randomization is

frequently used to achieve a diversity of solutions. These algorithms are also referred to as stochastic algorithms that include global exploration and randomization (Gandomi, Yang, Talatahari, & Alavi, December 2013).

The metaheuristic goal is to identify a suitable, practical solution in a reasonable amount of time because the complexity of the problem makes it difficult to search through every possible answer or combination (Yang X. S., 2008).

There are many metaheuristic algorithms, but the ones used in this thesis are

1. **Artificial Bee Colony Optimization (ABC)**: is based on honey bees' behavior in searching for food.
2. **Teacher-Learning Based Optimization (TLBO)**: is obtained from the way of students in learning through teaching and studying with their colleagues.
3. **Differential Evolution (DE)**: develops new potential solutions using the variation in the solution vectors (Yang X. S., 2010).

Metaheuristic algorithms were developed for unconstrained optimization problems. However, engineering design problems are all constrained optimization problems. It becomes necessary to transform the constrained optimization problem into an unconstrained optimization problem using the penalty function method as given in the following equation.

$$\emptyset = Q \{1 + \alpha (\sum_{i=1}^n g_i)\} \quad (1-13)$$

Where $\emptyset$ the converted unconstrained equation, Q is the constraint equation, α is, a penalty constant and usually is equal to 1 and n is the number of used constraints in the problem (Saka & Aydogdu, Mathematical and metaheuristic applications in design optimization of steel frame structures: an extensive review., 2013).

g_i is computed as follows:

$$g_i = \begin{cases} 0, & g_i(\mathbf{x}) \leq 0 \\ g_i(\mathbf{x}), & g_i(\mathbf{x}) > 0 \end{cases} \quad (1-14)$$

Where $g_i(\mathbf{x})$ is the normalized expression of each constraint. If the i^{th} constraint is satisfied at the design point under consideration, then g_i is taken as zero; if not, g_i is equal to whatever the value of the regulation. It should be emphasized that each constraint in the optimization problem is needed to be normalized before the metaheuristic algorithm is applied. Normalization is made by dividing each constraint by its allowable value, as shown in equation 1.6

$$g_i(\mathbf{x}) = \frac{\text{constraint } i}{\text{its allowable bound}} - 1 < 0 \quad (1-15)$$

1.6 Research Questions

- What is the procedure for designing a horizontal curve footbridge based on the I-4 Maitland footbridge's old concept?
- What are the optimum sections of horizontal curve footbridge structure members?

1.7 Research Objective

- Design the old concept of the I-4 Maitland pedestrian bridge in Florida according to provisions of AASHTO LRFD Guide Specifications.
- Achieve an eligible safe optimum design for the mentioned pedestrian bridge as per AISC360-16 specifications.
- Evaluate the reliability of each algorithm executed in the research.

1.8 Research Method

The design optimization of suspended and curved pedestrian bridges may be performed in several stages. Initially, the I-4 Maitland pedestrian bridge is a 100 m long curved steel frame deck carried by a 120 m span arch. The arch is inclined 20 degrees from normal and its height is 24.5m. the bridge will be modeled in SAP 2000, a structural analysis program developed by Computers and

Structures, Berkeley, USA. The design loads are assigned as stated in AASHTO LRFD for the Design of Pedestrian Bridges. Suspended structures are geometrically nonlinear which be respected during analysis. The response of the bridge by using linear elastic analysis will not reflect the actual behavior of the structure for suspended structures. Accordingly, the geometric nonlinearity of the structure should be considered in the structural analysis. SAP2000 has a facility for carrying out analysis of geometrically nonlinear structures. After completion of the structural modeling and analysis of the bridge structure in SAP2000, optimization algorithms are developed by using MATLAB. The optimum design problem of the suspended and curved bridge, when formulated by taking the cross-sectional properties of its members as design variables and implementing the design constraints from the AASHTO LRFD design specification and AISC-360-2016, is a discrete programming problem. Recent reviews have shown that swarm intelligence techniques are efficient in obtaining the solution to such optimization problems (Saka, Dogan, & Aydogdu, Analysis of swarm intelligence-based algorithms for constrained optimization, 2013).

It is intended to use contemporary swarm intelligence techniques to solve the optimum design problem of the suspended and curved pedestrian bridge. Among these, the artificial bee colony algorithm (ABC), Teaching and Learning-Based Optimization (TLBO), and Differential Evolution (DE) are the ones that are employed in the study. These algorithms update design variables in every design cycle according to some phenomena. For example, the bridge members' cross-sectional properties are changed, its behavior under the external load would also change. Therefore, there is a need for new analysis. This will be achieved using the application programming interface (API) syntaxes. This facility provides a connection between the MATLAB program written and SAP. It allows the flow of data in both directions. Iterations will be continued until convergence criteria are attained.

1.9 Research Value

Optimizing a curved suspended pedestrian bridge is a challenging task. Such bridges need nonlinear analysis to predict their response to external loading, which is a complicated and iterative procedure. On top of this, the optimum design of such bridges is more complex than pedestrian bridges with straight geometry. Therefore, in this thesis, an algorithm will be developed by which it will be possible to obtain the optimum design of suspended and curved plane pedestrian bridges. This is a profound contribution to the creation of such structures. The impact of using such an algorithm is that it will be possible to construct the bridge using the minimum amount of steel material by attaining the optimum design. This will contribute to sustainability. Because steel production contributes significant amounts of CO₂ emission to the atmosphere and any reduction in the use of steel certainly helps sustainability. This thesis brings additional value to this research study.

1.10 Literature Review

Due to the specific character of the bridge design challenge, the topic of bridge optimization did not receive as much attention in the literature as building structures did in previous decades; thus, the footbridge does not have many researchers in design or optimization design. In addition, bridge design and analysis involve a lot of time and work, which makes the trial-and-error procedure in the design stage monotonous. However, the conventional optimization techniques used at the time were ineffective, and the reason the issue requires that many discrete variables be chosen from design Tables (Saka & Aydogdu, Mathematical and metaheuristic applications in design optimization of steel frame structures: an extensive review., 2013) & (Rana, Islam, Ahsan, & Ghani, 2013).

1.10.1 Cable-Stayed Footbridge:

In 2021, Atmaca optimized a cable-stayed footbridge using MATLAB for optimization and SAP2000 in the structural analyzing process via an open applicable Programming Interface (OAPI). The desired footbridge structure consists of a couple of 13 m towers holding a 32m main bridge deck and a 14.3 m side deck. Optimization aims to get the total weight of the structure and find the optimum adequate post-tensioning force of the cable using the JAYA metaheuristic algorithm. The total weight is reduced by 66.7% with a deflection of 58.02mm. This reduction in total weight makes up 88% of the steel capacity used to carry the static load of the footbridge instead of 25% (Atmaca, 2021).

1.10.2 Multi-Objective Optimization of Polyester-Rope and Steel-Rope Suspended Footbridges

In 2015, Edward M., Landolf Rhode, Sigrid-A., and Rajan D. did an optimization design for a suspended footbridge to compare polyester and steel ropes. Two configurations are assumed for the structure design in which a suspended rope hangs the footbridge. In another case, it is supported by a suspended rope with a vertical stayed rope in its center. These configurations for each string are studied under two points of rope status; prestressed and unprestressed. The optimization is carried out with two objective functions: maximizing the ropes/bridge span and minimizing its volume respecting static and natural frequency constraints as per AASHTO standards. The optimization is executed through a non-dominated sorting genetic algorithm (NSGA-II). Although the proposed sections of both ropes failed to meet the 64m span footbridge requirements, the polyester rope manifests its levity against steel rope. Consequently, it is easier to dispatch and cheaper to purchase. (Segal, Barbarigos, Adriaenssens, & Coelho, 2015)

1.11 Research Outlines

The research will be explained in detail in the sequence of the following:

- a) **Chapter one, “Introduction,”** explains the research aim and procedure and a few literature reviews about the optimum design of the footbridge shortly.
- b) **Chapter two, “Footbridge Design and Model,”** briefs the modeling procedure of the bridge and assigning external loads respecting AASHTO and AISC standards.
- c) **Chapter three, “Optimization Approach Procedure,”** describes the whole design optimization process for the bridge.
- d) **Chapter four, “Results & Discussion,”** shows all obtained results and discusses all information about them and their quality.
- e) **Chapter five, “Conclusion,”** summarizes the thesis, and further research could be done in the future.

CHAPTER TWO
FOOTBRIDGE DESIGN
AND MODEL

Chapter 2 Footbridge Design and Model

2.1 Introduction:

In 2014, a suspended curved pedestrian bridge project was decided to build over Interstate 4 at Maitland in Florida State, US (Figure 2.1). It was planned to be a landmark for Maitland, connecting sidewalks along Wymore Road and Lake Destiny Drive. The bridge was a bright idea for using bikes due to its length of more than 1.5 miles, which is too long for crossing by walking (Spear, 2019).



Figure 2-1 Maitland I-4 Pedestrian Bridge First Design Concept (Gillespie, 2017)

Unfortunately, later the design was changed to be a straight bridge (Figure 2-2) due to the problems expected in the construction phase of the bridge that might cause a delay in the realization of the bridge (FDOT, 2020). Therefore, in this study, the original design shown in Fig. 2-1 is considered a horizontally curved pedestrian bridge to optimize its structural members.



Figure 2-2 Maitland I-4 Pedestrian Latest Design Concept (FDOT, 2020)

2.2 Pedestrian Bridge Modeling Assumptions and Consideration:

The modeling is a challenging part of the thesis since the model depends on rendered photos, as shown in Figures 3-1 & 3-3, to realize the natural shape of the design concept. Therefore, some parameters and considerations were collected from websites and conversations of Maitland's Mayor "Dale McDonald" in press conversation (Spear, 2019).

The footbridge is a steel structure consisting of a 213.5m long deck with a 3.75 m width, which is mounted at 8m height, supported by an arch that is 24.5m height and is inclined by 200 from the vertical line. The arch is connected to the bridge deck through pairs of cables attached to 22 numbers of hexagons built-in with the bridge deck. The hexagons are distributed radially with a 4m center-to-center distance.

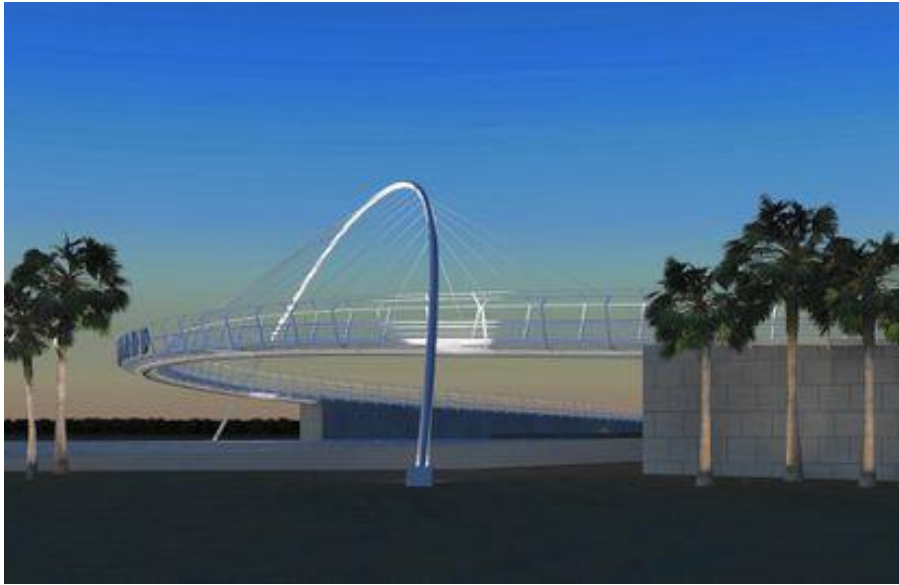


Figure 2-3 Rendered Photo of Maitland First Design (Bike/Walk Central Florida, 2014)

As per rendered photo in fig. 2-4, hexagons are modeled having 5-meter heights as shown in Figure 2.5 in which the bottom members are extended by 1 m to connect the lower cables while the upper cables are connected to 1/3 far from the top member of hexagons (Figure 2-6).



Figure 2-4 Rendered Photo of Maitland Bridge (crosswalk) (Bike/Walk Central Florida, 2014)

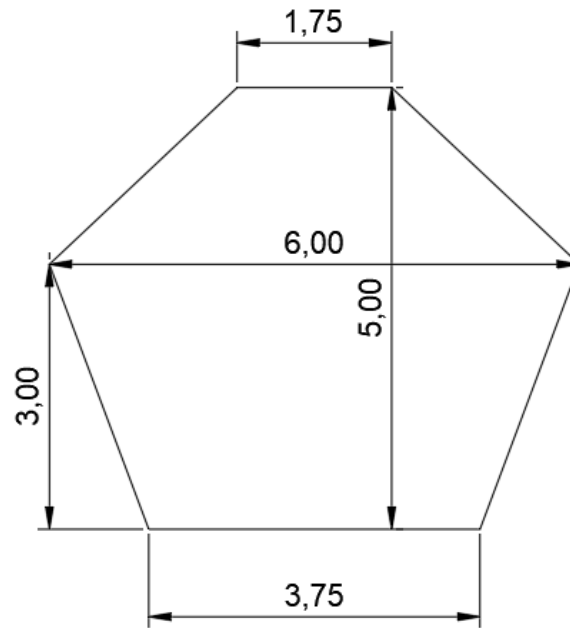


Figure 2-5 Dimensions Assumption of Hexagons

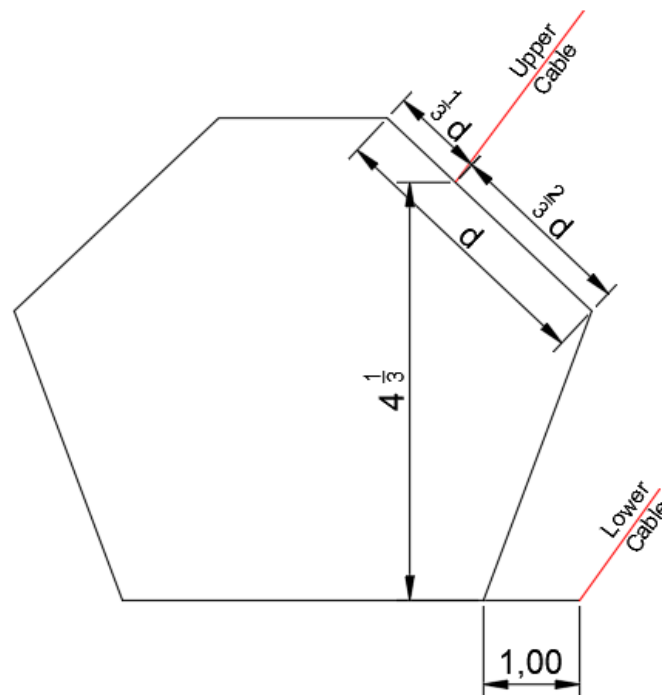


Figure 2-6 Assuming Locations of the Cables Connection

2.3 Pedestrian Bridge Modeling Procedures Using SAP2000:

2.3.1 Grid Lines Considerations:

The cylindrical grids are selected as it is more suitable for the shape of the footbridge. As per assumptions and considerations in section 3.2, the required grid lines are classified as in the following:

- 9 lines along the radial axis where:
 - The center line of the bridge.
 - 6 lines represent 6 corners of hexagon shapes.
 - Location line of bottom cable.
 - The arch line supports locations (assumption)
- 28 lines along theta axis where:
 - 22 lines for hexagon numbers.
 - 1 line for each bridge deck end.
 - 2 lines are far from each bridge deck end because their intersection points with the radial axis line mentioned above represent the support ends locations.
- 5 lines along Z-axis where:
 - 0 m for arch support level.
 - 8 m for the bridge deck level, the bottom member the of hexagon member.
 - 11 m for the intermediate level of hexagon corners.
 - $12\frac{1}{3}$ m for upper cable location with hexagons supports as in Figure 2-7.
 - 13 m for the top member of hexagons.

2.3.2 Grid Lines Calculations:

2.3.2.1 Lines along theta:

The bridge is assumed to be half-circle including its end ramps, and the arch length is calculated as:

$$L = r\theta^r \quad (3-1)$$

- where the arch length is L , the arch radius is r , and the angle of the arch is θ^r in radians.

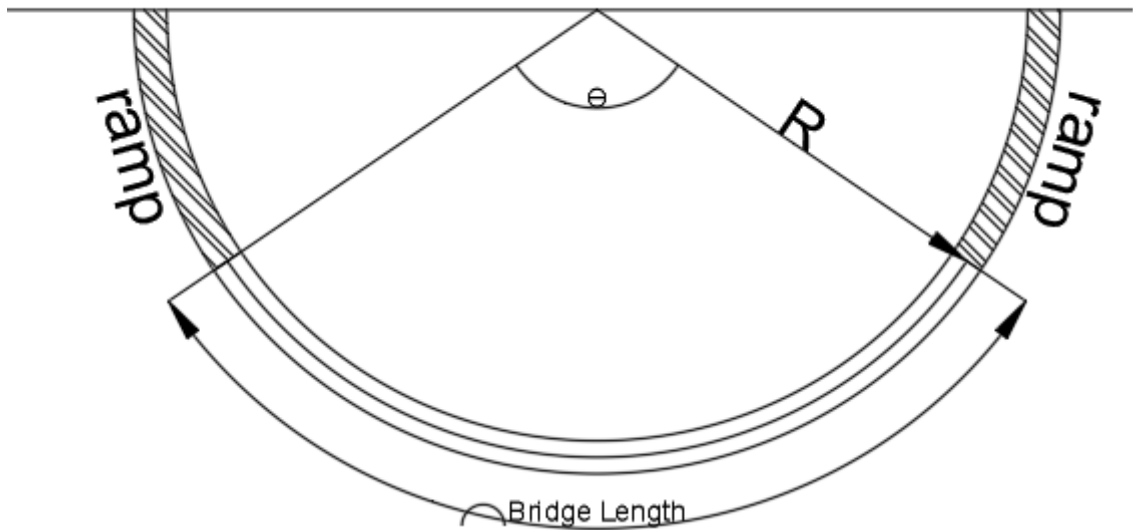


Figure 2-7 The footbridge deck geometry

Using equation (3-1) to obtain the radius of the bridge curve, $L=213.5m$, and $\theta^r = \pi$

$$r = \frac{213.5}{\pi} = 67.96 \simeq \underline{\underline{68 \text{ m}}}.$$

- Assuming the ramps end equals $113.5m$, the bridge deck length becomes $100m$ ($L_{arch}=100m$) long.

Using equation (3-1) again to obtain the angle of the bridge deck curve:

$$L=100 \text{ m and } r = 68m.$$

$$\theta^r = \frac{100}{68} = 1.471 \times \frac{180}{\pi} = 84.26^\circ \simeq 84^\circ.$$

As mentioned in section 3.3.1, 24 lines (23 slices) are required along theta for only the bridge deck. So, $\theta_{\text{bridge}} = \frac{84}{23} = 3.65^\circ \simeq 3.5^\circ$ (rounded to near 0.5); where θ_{bridge} is the slice angle.

- After adding four lines with the same angles at end of the bridge to locate the arch support as mentioned in section 3.3.1, the grid lines Table becomes as shown in the following.

Table 2-1 Grid Line of Theta Direction

TABLE: Grid Lines								
CoordSys	AxisDir	GridID	XRYZCoord	TAngle	LineType	LineColor	Visible	BubbleLoc
Text	Text	Text	m	Degrees	Text	Text	Yes/No	Text
GLOBAL	T	0		-3.5	Primary	Gray8Dark	Yes	End
GLOBAL	T	1		0	Primary	Gray8Dark	Yes	End
GLOBAL	T	2		3.5	Primary	Gray8Dark	Yes	End
GLOBAL	T	3		7	Primary	Gray8Dark	Yes	End
GLOBAL	T	4		10.5	Primary	Gray8Dark	Yes	End
GLOBAL	T	5		14	Primary	Gray8Dark	Yes	End
GLOBAL	T	6		17.5	Primary	Gray8Dark	Yes	End
GLOBAL	T	7		21	Primary	Gray8Dark	Yes	End
GLOBAL	T	8		24.5	Primary	Gray8Dark	Yes	End
GLOBAL	T	9		28	Primary	Gray8Dark	Yes	End
GLOBAL	T	10		31.5	Primary	Gray8Dark	Yes	End
GLOBAL	T	11		35	Primary	Gray8Dark	Yes	End
GLOBAL	T	12		38.5	Primary	Gray8Dark	Yes	End
GLOBAL	T	13		42	Primary	Gray8Dark	Yes	End
GLOBAL	T	14		45.5	Primary	Gray8Dark	Yes	End
GLOBAL	T	15		49	Primary	Gray8Dark	Yes	End
GLOBAL	T	16		52.5	Primary	Gray8Dark	Yes	End
GLOBAL	T	17		56	Primary	Gray8Dark	Yes	End
GLOBAL	T	18		59.5	Primary	Gray8Dark	Yes	End
GLOBAL	T	19		63	Primary	Gray8Dark	Yes	End
GLOBAL	T	20		66.5	Primary	Gray8Dark	Yes	End
GLOBAL	T	21		70	Primary	Gray8Dark	Yes	End
GLOBAL	T	22		73.5	Primary	Gray8Dark	Yes	End
GLOBAL	T	23		77	Primary	Gray8Dark	Yes	End
GLOBAL	T	24		80.5	Primary	Gray8Dark	Yes	End
GLOBAL	T	25		84	Primary	Gray8Dark	Yes	End
GLOBAL	T	26		87.5	Primary	Gray8Dark	Yes	End
GLOBAL	T	27		91	Primary	Gray8Dark	Yes	End

2.3.2.2 Lines along radius:

9 lines are considered along radius and the lines are drawn as shown in Figure 2-8 according to R=68m, bridge deck width= 3.75m, length of top hexagon

member = 1.75m, and bottom cable far from center line by $3.75/2 + 1$ m toward the arch side. Also, one more curve is added where the arch support location.

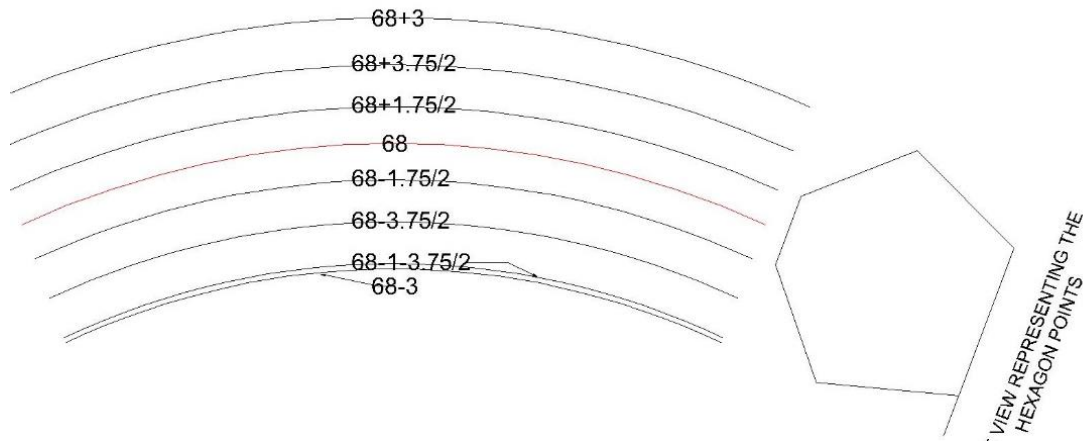


Figure 2-8 Top View of Grid Lines Respecting the Hexagon Corners

Table 2-2 Grid Line of Radian Directions

TABLE: Grid Lines								
CoordSys	AxisDir	GridID	XRYZCoord	TAngle	LineType	LineColor	Visible	BubbleLoc
Text	Text	Text	m	Degrees	Text	Text	Yes/No	Text
GLOBAL	R	A	0		Primary	Gray8Dark	Yes	End
GLOBAL	R	C	65		Primary	Gray8Dark	Yes	End
GLOBAL	R	B	65.125		Primary	Yellow	Yes	End
GLOBAL	R	D	66.125		Primary	Gray8Dark	Yes	End
GLOBAL	R	E	67.125		Primary	Gray8Dark	Yes	End
GLOBAL	R	F	68		Primary	Red	Yes	End
GLOBAL	R	G	68.875		Primary	Gray8Dark	Yes	End
GLOBAL	R	H	69.875		Primary	Gray8Dark	Yes	End
GLOBAL	R	I	71		Primary	Gray8Dark	Yes	End
GLOBAL	R	J	80		Primary	Gray8Dark	Yes	End

2.3.2.3 Lines at Z-axis (Heights):

Along Z-axis, 5 lines are drawn according to Table 2-3. The grid lines established in all directions are presented in Figure 2.9.

Table 2-3 Grid Line of Z-axis Direction

TABLE: Grid Lines								
CoordSys	AxisDir	GridID	XRYZCoord	TAngle	LineType	LineColor	Visible	BubbleLoc
Text	Text	Text	m	Degrees	Text	Text	Yes/No	Text
GLOBAL	Z	Z1	0		Primary	Gray8Dark	Yes	End
GLOBAL	Z	Z2	8		Primary	Gray8Dark	Yes	End
GLOBAL	Z	Z3	11		Primary	Gray8Dark	Yes	End
GLOBAL	Z	Z4	12.3333		Primary	Gray8Dark	Yes	End
GLOBAL	Z	Z5	13		Primary	Gray8Dark	Yes	End

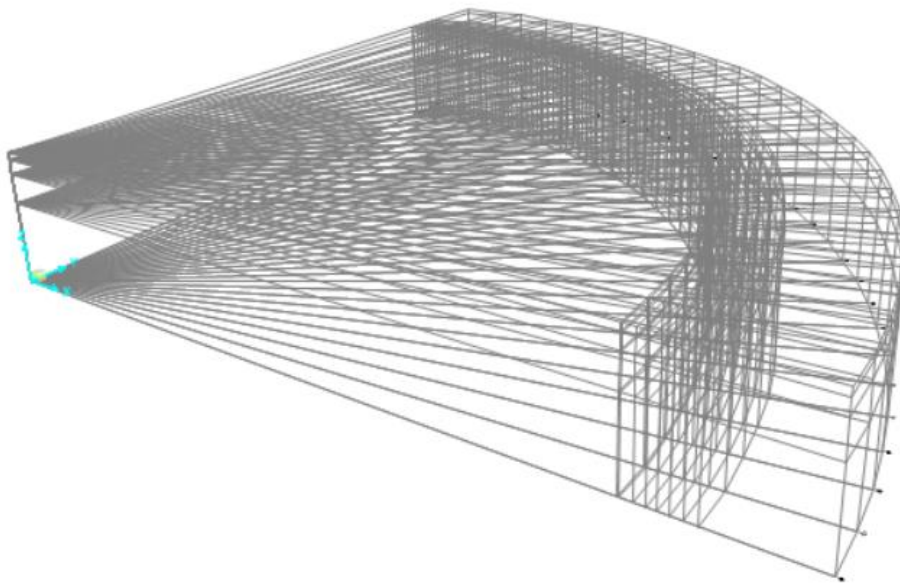


Figure 2-9 Final Grid Lines

2.3.3 Modeling the Bridge with Its Hexagon Frames:

2.3.3.1 Defining Steel Sections:

By trial and error, the following sections are selected to be the initial safe design for the model to start the following stage of the thesis as in Table 2-4.

Table 2-4 Steel Section of each Group Respecting AISC Sections

Member Name	Section Shape	Section Name	Depth (mm)	Width (mm)	Flange Thick. (mm)	Web Thick. (mm)
Arch	HSS (Hollow Tube)	Built-Up Section 5mx2m	2000	5000	100	100
Bridge Deck Long	W (I-section)	W610X101	602	228	10.5	14.9
Bridge Deck Long Intermediate	W (I-section)	W610X101	602	228	10.5	14.9
Bridge Deck Trans.	W (I-section)	W360X287	394	399	36.6	22.6
Bridge Deck Trans. Intermediate	W (I-section)	W360X287	394	399	36.6	22.6
Bracing	Pipe	Pipe100STD	Outer Diameter=114.3 mm		Wall Thickness =6.02 mm	
Hexagons	HSS (Hollow Tube)	HSS508X508 X12.7	508	508	12.7	12.7
Cable	Circle	Diameter=32mm				

The hexagons are defined as hollow sections which have stiffness in both the major and minor axis. The structure weight is **18441.271 KN (1879.84 Tons).**

2.3.3.2 Modeling the Bridge Deck Frames:

At Z = 8m with rt view (Top view), the drawing of the footbridge is accomplished according to the following steps.

- Draw the bridge deck steel longitudinal girder using Draw Frame/Cable function at the sidebar > Select girder section and start from any end leaving 2 lines where along theta then draw at 68 and $68 \pm 3.75/2$ lines along the radius.
- Connect each joint correspondingly for establishing traverse beams by selected beam section and to be from joint at $(68 + 3.75/2)$ to $(68 - 3.75/2 - 1)$ lines along radius except last 2 lines of the bridge ends $68 \pm 3.75/2$ connected.

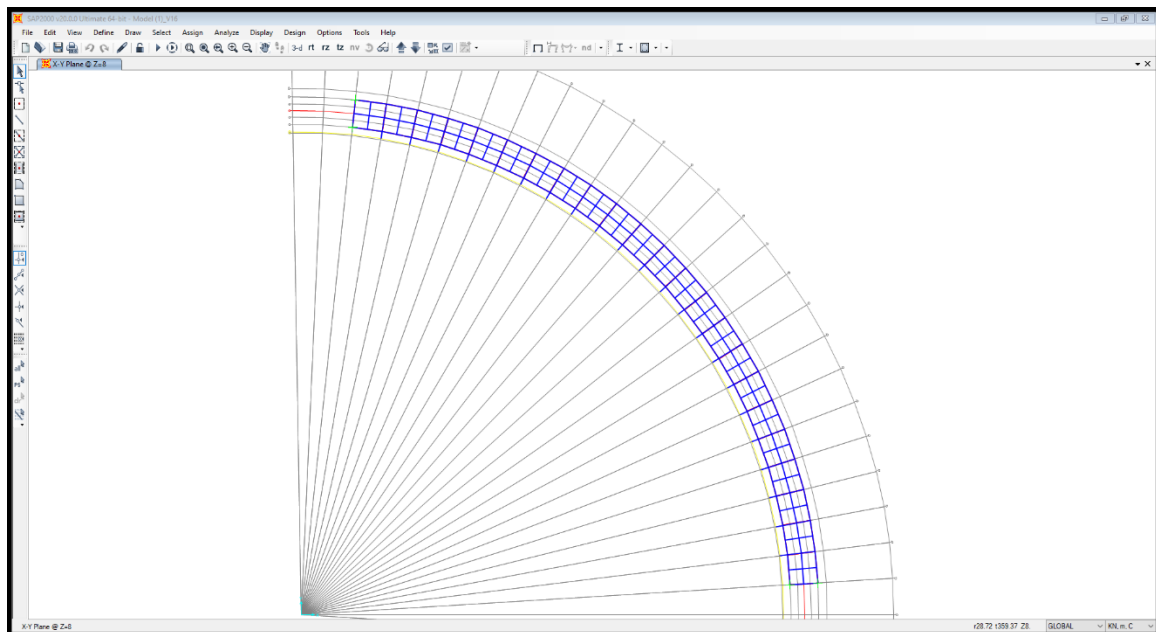


Figure 2-10 Top View of Bridge Framing

2.3.3.3 Modeling the Hexagons:

At rz view (radial elevation),

- Draw the hexagon using Draw Frame/Cable function at the sidebar > Select beam section.
- Leave 2 lines from one end of bridge supports and draw hexagon like follow cylindrical grid point where (r, z): $(68+3.75/2, 8) > (68+3, 11) > (68+1.75/2, 13) > (68-1.75/2, 13) > (68-3, 11) > (68-3.75/2, 8)$ as shown in Figure 2-10.

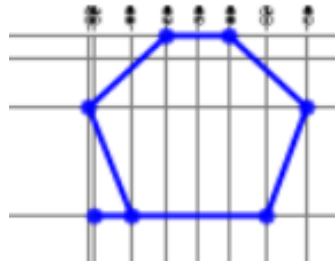


Figure 2-11 Hexagons Model

- Repeat the previous step 22 times to complete the all hexagons

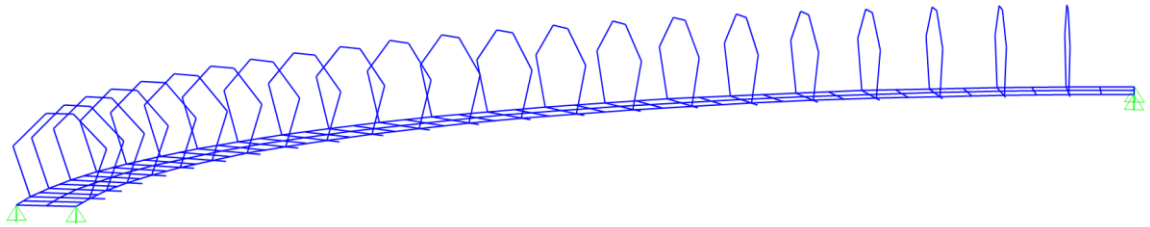


Figure 2-12 Bridge Deck Framing Model

- Connect each node in the upper level of hexagons to provide three-dimensional stability.

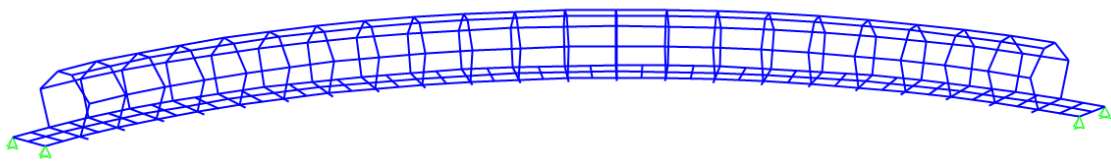


Figure 2-13 Final Bridge Deck Model

D) Modeling the Arch:

The modelling of the Arch is performed as in the following steps. At rt view with $z=0$,

- Draw a straight frame at the ends of grid lines say (Line-A) where their points are (r, t): (80, -3.5⁰) and (80, 91⁰).
- Draw another one (Line B) from the original point to Line-A horizontally.
- Rotate Line-B to 45 degrees where the highest point of the arch will be, using Edit > Replicate > Radial > parallel around the Z axis, and rotate point will be the original point (0, 0) > Angle 45⁰ > select delete original object like the following Figure.

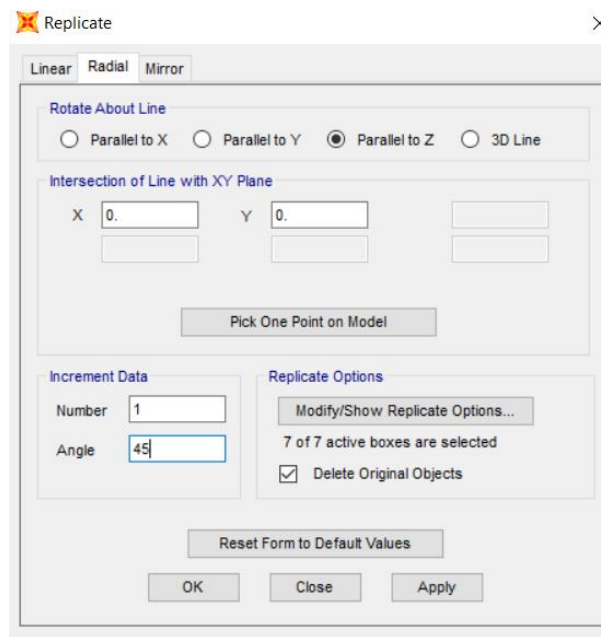


Figure 2-14 Replicate Function of SAP2000

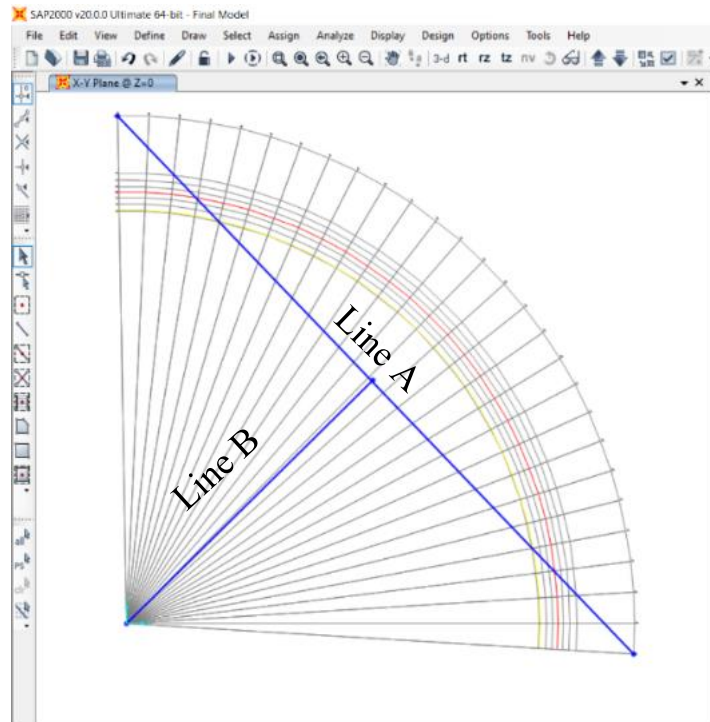


Figure 2-15 Identifying the point of the highest point of the arch if it's not inclined after rotating Line-B degree

- Right click on Line-B to get its properties > Location > Length $\simeq 54.55\text{m}$.
- Draw a line with the same length on Auto Cad software and draw a perpendicular line at its end and rotate it to be 20 degrees which is the assumed inclined angle of the arch.
- Draw another line that has a height of 24.5m (Assumption of arch height) and drags it to intersect the inclined line.

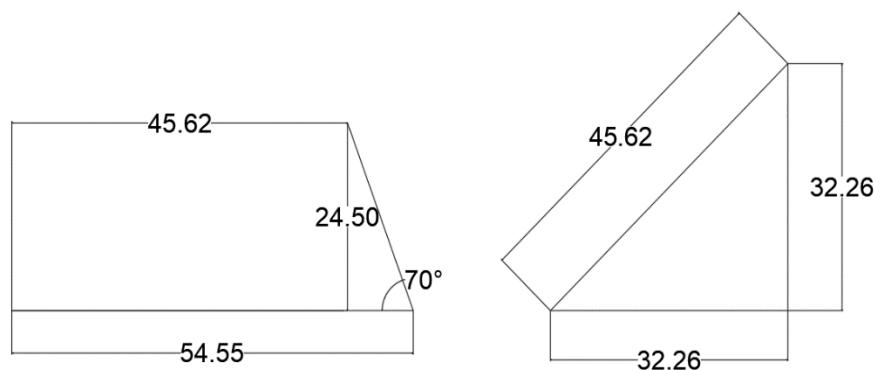


Figure 2-16 Obtaining the x and y values of the Highest point of the inclined arch

- Draw a line from the end of the horizontal line to the vertical line to obtain its length ($L \simeq 45.62\text{m}$) and use $\text{Cos}(45) = \frac{X}{L}$.
- $X=Y= L \times \text{Cos}(45) = 45.62 \times \text{Cos}(45) = 32.62\text{ m}$ (X and Y coordinates of the highest point of the arch).
- Draw Arch like the following steps:

From Ribbon bar > Draw > Draw Frame/Cable/Tendon >Line Object Type (Curved Frame) > Section (Arch section that we selected-Hollow Box-) > Draw from point (r, t): (80, -3.5) to (80, 91) > It will be opened new window > **At Line Object Parameters** Curve Type (Parabola Arc – 3rd Pont Coordinates) > 3rd Point (32.26, 32.26, 24.5) > **At Curve Parameters** Number of Linear Segments is 22 > **At Line Object Meshing** Select Break into multiple Equal Length Objects as shown in following Figure 2-17. The number of Linear Segments is obtained as the average length of steel section production is 6m. To make calculations more realistic, the length of the total curve is divided by 6m to get several sections required for the arch, which will be 22 sections.

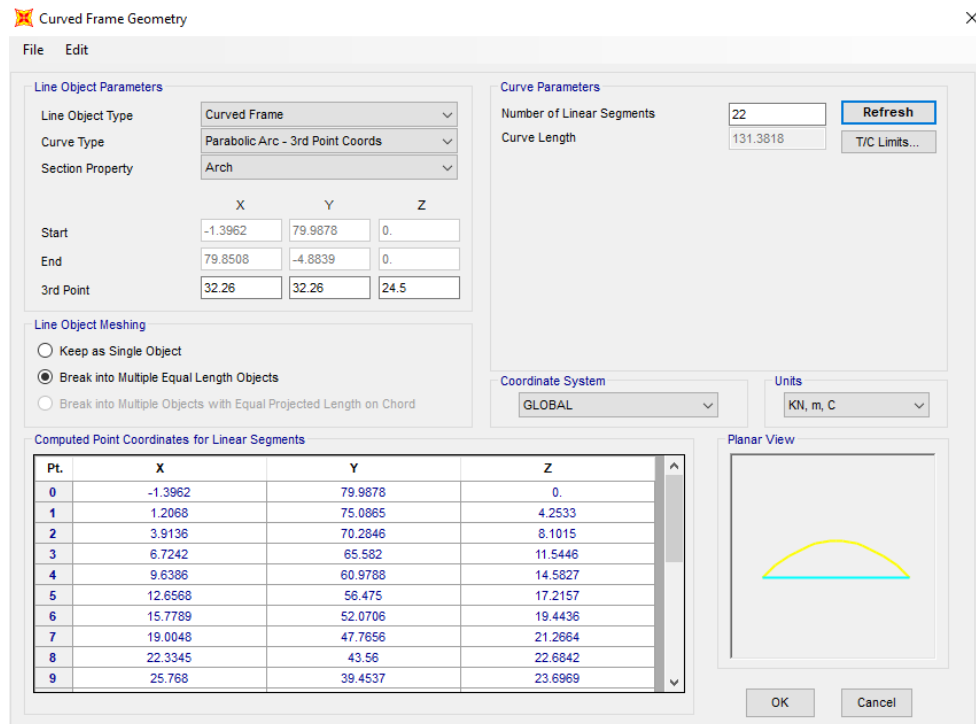


Figure 2-17 The properties box of drawing parabolic arch

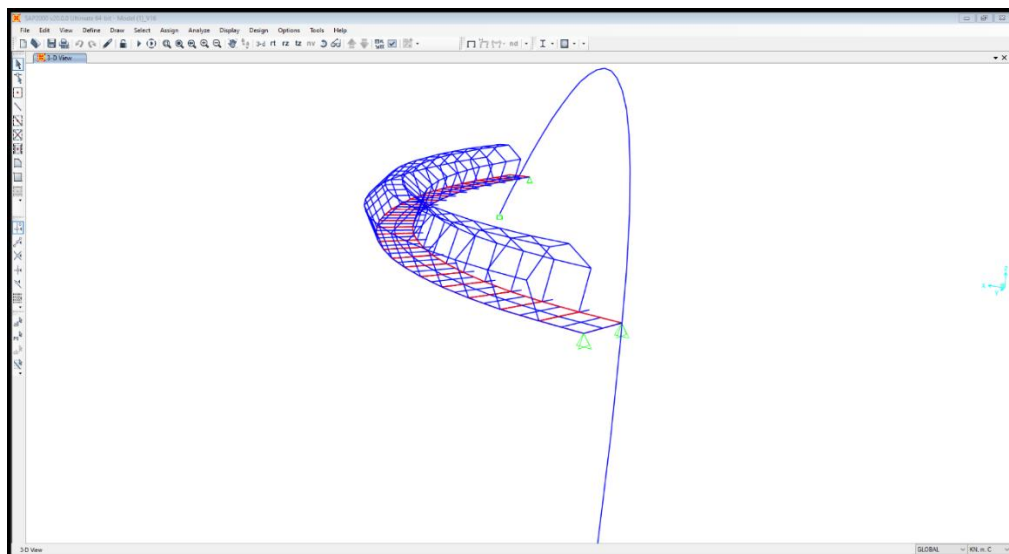


Figure 2-18 Arch Modeling

2.3.3.4 Modeling the Area of the Slab Deck:

Define Area Section > Shell > Add New Section > Shell – Thin > Thickness is **0.35m** for (Membrane & Bending) Material (Light Weight Concrete C25/30). Quick Draw Poly Area > Select Joints of Bridge.

2.3.3.5 Restraints and Meshing:

To define the exterior supports, the right click of support required for the structure of the arch will be fixed from both ends while the bridge itself will be pinned from both ends.

To improve the results of the analysis it is recommended to mesh the frame and areas together. Frame mesh should be with intermediate joints and intersections of other frame objects and points of area edges. Area mesh should be with intersections of straight-line objects and point objects in the meshing group as shown in Figure 2-19.

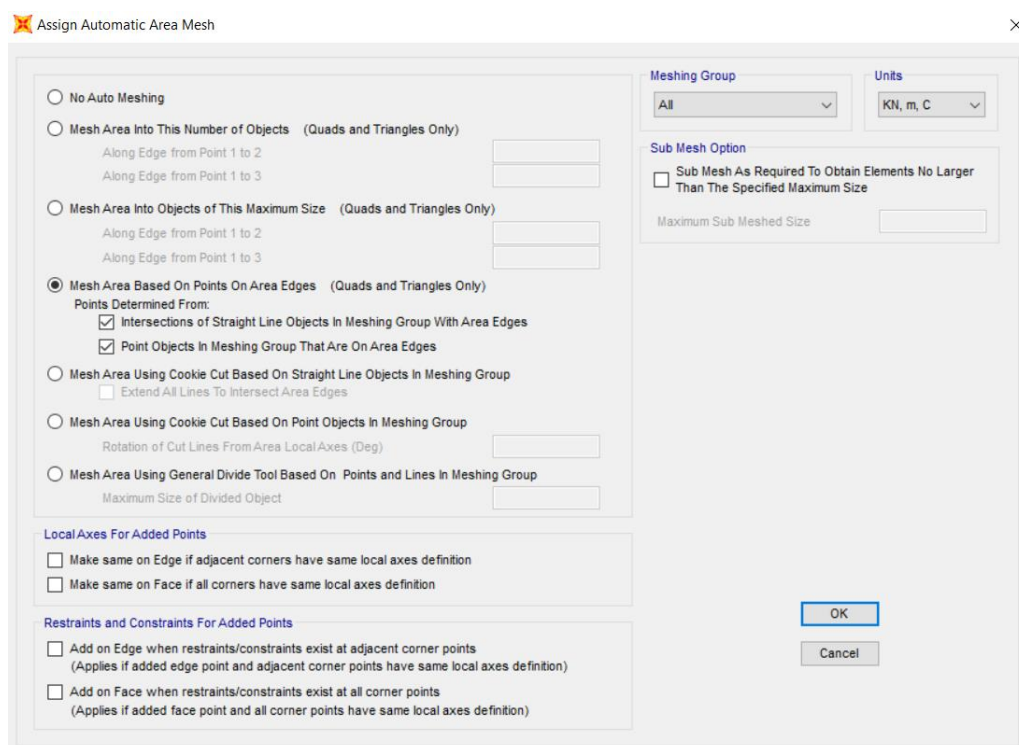


Figure 2-19 Area Mesh Details

2.3.3.6 Modeling the Cables:

Make Arch Points Corresponding to Hexagons:

- From the 3D view select all arch segments > From Ribbon Bar select Edit > Extrude > Lines to Area > dz (-20) to be lower than all hexagon > Number.

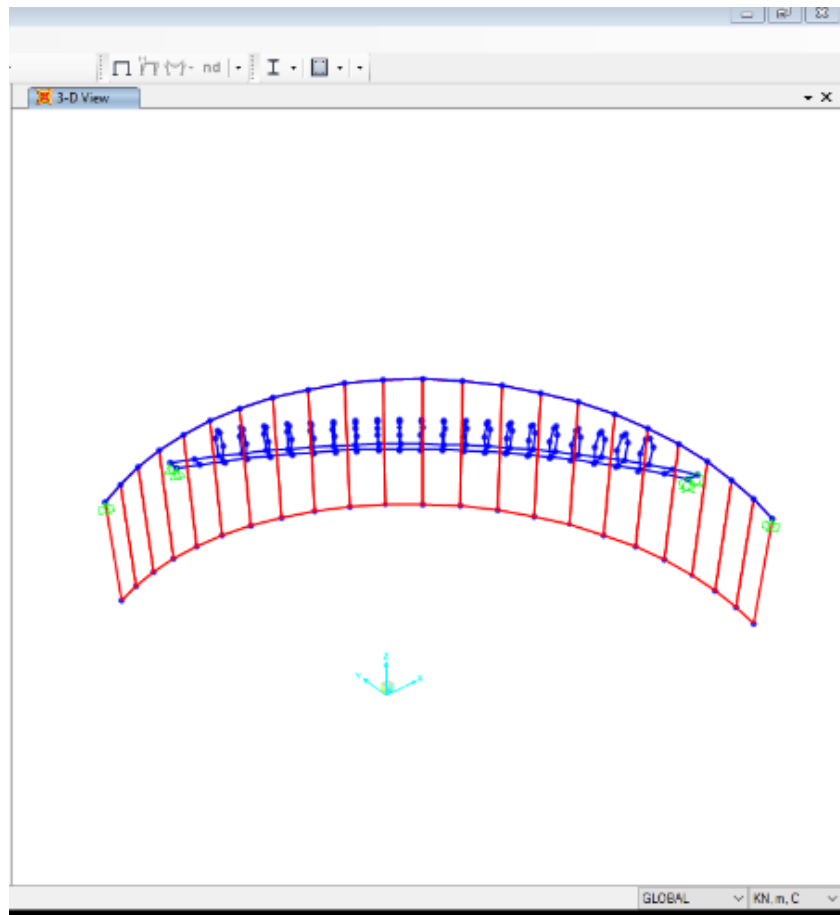


Figure 2-20 The model after extruding the arch

- Select all drawn areas > Ribbon Bar > Edit > Edit Areas > Divide Areas > Divide Areas based on Points on Area Edges > Points Determined From (Intersection of Visible Straight Grid Lines with Area Edges will get the same Figure 2-21.

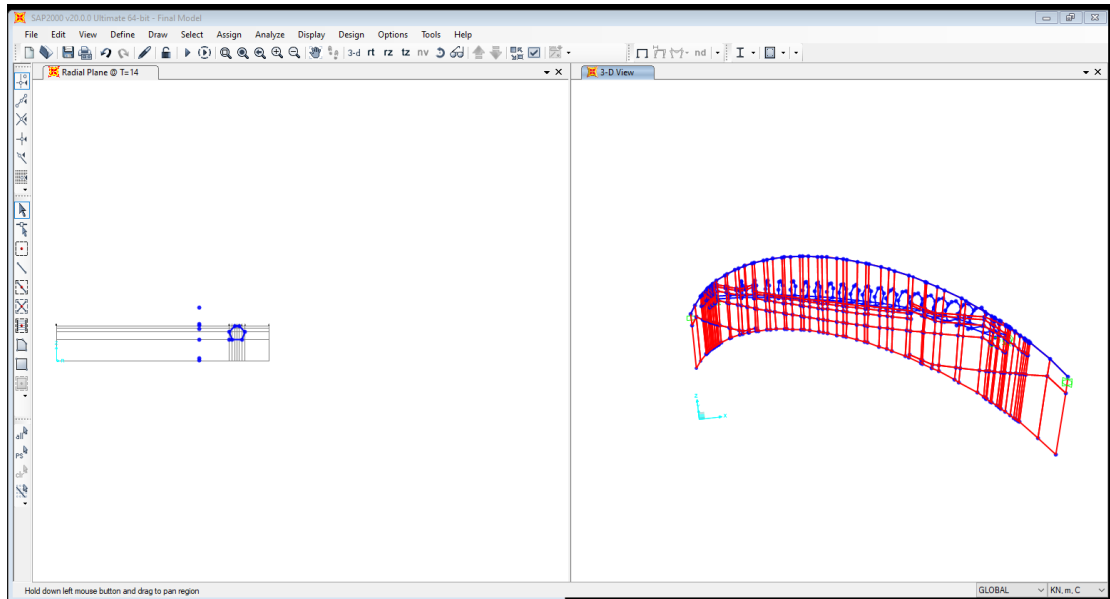


Figure 2-21 The intersection lines of the grid with the area

Connect Cables between Hexagons and Arch:

- From Ribbon Bar > Draw > Snap to > Intersections to be able to draw cable from arch to hexagon frame at the top level since its location is defined by $z=12\frac{1}{3}$ m but no other line.
- Each Hexagon at the rz view has many points from intersection-drawn areas. Connect the highest point for each one since it is the desired point on the arch line as shown in Fig. 2-22.
- In each level of the rz view, from Ribbon Bar > Draw > Draw Frame/Cable/Tendon > Straight Frame Model.

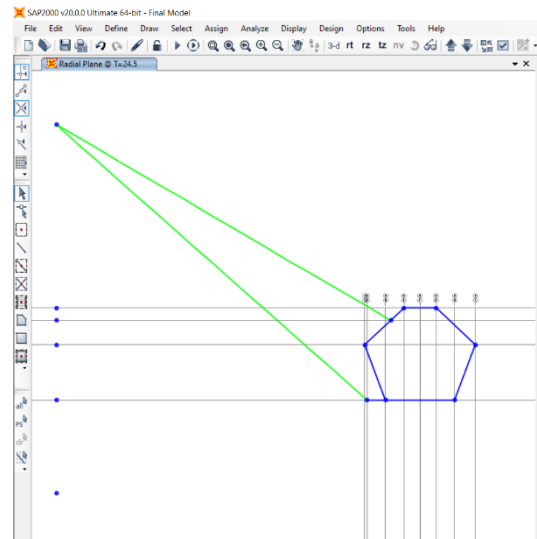


Figure 2-22 Connection point of cable at Arch

- Delete all areas to get only the points which are corresponding to hexagon locations only at the rz view. With this, the model is completed as shown in the following Figure 2-23.

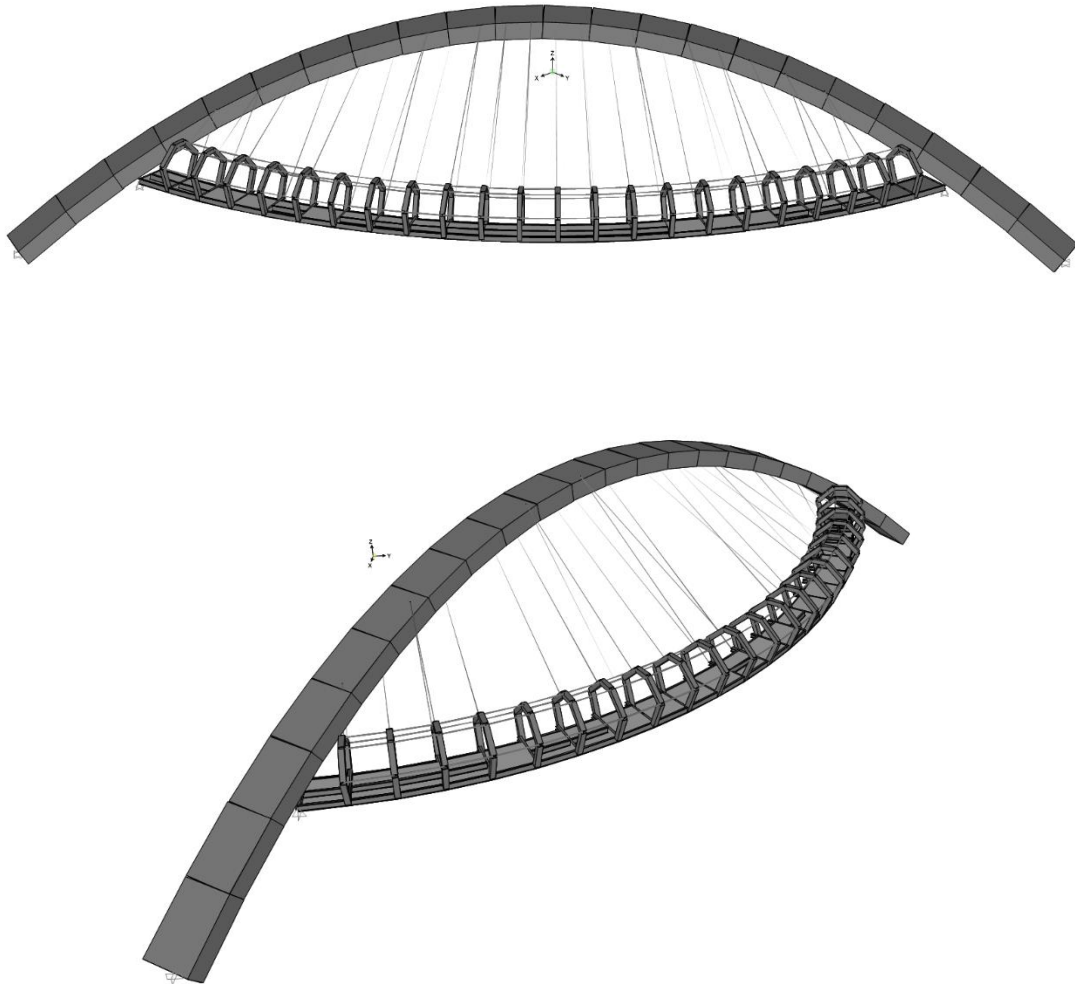


Figure 2-23 The Final Model

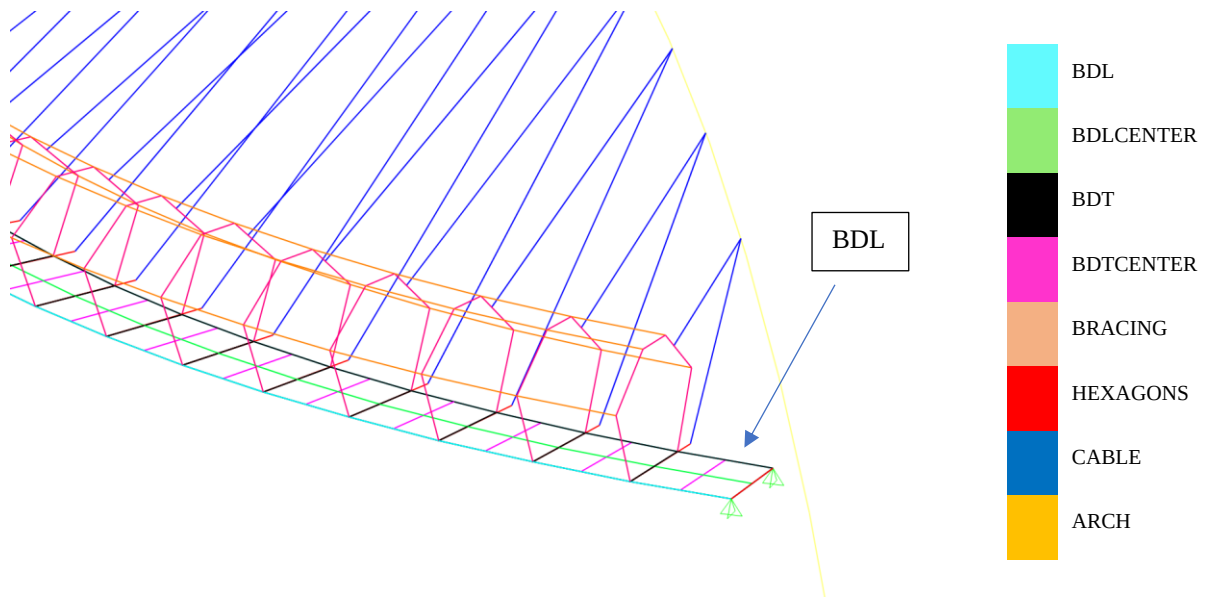


Figure 2-24 The Group Section

Defining the Cable properties and Material:

To make the frame element a cable, all cable frame is selected and modified to have 0 value in A2, A3, J, I2, and I3 where A2 and A3 are cross-sectional areas, “I” is the moment of inertia and “J” is torsional rigidity. In addition, the ends joint of the cable their torsional and moments are released in minor and major axis to make it a cable that only carries axial loads.

Cable material is defined as tendon material that has the modulus of elasticity (E), yield stress (F_y), and tensile stress (F_u) equal to 196.5GPa, 1.49GPa, and 1.72 GPa respectively.

Object Model - Line Information

Location Assignments Loads Design

Identification

Label 409 Design Procedure None

Section Property	Cable
Property Modifiers	
A2	0.
A3	0.
J	0.
I2	0.
I3	0.
Material Overwrite	None
Releases End-I	T, M2, M3
Releases End-J	M2, M3
Partial Fixity Springs	None
Local Axes	Default
Insertion Point	Default
End Length Offsets	None
Min. Number Stations	3
Station at Elm Intersect	Yes
Station at Conc Loads	Yes
P-Delta Force	None
T/C Limits	None

KN, mm, C

Reset All

Update Display

Modify Display

OK

Cancel

Double click white background cell to edit item.

Figure 2-25 Cable Properties

2.4 Bridge Design Loads

2.4.1 Dead Load

The dead loads of the bridge are the self-weight of all steel frames, concrete deck, and safety handrail. These loads are calculated automatically by the software except for the pedestrian rail load, which is added manually as 2.92 kN/m. The handrail load is applied along the bridge on both sides.

2.4.2 Live Load

As per AASHTO LRFD Guide Specifications for the Design of Pedestrian Bridges, the pedestrian load of 4.31kPa (kN/m²) is applied on the deck slabs.

Noticing the fact that the bridge serves only pedestrians, vehicles, equestrians, or fatigue loads is not considered in the calculations.

2.4.3 Wind Load

According to Unified Facilities Criteria (UFC) structural engineering, Navy Federal Credit Union (NSA) at Bahrain assumes wind speed is 47m/s (105mph) as the project is considered under risk category III respecting ASCE/SEI 7-16.

Table 2-5 Load Design Summary

Loading Pattern	Location	Specification & Values
Dead Load	All Structure	Self-Weight of Structure
	Outer Longitudinal Girders	$\Sigma_{\text{Rail}} = 2.92 \text{ kN/m.}$
Live Load	Bridge Deck Areas	4.31kPa.
Wind Load	All Structure	Auto Lateral Load Pattern ASCE 7-16
		Wind Speed 105 mph
		Exposure C
		Topographical Factor, K_{zt} 1.0
		Gust Factor, G 0.85
		Directionality Factor, K_d 0.85
		Solid/Gross Area Ratio 0.2

		Exposure frame & Area Objects Include Area Objects & Frames considering Open Structure
		Wind Direction 0, 45, 90, 135, 180, 225, 270 & 315

2.4.4 Load Combinations

As per AASHTO LRFD Guide Specifications for the Design of Pedestrian Bridges, the load combination will be strength-I and strength-III summarized in the following Table.

Table 2-6 Load Combinations

Strength-I	Strength-III
0.9 D.L + 1.5 L.L	0.9 D.L + 1.0 W.L 0
	0.9 D.L + 1.0 W.L 45
	0.9 D.L + 1.0 W.L 90
	0.9 D.L + 1.0 W.L 135
	0.9 D.L + 1.0 W.L 180
	0.9 D.L + 1.0 W.L 225
	0.9 D.L + 1.0 W.L 270
	0.9 D.L + 1.0 W.L 315
1.25 D.L + 1.5 L.L	1.25 D.L + 1.0 W.L 0
	1.25 D.L + 1.0 W.L 45
	1.25 D.L + 1.0 W.L 90
	1.25 D.L + 1.0 W.L 135
	1.25 D.L + 1.0 W.L 180
	1.25 D.L + 1.0 W.L 225
	1.25 D.L + 1.0 W.L 270
	1.25 D.L + 1.0 W.L 315

In Table 2-6, the highlighted combinations are only selected for optimization process to reduce the time consumption in running the optimization program.

The analysis method is taken as non-linear (p-delta) because it gives more reliable results according to the comparisons between linear and non-linear analysis for ensuring the quality of results as shown in Tables 3-7 to 3-9.

Table 2-7 Linear Analysis Results

Results	Linear Analysis		
	Analysis Case	Member/Location	Value
Max Displacement Uz (mm)	Un-factored Live Load	Joint 203	(-) 53.096
Max Displacement Ux (mm)	Un-factored Wind Load	Joint 228	(+) 21.025
Max Displacement Uy (mm)	Un-factored Wind Load	Joint 182	(-) 19.952
Max P force of members (kN)	1.25D+1.5L	Frame 3	(-) 21853.348
	0.9D+1W315	Frame 187	(+) 467.917
Max V2 force of members (kN)	1.25D+1W315	Frame 24	(-) 1904.41
	1.25D+1.5L	Frame 3	(+) 1395.636
Max V3 force of members (kN)	1.25D+1.5L	Frame 8	(-) 2105.127
	1.25D+1.5L	Frame 19	(+) 2105.127
Max T torque of members (kN.mm)	1.25D+1.5L	Frame 8	(-) 7185145.55
	1.25D+1.5L	Frame 19	(+) 7185145.55
Max M2 moment of members (kN.mm)	1.25D+1.5L	Frame 3	(-) 41283813
	1.25D+1.5L	Frame 13	(+) 32568784.07
Max M3 moment of members (kN.mm)	1.25D+1W315	Frame 19	(-) 9650184.63
	1.25D+1W315	Frame 24	(+) 19667484.33

Table 2-8 Non-Linear Analysis Results (P-Delta)

Results	Non-Linear Analysis (P-Delta)		
	Analysis Case	Member/Location	Value
Max Displacement Uz (mm)	Un-factored Live Load	Joint 203	(-) 53.114
Max Displacement Ux (mm)	Un-factored Wind Load	Joint 228	(+) 21.07
Max Displacement Uy (mm)	Un-factored Wind Load	Joint 182	(-) 19.904
Max P force of members (kN)	1.25D+1.5L	Frame 3	(-) 21912.367
	0.9D+1W315	Frame 187	(+) 467.934
Max V2 force of members (kN)	1.25D+1W315	Frame 24	(-) 1912.573
	1.25D+1.5L	Frame 3	(+) 1405.487
Max V3 force of members (kN)	1.25D+1.5L	Frame 8	(-) 2100.198
	1.25D+1.5L	Frame 19	(+) 2100.198
Max T torque of members (kN.mm)	1.25D+1.5L	Frame 8	(-) 7199197.32
	1.25D+1.5L	Frame 19	(+) 7199197.32
Max M2 moment of members (kN.mm)	1.25D+1.5L	Frame 3	(-) 41265424
	1.25D+1.5L	Frame 13	(+) 32666916.2
Max M3 moment of members (kN.mm)	1.25D+1W315	Frame 19	(-) 9730786.07
	1.25D+1W315	Frame 24	(+) 19797680.94

Table 2-9 Non-Linear Analysis Results (P-Delta plus large Displacements)

Results	Non-Linear Analysis (P-Delta plus large Displacements)		
	Analysis Case	Member/Location	Value
Max Displacement Uz (mm)	Un-factored Live Load	Joint 203	(-) 53.132
Max Displacement Ux (mm)	Un-factored Wind Load	Joint 228	(+) 21.045
Max Displacement Uy (mm)	Un-factored Wind Load	Joint 182	(-) 19.931
Max P force of members (kN)	1.25D+1.5L	Frame 3	(-) 21912.367
	0.9D+1W315	Frame 187	(+) 472.602
Max V2 force of members (kN)	1.25D+1W315	Frame 24	(-) 1915.598
	1.25D+1.5L	Frame 3	(+) 1406.987
Max V3 force of members (kN)	1.25D+1.5L	Frame 8	(-) 2111.227
	1.25D+1.5L	Frame 19	(+) 2111.227
Max T torque of members (kN.mm)	1.25D+1.5L	Frame 8	(-) 7197683.3
	1.25D+1.5L	Frame 19	(+) 7197683.3
Max M2 moment of members (kN.mm)	1.25D+1.5L	Frame 3	(-) 41272076
	1.25D+1.5L	Frame 13	(+) 32677228.08
Max M3 moment of members (kN.mm)	1.25D+1W315	Frame 19	(-) 9728567.29
	1.25D+1W315	Frame 24	(+) 19802840.13

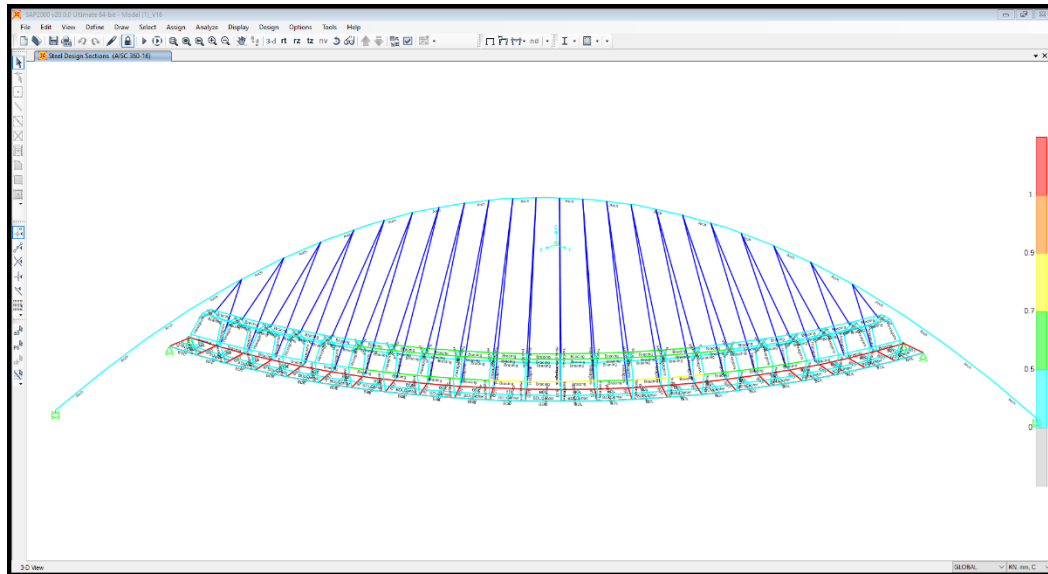


Figure 2-26 The PMM Ratio Contour Line Under Maximum Value Obtained from Load Combination

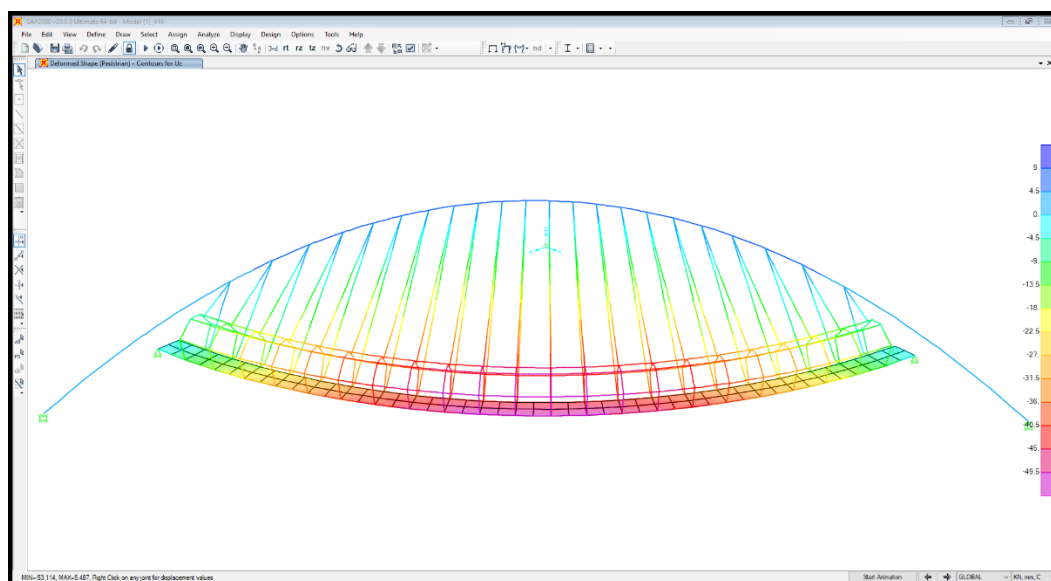


Figure 2-27 The Vertical Deflection (U_z) under Un-factored Live Load

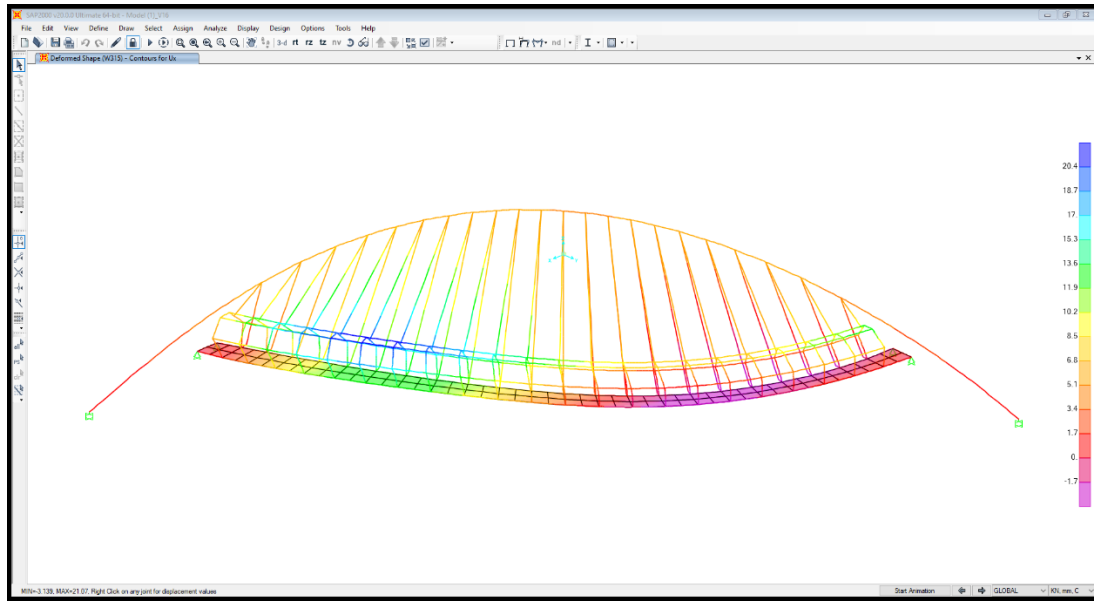


**Figure 2-28 The Horizontal Deflection (U_x) due to Wind Load in 315 Direction
(Worse Case)**

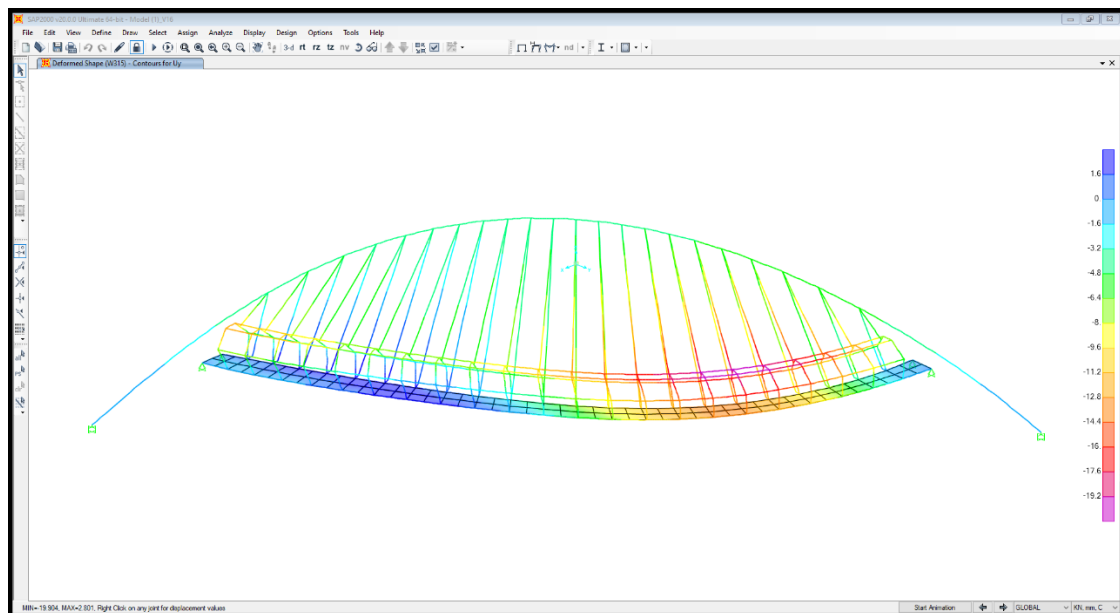


**Figure 2-29 The Horizontal Deflection (U_y) due to Wind Load in 315 Direction
(Worse Case)**

In Figures 2-26 to 2-29, the PMM ratio, vertical deflection and horizontal deflections under un-factored live and wind loads respectively. This is carried out to check the validity of the model constructed. As seen in the Figure, SAP accepts

the model and carries out the analysis of the structure under external loads considered.

CHAPTER THREE
OPTIMIZATION
APPROACH PROCEDURE

Chapter 3 Optimization Approach Procedure

3.1 Introduction:

This chapter describes the design optimization algorithm proposed for the optimum design of suspended and curved in-plane pedestrian bridges. In engineering design problems, the cost is one of the prime targets which is expected to be minimized. For example, in steel structures, the overall cost is closely related to the amount of steel required to construct the steel structure. This is one of the reasons why weight minimization is considered in the optimum design procedure.

The development of the optimum design algorithm for footbridges that are suspended and curved in the plan is carried out through the following four stages:

1. Preparation of the coding of the application programming interface (API) of SAP2000.
2. Identifying the objective function and the design constraints.
3. Deciding the design variables and preparing the design pool
4. Determination of the metaheuristic algorithm that finds the solution of the optimum design problem formulated.

3.2 Application Programming Interface (API):

Application programming interfacing (API). It is a link that connects the analysis software SAP2000 and the programming software MATLAB. SAP2000 is a structural engineering software developed by Computers and Structures (CSI), Inc. It is widely used worldwide by practicing structural design offices as well as by research communities in the analysis and design of structures. On the other hand, MATLAB is developed by MathWorks. It has the capability to deal with many numeric operations such as matrix manipulation, function, and data visualization, algorithm implementation, user interface building, and connecting with other programming languages. API provides the required link between

SAP2000 and MATLAB, enabling the users to analyze and design a structure in SAP2000 and transfer the results to the MATLAB environment. It also allows transferring of information from MATLAB to SAP2000. Therefore, API can be called a common language could each software understand.

SM toolbox makes the use of API much easier than before. After downloading this toolbox, it is opened in the MATLAB environment. When it is opened, it extracts all the required syntax and becomes ready to run. All syntaxes used in this study are described in Table 3-1.

Table 3-1 Used API Syntaxes

No.	API Command Syntax	Syntax`s function
1	SM.App('sap') SM.Ver('20') APIDLLPath ='Path' ProgramPath ='Program.exe Path' [Sobj] = SM.Helper.CreateObject(ProgramPath, APIDLLPath) [Smdl]=SM.SapModel();	The fixed syntax for initiating the program by creating the SAP2000 objective
2	SM.ApplicationStart	Starting SAP2000 application
3	ret = SM.InitializeNewModel	Initiating new model
4	ModelName = 'Model file name' ModelPath = full file('Model file location path', ModelName); ret = SM.File.OpenFile(ModelPath);	Open existed model

No.	API Command Syntax	Syntax`s function
5	ret = SM.SetPresentUnits(SM.eUnits.kN_mm_C)	Set the desired unit
6	ret = SM.design steel.DeleteResults	Delete all results of any previous design
7	ret = SM.SetModelIsLocked(false)	Unlock the run of analysis
8	ret=SM.File.Save()	Save the work
9	SM.ApplicationExit (false)	Close the application
10	ret=SM.PropFrame.detection(section name, Material name, depth, top flange width, top flange thick, web thick, bottom flange width, bottom flange thick)	Defining (W) - section`s parameters
11	ret=SM.PropFrame.SetTube(section name, Material name, depth , width, flange thick, web thick);	Defining hollow section (HSS) parameters
	ret=SM.PropFrame.SetPipe(section name, Material name, outer diameter, wall thick.);	Defining Pipe section parameters
12	ret=SM.PropFrame.SetCircle(section name, Material name, diameter);	Defining Circle parameters
13	[ret,Fy,Fu,SSType,SSHysType]=SM.Prop Material.GetOTendon(Material Name);	Get Tendon/Cable parameters
14	ret = SM.Analyze. run analysis;	Start Analysis (Run)

No.	API Command Syntax	Syntax`s function
15	ret = SM.Results.Setup.SetCaseSelectedForOutput(Case Name);	Set particular case
16	[ret,NumberResults,Obj,Elm,LoadCase,StepType,StepNum,U1,U2,U3,R1,R2,R3]=SM.Results.JointDisplAbs(Joint name,SM.eItemTypeElm.GroupElm);	Obtaining displacement and the rotational results of joints
17	[ret,NumberResults,Obj,ObjSta,Elm,ElmSta,LoadCase,StepType,StepNum,P,V2,V3,T,M2,M3]=SM.Results.FrameForce(Frame Name ,SM.eItemTypeElm.GroupElm);	Obtaining forces, moments, shears, and torques values
18	ret = SM.DesignSteel.StartDesign	Start design checking
19	[ret,NumberItems,FrameName,Value]=SM.DesignSteel.GetDetailResultsValue(frcode(j),SM.eItemType.Group,3,'Desired Result')	Get design results of shear, PMM.

3.3 Objective Function and Design Constraints:

3.3.1 Objective Function:

The objective function as mentioned in the preceding chapter is taken as the total weight of the footbridge which is to be minimized. The mathematical expression of the objective function is given in equation (3-1).

$$w = \sum_{i=1}^m \rho A_i L_i \quad (3-1)$$

- where w is the total weight of the footbridge, ρ is the unit weight of steel, A_i is the cross-section area for each member, L_i is the length of each member and m is the total number of members.

3.3.2 Design Constraints

The implemented design constraints like deflection and strength are taken from “AASHTO LRFD Guide Specifications for the Design of Pedestrian Bridges” and “AISC 360-16 LRFD” standards, respectively because SAP2000 has AISC 360-16 standards, and he will be responsible for checking part in the analysis process. It is appropriate to mention that the strength constraints taken from AISC360 LRFD Standards are the same as AASHTO.

3.3.2.1 The Strength Constraints:

To reduce the time consumption in running the program, it's elected from 18 combinations as explained in section 3.4.4 the load combinations that apply the largest loads on the structure which are (1.25D.L. + 1.5L.L) & (1.25D.L + 1.0 W315).

A) All members except cables:

All structure members (except cables) under flexural and compressive/tensile stress that follows clause H1:

$$\frac{Pr}{P_c} + \frac{8}{9} \left(\frac{Mr_x}{Mc_x} + \frac{Mr_y}{Mc_y} \right) \leq 1.0 \quad \text{when } \frac{Pr}{P_c} \geq 0.2 \quad (3-2)$$

$$\frac{Pr}{2P_c} + \left(\frac{Mr_x}{Mc_x} + \frac{Mr_y}{Mc_y} \right) \leq 1.0 \quad \text{when } \frac{Pr}{P_c} < 0.2 \quad (3-3)$$

Where P_r is ultimate axial strength (tension in hexagons and compression in the arch and bracing members) (N), P_c is capacity axial strength (tension in hexagons and compression in the arch and bracing members) (N), M_r is ultimate flexural strength (N.mm), M_c is capacity flexural strength (N.mm), M_x is a capacity flexural strength related to the major axis and M_y is a capacity flexural strength

related to the minor axis and all these strength capacities are obtained according to chapters D, E & F of AISC360-16 standards. Also, the bracing members since under compression force only the moment value will be zeros.

The arch section is a built-up section so it should first be checked to find out whether it is compact or non-compact.

As per AISC360-16 Table B4.1b,

The flange of rectangular HSS:

$$\frac{b}{t_f} \leq 1.12 \sqrt{\frac{E}{F_y}} \quad (3-4)$$

$$\frac{d}{t_w} \leq 2.42 \sqrt{\frac{E}{F_y}} \quad (3-5)$$

Where t_f is the flange thickness, t_w is web thickness, $b = \text{width} - 2 \cdot t_w$, $d = \text{depth} - 2 \cdot t_f$, E is the modulus of elasticity, and F_y is yield stress.

Moreover, the arch's depth is assumed to be less than or equal to its width as shown in Figure 3-1 same as hexagons sections to have the capacity for handling the torsion loads

B) Cables:

The member under tensile strength shall follow clause D2:

$$P_{n,y} = \Phi_y F_y A, \text{ and } P_{n,u} = \Phi_r F_u A \quad (\text{less value to be selected}) \quad (3-6)$$

Where P_n is the tensile strength (MPa), F_y is the minimum yield stress (MPa), A is a cross-section (mm^2), Φ_y is tensile yield resistance factor equal to 0.90, Φ_r is tensile rupture resistance factor equal to 0.75 and F_u is the minimum tensile strength (MPa). The strength of cables is checked manually since SAP2000 isn't able to check it for unknown reasons.

C) Shear Constraints:

For checking shear constraints for doubly symmetric members shall follow clause G4:

$$V_n = \Phi_v 0.6 F_y A_w C_{v2} \quad (3-7)$$

Where V_n is capacity shear strength (N), A_w is web cross section area (mm²), h = width resisting the shear force, taken as the clear distance between the flanges less the inside corner radius on each side for HSS or the clear distance between flanges for box sections (mm), C_{v2} is web shear buckling strength coefficient and equals to h/t_w and $K_v=5$ and Φ_v is shear resistance factor equal to 0.90.

3.3.2.2 The Deflection Constraints:

As per AASHTO LRFD Guide Specifications for the Design of Pedestrian Bridges, the deflections shall be as follows:

$$\delta_{\max} = \text{Span}/360, \text{ (horizontally and vertically)} \quad (3-8)$$

where horizontal and vertical deflection is to be calculated under un-factored wind load (in each direction) and un-factored live load respectively.

After normalization all previous constraints will be:

$$c_1 = \frac{P_{\max}}{\min(P_u, P_y)} - 1 \quad (3-9)$$

$$c_2 = \text{PMM ratio} - 1 \quad (3-10)$$

$$c_3 = \frac{b/t}{1.12 \sqrt{\frac{E}{F_y}}} - 1 \quad (3-11)$$

$$c_4 = \frac{d/t}{2.42 \sqrt{\frac{E}{F_y}}} - 1 \quad (3-12)$$

$$c_5 = V_{\text{ratio}} - 1 \quad (3-13)$$

$$c_6 = \frac{\delta_{\text{obtained}}}{\delta_{\max}} - 1 \quad (3-14)$$

where $P_{\max}$ is the maximum value of axial force in cables, PMM ratio is the maximum value related to equations (3-2 & 3-3), V_{ratio} is the maximum ratio of shear strength to shear capacity related to equation (3-7) (in minor and major axis), δ_{obtained} is the maximum displacement of structure joints (horizontally and vertically), and $\delta_{\max}$ is the deflection limitation calculated from equation (3-8) and all these values are obtained from analyzing the structure by SAP2000.

Mostly, the metaheuristic is designed for processing unconstrained equations which is opposite to the engineering problems desired since the engineering problems have standards limits, and constraints that should be respected so for converting this kind of problem to be unconstrained, it's required for normalizing all constraints to be equations instead of being inequality as follows:

$$c = \begin{cases} 0, & g(x) \leq 0 \\ g(x), & g(x) > 0 \end{cases} \quad (3-15)$$

where $g(x)$ is the normalized equation of each constraint as in equation (3-3).

$$g(x) = \frac{x_{\text{obtained}}}{x_{\text{allowable}}} - 1 \quad (3-16)$$

By implementing equation (3-15) to equation (3-1), the desired objective function will be evaluated to be suitable for use in metaheuristic algorithms:

$$W = w(1 + C)^\varepsilon \quad (3-17)$$

$$\text{where } C = \sum_1^j c$$

where W is the evaluated objective function that will be used in the algorithm processes, w is the total weight obtained from equation (3-1), ε is the penalty constant and it's defined as $\varepsilon = 1 \text{ or } 2$ which represents the golden ratio and j is a total number of constraints will be checked

3.3.2.3 The Geometrical Constraints:

It is required that the depth of longitudinal beams (BDL) & (BDLcenter) should be more than or equal to that of transverse beams (BDT) & (BDTcenter) due to constructability condition as shown in Figure 3-1. The normalized form of such constraint is given in equation 3-16.

$$c_7 = \frac{Depth_{Trans.}}{Depth_{Long}} - 1 \quad (3-18)$$

Similarly, the outer diameter of bracing members should be less than the depth of steel sections adopted for hexagons.

$$c_8 = \frac{Outer\ dia.\ Bracing}{Depth_{Hexagons}} - 1 \quad (3-19)$$

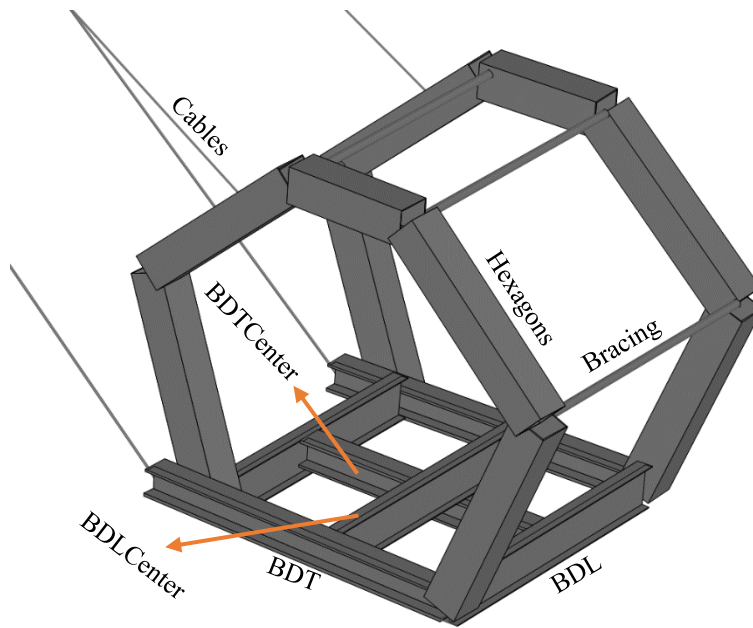


Figure 3-1 3D Frame Layout

3.4 Design Variable & Design Pool:

3.4.1 Design Variable:

The design variables as stated in section 4.1 are taken as the cross-section areas of steel sections adopted by the members of the footbridge. In the mathematical formulation of the design problem, 11 different design variables are

considered. These are defined in Table 3-2. Hexagons are defined as HSS section in which its depth is less than its width.

Table 3-2 Sections Definition

Member Name	Group defined name in SAP200	Member Section Type	The Design Variable vector (mm)
Bridge deck longitudinal beam	BDL	W-Section	W-Section area (A_1)
Bridge deck longitudinal beam (Intermediate)	BDLCenter	W-Section	W-Section area (A_2)
Bridge deck transverse beam (the bottom beams of hexagons)	BDT	W-Section	W-Section area (A_3)
Bridge deck transverse beam (Intermediate)	BDTCenter	W-Section	W-Section area (A_4)
Bracing	Bracing	Pipes	Pipes area (A_5)
Hexagons	Hexagons	HSS	HSS area (A_6)
Arch	Arch	HSS (Built-up Section)	Depth (D) Width (B) Flange Thick. (FT) Web Thick. (WT)
Cable	Cable	Circular-Section	Diameter (Dia.)

Furthermore, the weight function needs values of the specific weight of used material in each section besides their length which is collected in Table 3-3.

Table 3-3 Steel Material definition for each section group

Section Name	Length (mm)	Steel type	Steel Specific weight
BDL	$L_1=191048.94$	S355	7.697×10^{-8} (KN/mm ³)
BDLCenter	$L_2=95524.47$	S355	
BDT	$L_3=112000$	S355	
BDTCenter	$L_4=86209.77$	S355	
Bracing	$L_5=348871.97$	S355	
Hexagons	$L_6=307874.85$	S355	
Arch	$L_7=131381.75$	S355	
Cable	$L_8=836164.26$	Tendon of 1.4934 GPa yield stress	

So, the final weight function (eq. 3-1) will be adjusted to be:

$$w = \sum_{i=1}^m \rho A_i L_i = 7.697 \times 10^{-8} (L_1 A_1 + L_2 A_2 + L_3 A_3 + L_4 A_4 + L_5 A_5 + L_6 A_6 + L_7 A_7 + L_8 A_8) \quad (3-20)$$

Where $A_7 = D * B - ((D - 2 FT)(B - 2 WT))$, and $A_8 = \frac{\pi}{4} Dia.^2$

3.4.2 Design Pool:

It is apparent that design variables are discrete and they are required to be selected from available steel profile list. There are 283W-sections and 516 sections for the HSS sections in AISC. The design pool is created from selecting 101 W-sections for vectors $A_1 \sim A_4$, 51 pipe sections (all AISC pipe sections available) for vector A_5 , 101 HSS sections for vector A_6 , 101 values for each dimension belong to arch built-up section (vectors $D \sim TW$) and 100 diameters for cable (vector $Dia.$) which are described in APPENDIX.

3.5 Metaheuristic Algorithms:

Mostly, every metaheuristic algorithm process is as simulation of nature, social culture, biology or laws of physics which is converted to sequences of mathematic operations. Metaheuristic algorithm does a global search which is preferable for obtaining the problem's solutions moreover, randomization is frequently used to achieve a diversity of solutions. The metaheuristic goal is to identify a suitable, practical solution in a reasonable amount of time because the complexity of the problem makes it difficult to search through every conceivable answer or combination. But the funny real truth is that no idea whether an algorithm will work or why (if it does) moreover finding the optimal answers is not guaranteed (Yang X. S., 2010).

In addition, metaheuristic approaches deal with discrete programming solution as same as optimum design problem of this thesis.

3.5.1 Artificial Bee Colony Algorithm

The artificial Bee Colony Algorithm is called commonly the ABC algorithm established by Karaboga and Akay in 2005. It is inspired by the behavior of honey bees during their foraging of food. The algorithm starts as there are some food positions available to honeybees that represent the possible population of values that could solve the aim function (usually the aim is minimizing the desired function) and there are three bee groups: employed bees, onlooker bees, and scout bees. They are in charge of selecting the best food position by collecting information about food positions by employed bees before comparing and choosing the better food position which is the onlooker bees' duty then it's come to the scout bee's role in looking for another food location randomly could have the best food what makes the algorithm finding solution globally not locally. (Karaboga & Akay, 2009)

Three control parameters for ABC must be chosen before the algorithm is applied. These are the colony size, the maximum number of cycles, and the colony limit (iterations). The number of working bees plus the observer bees equals the size of the colony. Keep in mind that the colony's half corresponds to the amount of beginning food sources (solutions). If the food sources are abandoned, the limit value regulates the transition of employed bees to scouts.

These behaviors of bee groups are translated to the following mathematician's process sequences:

1. Initialize the solution population using the upper and lower limits of variable values:

$$x_{ij} = x_j^{lower} + rand * (x_j^{upper} - x_j^{lower}) \quad (3-21)$$

Where x_{ij} is i^{th} is ($i=1, \dots, N.A$) solution number, j^{th} is the variable number, x_j^{lower} and x_j^{upper} are the boundaries values of variable and $rand$ is a random number in $[0,1]$.

2. **Employed Bees:** picking out new food sources using the following equation

$$v_{ij} = x_{ij} + \emptyset_{ij} (x_{ij} - x_{kj}) \quad (3-22)$$

Where v_{ij} is i^{th} is ($i=1, \dots, N.A$) new food source, $\emptyset_{ij}$ is random real-number in $[-1,1]$ and x_{kj} is a k th solution obtained through $k = \text{int}(\text{rand} * N_p) + 1$ (N_p is several solutions). Then they will collect information about food sources by calculating the fitness of each food source, using the following equation:

$$fitness = e^{-\frac{f(x_i)}{mean}} \quad (3-23)$$

$$\text{where } mean = \frac{\sum f(x_i)}{N_p}$$

3. **Onlooker Bees:** evaluating the best food sources through eq (3-22), depending on the given information by getting the probability of the obtained fitness using the equation:

$$prop (fitness)_i = \frac{fitness_i}{\sum fitness} \quad (3-24)$$

4. **Scout Bees:** each time picking out or evaluating the food sources, the new food source may be incapacitated. There is a counter for each solution and if it's gotten the selected limit (usually obtained through eq. 3-25), the scout bees will terminate it and pick out a random new source instead using eq (3-21).

$$Limit = \frac{1}{2} * Nx * Np \quad (3-25)$$

Where Nx is the number of available food sources (number of variables).

After all bees' groups complete their duty, one iteration ends and starts from the employed bees' step again for the next iteration.

3.5.2 Teacher-Learning-Based Optimization (TLBO)

In 2011, Rao, Savsani, and Vakharia proposed a new algorithm using populations of solutions to obtain a global solution which is TLBO. "TLBO" is an abbreviation of "teacher-learning based optimization" and from its name, the algorithm is inspired by the approach of students/learners in learning and gaining information from teachers and their colleagues; thus, the algorithm consists of two phases: the teacher phase and the learner phase (Rao, Savsani, & Vakharia, 2011).

The teacher phase: After using equation (3-21) for initializing the population (students/learners), the best solution is elected according to that it's achieving the best optimization of the goal function and it's called " $x_{teacher}$ "

Using equations (3-26) for modifying the solutions and comparing new solutions with old ones and nominating the best.

$$x_{new} = x_{old} + rand * (x_{teacher} - T_f * mean) \quad (3-26)$$

where T_f is the teacher factor and is selected as 1 or 2 randomly, and “rand” is a random number between 0 and 1, and the mean is the average value of all populations.

The learner phase: before starting the learner phase, a couple of solutions is chosen randomly as x_i & x_j and are compared between them. Solutions are upgraded respecting equation (3-27).

$$x_{new} = \begin{cases} x_{old} + rand(x_i - x_j), & f(x_i) < f(x_j) \\ x_{old} + rand(x_j - x_i), & f(x_i) > f(x_j) \end{cases} \quad (3-27)$$

Moreover, the contrast shall be done as per the less of objective function is the best since the goal of optimization is obtaining the minimum value. If the new solutions are disqualified, the old value will not be updated. By the end of this phase, a single iteration is completed. In Figure 3-2, the flowchart will explain the algorithm process.

3.5.3 Differential Evolution (DE)

Differential Evolution (DE), which was first put out by Storn R. and Price K., is a well-liked optimization metaheuristic that performs admirably in a broad range of problems from several scientific disciplines since it's distinguished by its procedure simpleness and has fewer parameters as a result, there is growing interest in using it to solve optimization across continuous spaces in several scientific and technical domains recently. DE algorithm approach is performed using mutation and crossover, also like other evolutionary algorithms, is population-based and looks for global solutions for the problems (Storn & Price, 1997).

DE algorithm starts by generating the population that will be used in the algorithm using eq (3-21) then the mutation phase comes. In the mutation phase, new vectors are obtained for each solution using equation (3-28).

Note: solution vector is a vector containing random values for each variable in the objective function (aim function). The population is containing various of these solution vectors

$$v = x_i + F_m * (x_a - x_b) \quad (3-28)$$

where v is the mutated vector, x_i is a solution vector that is created in initializing stage, F_m is the mutation factor and it's defined as a random number between two numbers that are defined by the user, x_a and x_b are random solution vectors. The new vector is compared with variable limitations before moving to the following phase (Crossover phase).

Crossover is a selecting stage to evaluate the current solution vectors. Shortly, the vectors are evaluated by conditional selection using equation (3-13).

$$x_j = \begin{cases} v_j, & \text{if } j = j_0 \text{ or } rand \leq P_{CR} \\ u_j, & \text{otherwise} \end{cases} \quad (3-29)$$

where x_j is the evaluated values in the vector, j is a position number in each vector and $j = \{1, 2, \dots, \text{vector size}\}$, j_0 is a random position number of each vector, P_{CR} is crossover probability and defined by the user, v_j the mutated value that is obtained using equation (3-28) and u_j is the current values in the vector.

After the completion of the crossover phase, the iteration is completed and starts over again from the mutation phase.

Table 3-4 Configuration of PC used to run the program

System Manufacture:	Dell Inc (PC).	Lenovo (LAPTOP)
System Model:	Precision Tower 5810	80WK
Processor:	Intel® Xeon® CPU E5-1620 v3 @ 3.50 GHz (8 CPUs), ~3.5GHz	Intel(R) Core(TM) i7-7700HQ CPU @ 2.80GHz (8 CPUs), ~2.8GHz
Memory (RAM):	65536 MB (64 GB)	16384 MB (16 GB)
Display Chip Type:	AMD Radeon Graphics Processor	Intel(R) HD Graphics 630 & NVIDIA GeForce GTX 1050
Display Memory:	34756 MB (32 GB)	12158 MB (12 GB)
DirectX Version:	DirectX 12	DirectX 12

3.6 Summary

To sum up the whole procedure for the optimization process as explained in flow chart Figure (3-3):

1. The model is created through SAP2000 software as explained in chapter 3.
2. The model is opened through API syntaxes using MATLAB program.
3. Prepare the desired variables that will be used in the aim function.
4. Determine the limitations of these variables.
5. Define the algorithm parameters and required iteration number.
6. Initialize the population of solution vectors.
7. Start the algorithm approach. and
8. Obtain new values of sections and define them in the SAP2000 using API syntaxes.
9. Analysis of the new sections and collect the result.
10. Compare the results with the required constraints.

11. Get the function value and define it back to the algorithm to identify the quality of the result and continue the process to reach desired iteration number.

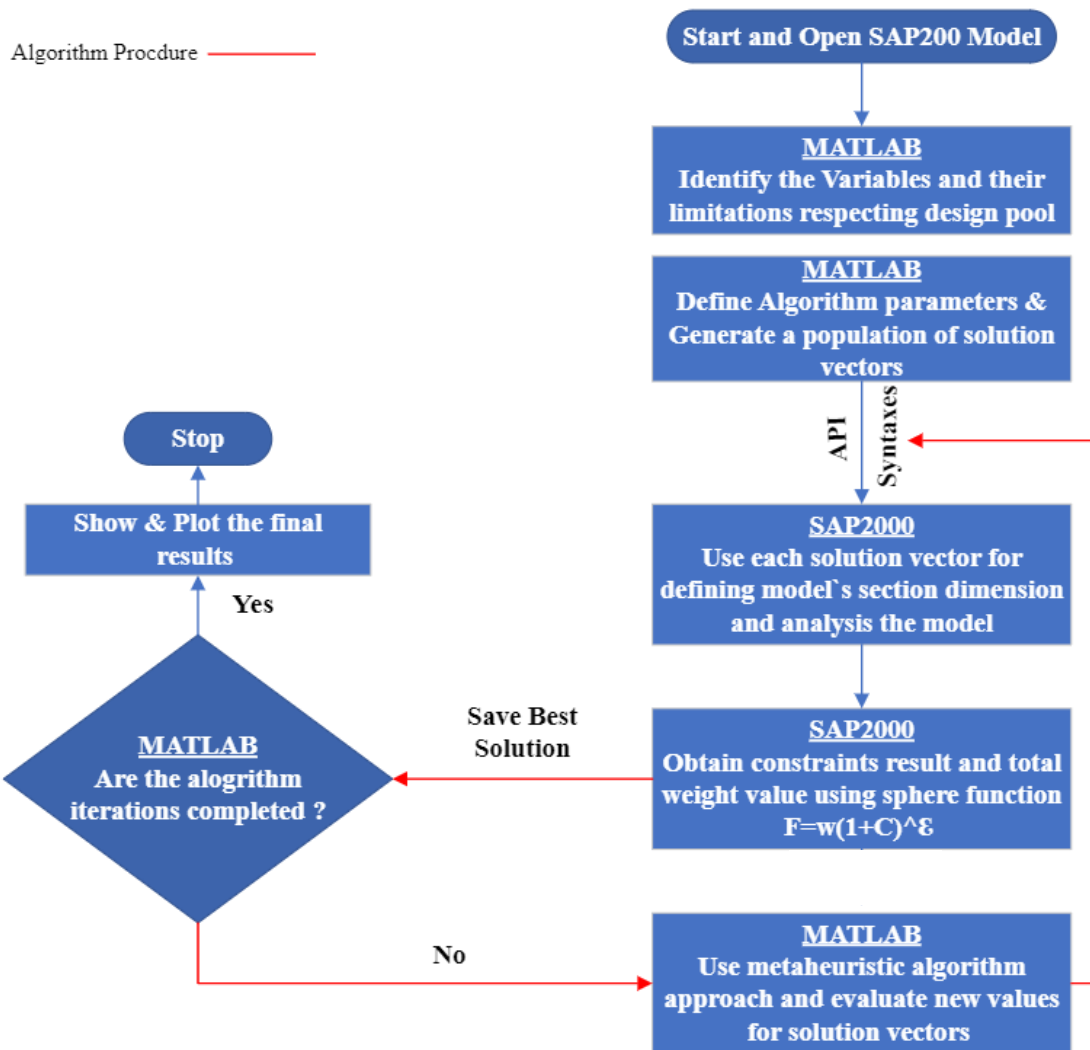


Figure 3-2 Optimization Design Process

CHAPTER FOUR

RESULTS & DISCUSSION

Chapter 4 Results & Discussion

After performing the procedure in the previous chapter, the optimization results are secured. In this chapter, these results will be investigated and debated.

4.1 Preparation & Substitutions

At the beginning, the member's sections of the footbridge structure are named as described in Table 3-2 in SAP2000 to confer MATLAB and API syntaxes re-defining the sections softly during the optimization process.

In addition, three MATLAB functions are created to enclose all available W, Pipe, and HSS sections in ascending arrangement same as in the AISC database. The name, area, and dimensions of sections can be gained from these functions.

More and above the sphere function of the metaheuristic algorithm command is evaluated to contain defining sections of each member and analyzing the structure under designated loads through SAP2000 and all this, to be capable of calculating eq. 3-17.

There are some parameters are set for ABC and DE algorithms. ABC parameter is the abandonment limit for the scout bee stage and it's recommended to be set as in eq. 3-25 but the limit is set as 100 not to take time in processing disqualified solutions, while DE parameters are defined to be 0.2 for PCR, beta min is 0.2 and beta max is 0.8.

Table 4-1 Algorithm Parameters

Algorithm	Population	Parameters
ABC	50	Abandonment Limit=100
TLBO	50	No Parameters
DE	50	PCR=0.2, Beta [0.2 0.8]

To identify the number of iterations required for each algorithm for obtaining the optimum results, 1000 iterations are run and it's found that TLBO and DE need 600 iterations while ABC requires 500 iterations.

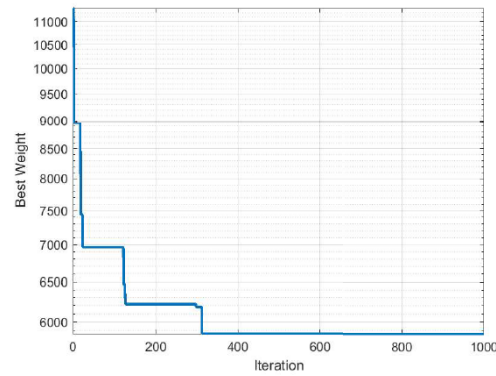


Figure 4-1 ABC Results of 1000 Iterations

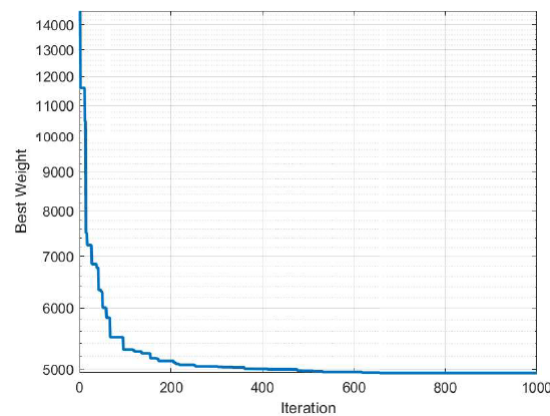


Figure 4-2 DE Results of 1000 Iteration

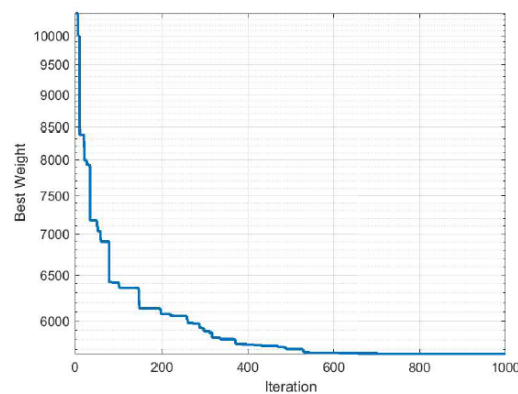


Figure 4-3 TLBO Results 1000 Iterations

Table 4-2 1000 Iterations Results

Algorithms	Weight (Ton)	Penalty	Time (Days)
ABC	597.29	0	46.80
TLBO	576.82	1.17×10^{-4}	46.16
DE	504.2	0	15.26

4.2 Optimizations Results

Each metaheuristic algorithm is repeated 5 times using different random numbers using “rng” function in MATLAB to check the quality of processes and results as shown in the Table 4-2 and Figures 4-4 to 4-8.

Table 4-3 Final Results of 5 different calculations

Rng No.	ABC			TLBO			DE		
	Weight (Tons)	Penalty	Time (Days)	Weight (Tons)	Penalty	Time (Days)	Weight (Tons)	Penalty	Time (Days)
1	636.57	0	21.48	522.48	0	30.89	505.38	0	11.61
2	651.99	0	21.15	563.52	0	31.08	502.76	0	11.61
3	655.28	0.0133	21.15	531.51	0	30.54	502.76	0	11.59
4	659.82	0.0133	20.99	588.32	0	23.77	502.76	0	11.63
5	655.54	0	21.00	571.51	0	25.02	506.06	0	12.68
Best	636.57			522.48			502.76		
Worst	659.82			588.32			506.06		
Average	651.84			555.468			503.944		
STD	8.977742			27.67503			1.63899		

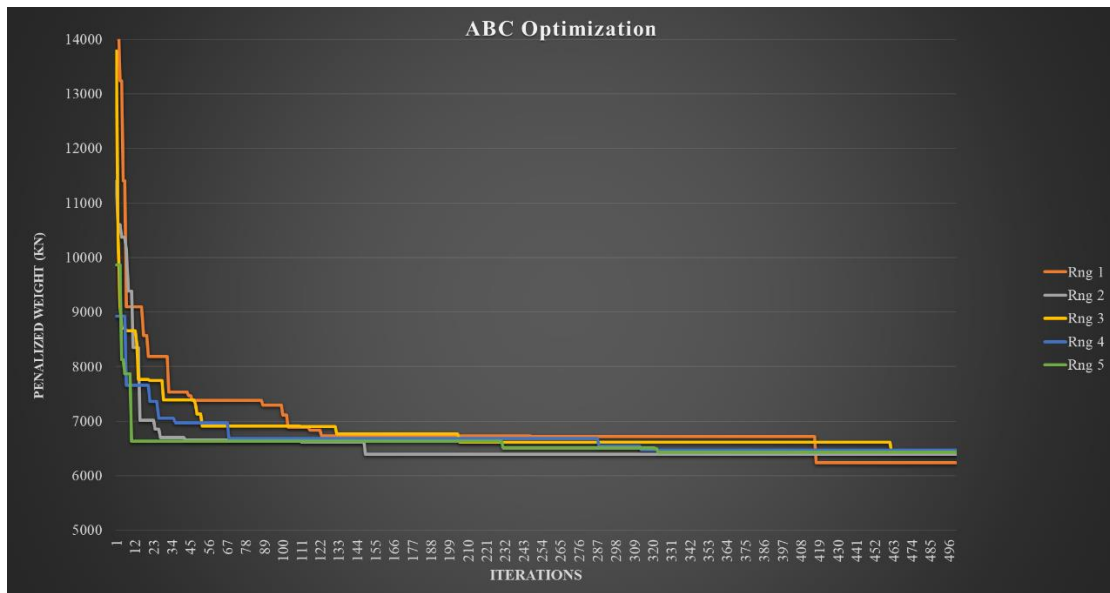


Figure 4-4 ABC Algorithm Results of 5 Different Runs

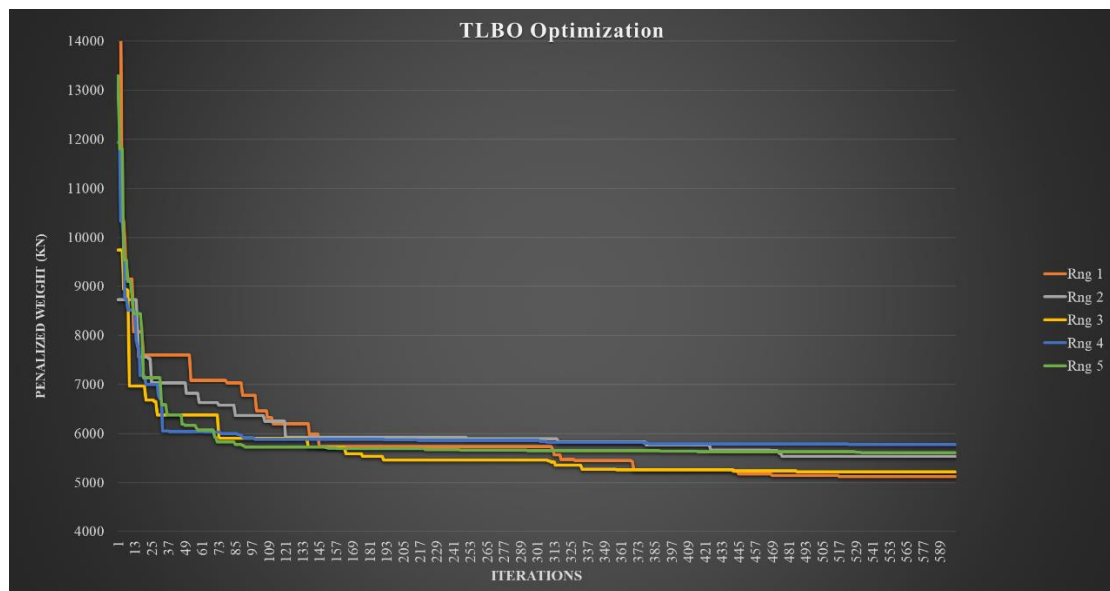


Figure 4-5 TLBO Algorithm Results of 5 Different Runs

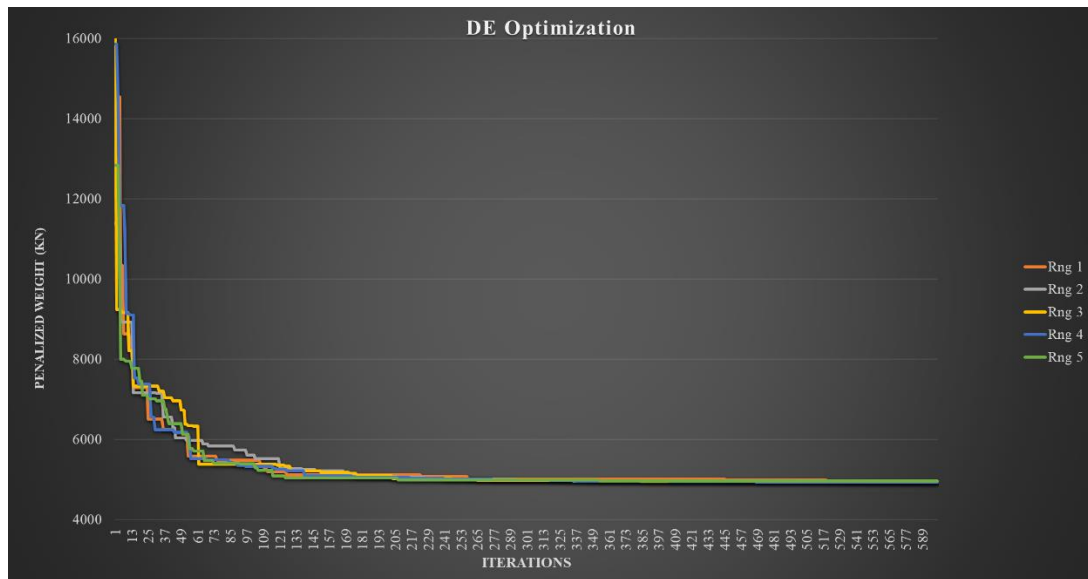


Figure 4-6 DE Algorithm Results of 5 Different Runs

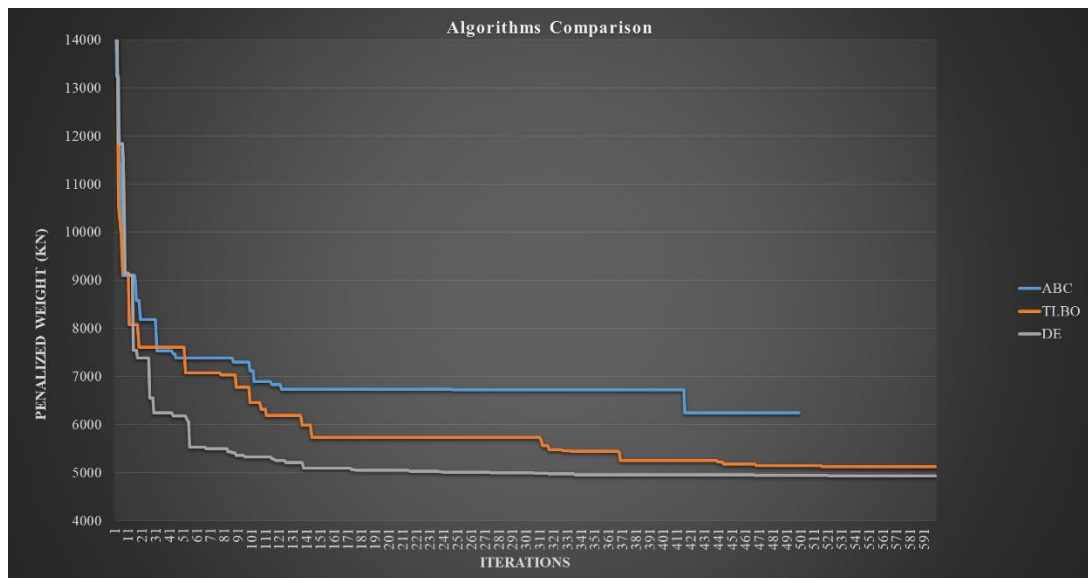


Figure 4-7 The Comparison for each Algorithm Best Results (5 Different Runs)

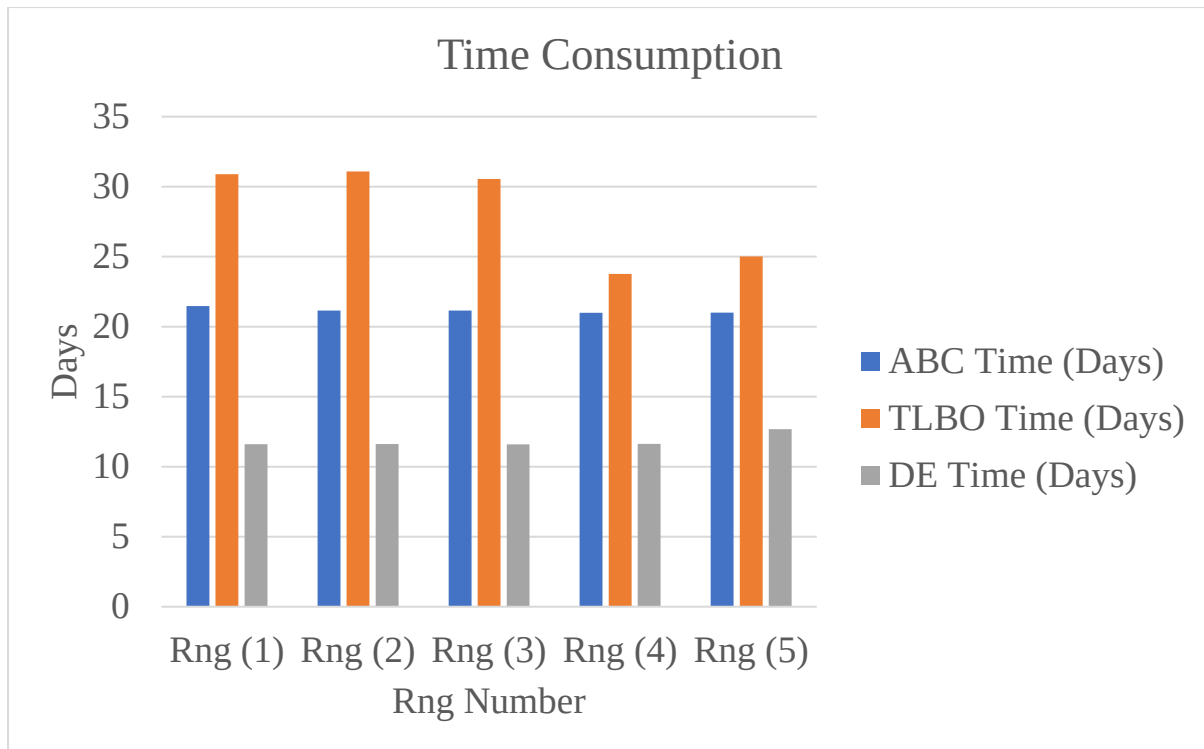


Figure 4-8 Time Consumption Comparison Between Algorithms

From the above results, it's realized that DE algorithm has the most efficiency in optimizing the design because it obtains the minimum sections with less running time as it gets **502.76 Tons (4932.04 KN)** of steel weight with **11.59 days** beside its results are so precious according to its standard deviation value (**1.252**) while the second rank algorithm goes to TLBO resulting steel weight **522.48 Tons (5125.54 KN)** with **30.89 days** but it has the highest standard deviation (**19.244**) which means its results have low precious and last rank is for ABC resulting steel weight **636.57 Tons (6244.75 KN)** with **21 days**. Moreover, DE algorithm succeeds to reduce the steel design weight up to **26.74%** of primary steel design weight **1879.84 Tons**, while ABC algorithm reduces **33.86%** and TLBO algorithm reduces **27.79%**.

DE algorithm selects sections in the Table 4-5 as they are the optimum sections that have less cross-section area and less capacity to handle the design load of the structure system by respecting design constraints as shown in Figures 4-9 to 4-19.

Table 4-4 Weight Reduction Efficiency of each Algorithms

rng No.	ABC				TLBO	
	Weight (Tons)	Weight Reduction (%)	Weight (Tons)	Weight Reduction (%)	Weight (Tons)	Weight Reduction (%)
rng 1	636.57	33.86	522.48	27.79	505.38	26.88
rng 2	651.99	34.68	563.52	29.98	502.76	26.74
rng 3	655.28	34.86	531.51	28.27	502.76	26.74
rng 4	659.82	35.1	588.32	31.3	502.76	26.74
rng 5	655.54	34.87	571.51	30.4	506.06	26.92
Maximum Reduction	636.57	33.86	522.48	27.79	502.76	26.74
Average	651.84	34.674	555.468	29.548	503.944	26.804

Table 4-5 Optimum Steel Design Section Selected by DE Algorithm (rng 2)

Member Name	Section Shape	Section Name	Depth (mm)	Width (mm)	Flange Thick. (mm)	Web Thick. (mm)
Arch	HSS (Hollow Tube)	Built-Up Section	1000	3000	65	50
Bridge Deck Long	W (I-section)	W530 X 66	526	165	11.4	8.89
Bridge Deck Long (Intermediate)	W (I-section)	W530 X 66	526	165	11.4	8.89
Bridge Deck Trans.	W (I-section)	W460 X 113	462	279	17.3	10.8
Bridge Deck Trans. (Intermediate)	W (I-section)	W 310 X 67	307	204	14.6	8.51

Member Name	Section Shape	Section Name	Depth (mm)	Width (mm)	Flange Thick. (mm)	Web Thick. (mm)
Bracing	Pipe	Pipe100STD	Outer Diameter=114.3 mm		Wall Thickness =6.02 mm	
Hexagons	HSS (Hollow Tube)	HSS 273.1 X 12.7	273	273	12.7	12.7
Cable	Circle	Diameter=37mm				

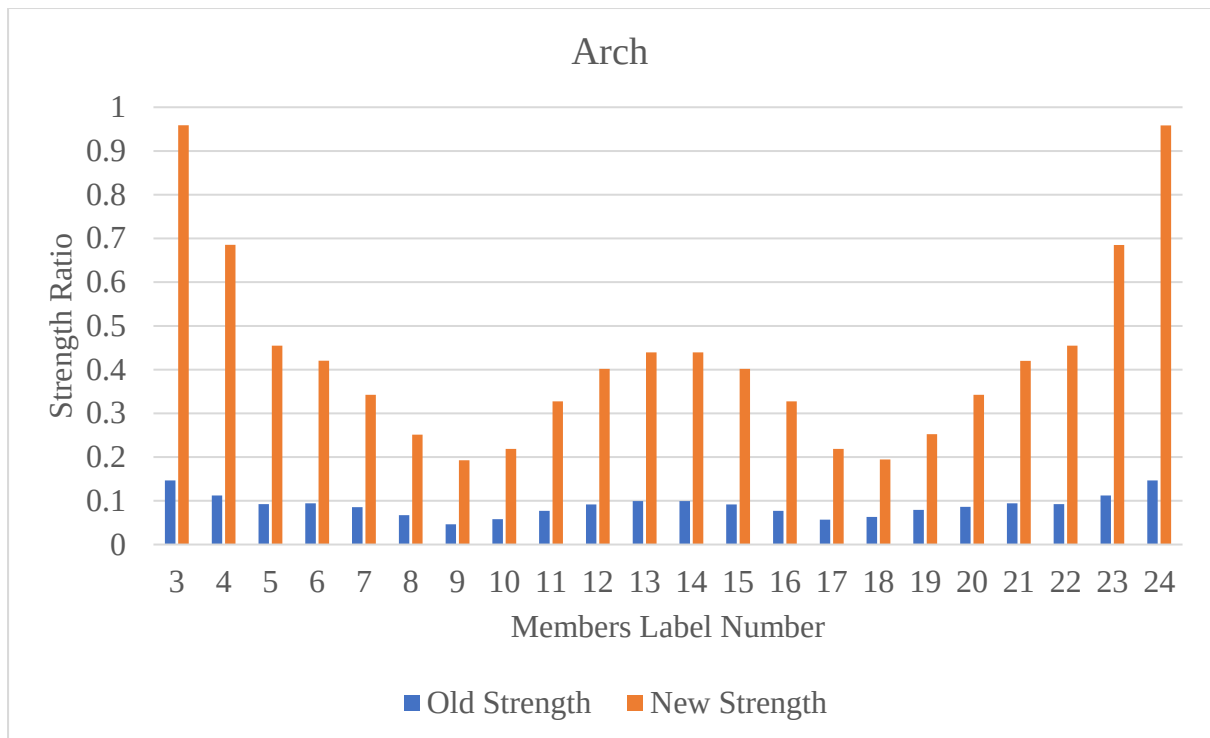


Figure 4-9 Arch Strength Ratio Before & After Optimization

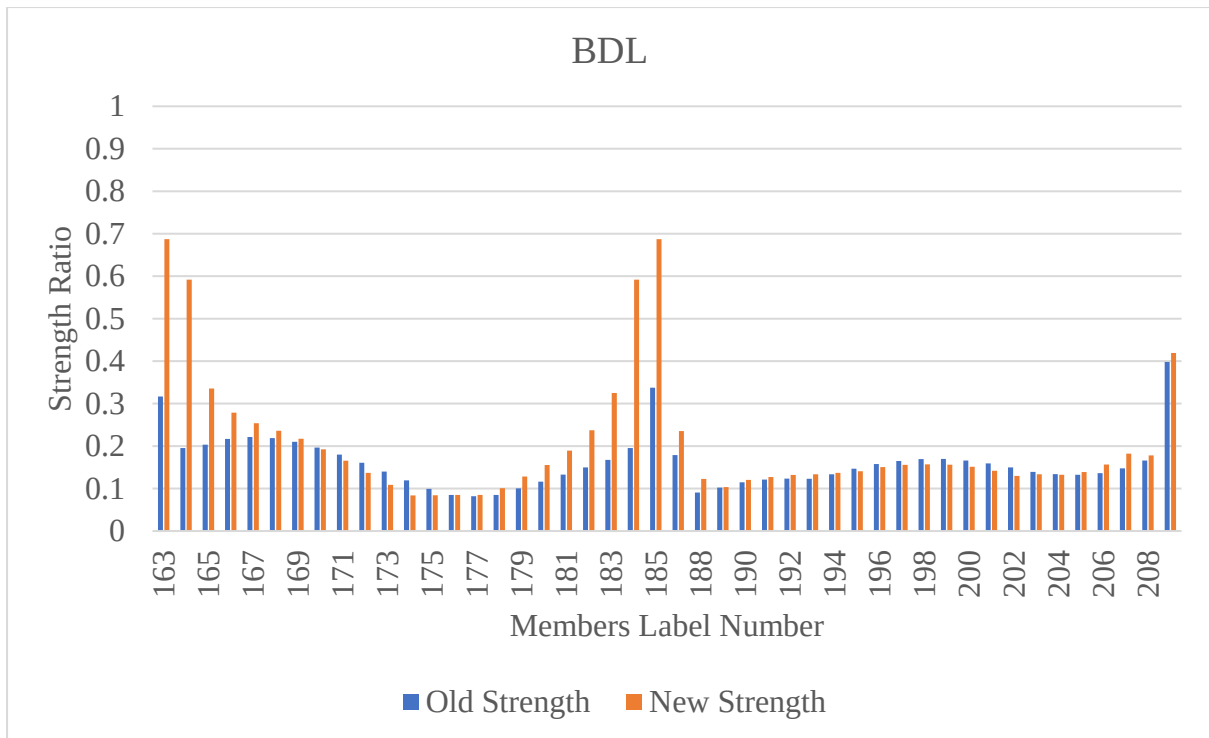


Figure 4-10 BDL Strength Ratio Before & After Optimization

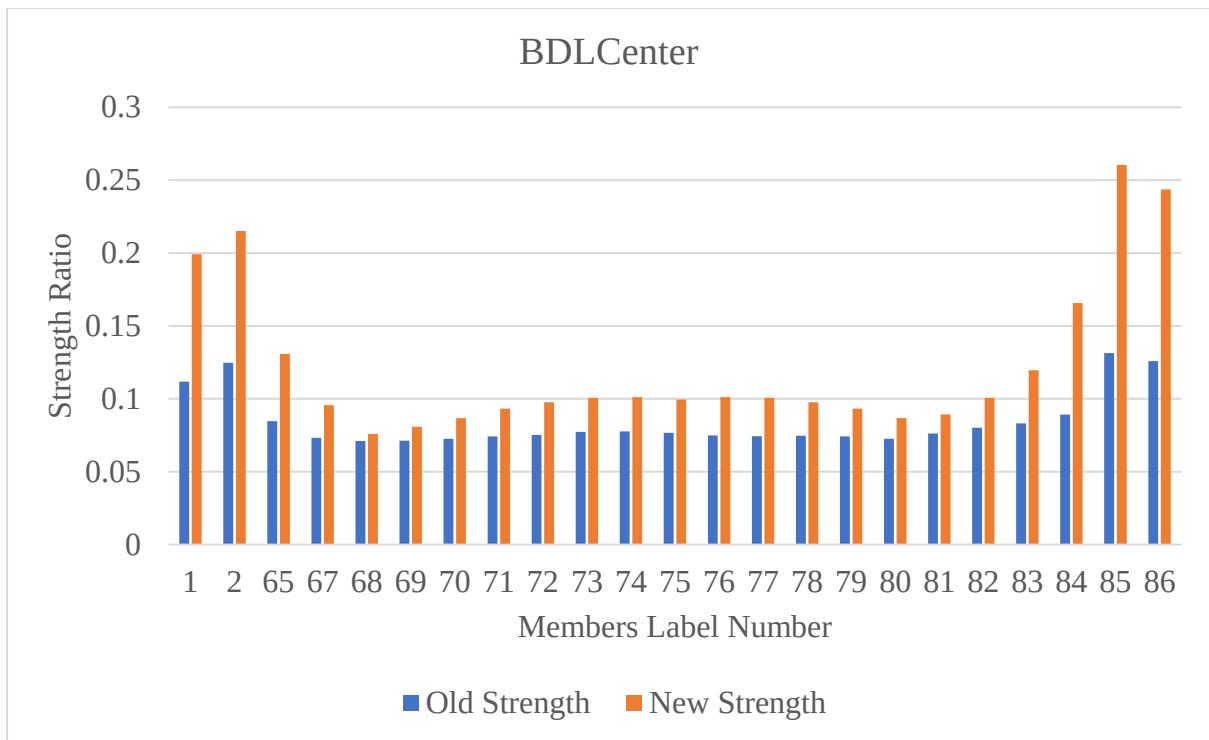


Figure 4-11 BDLCenter Strength Ratio Before & After Optimization

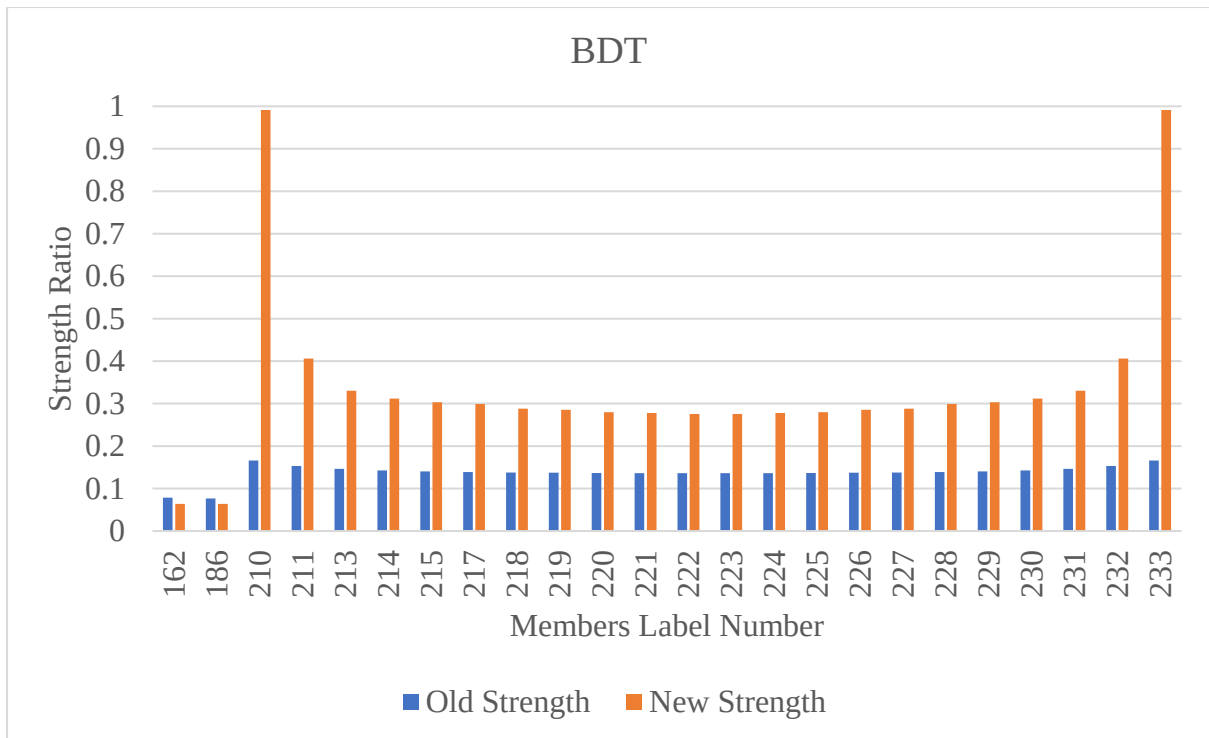


Figure 4-12 BDT Strength Ratio Before & After Optimization

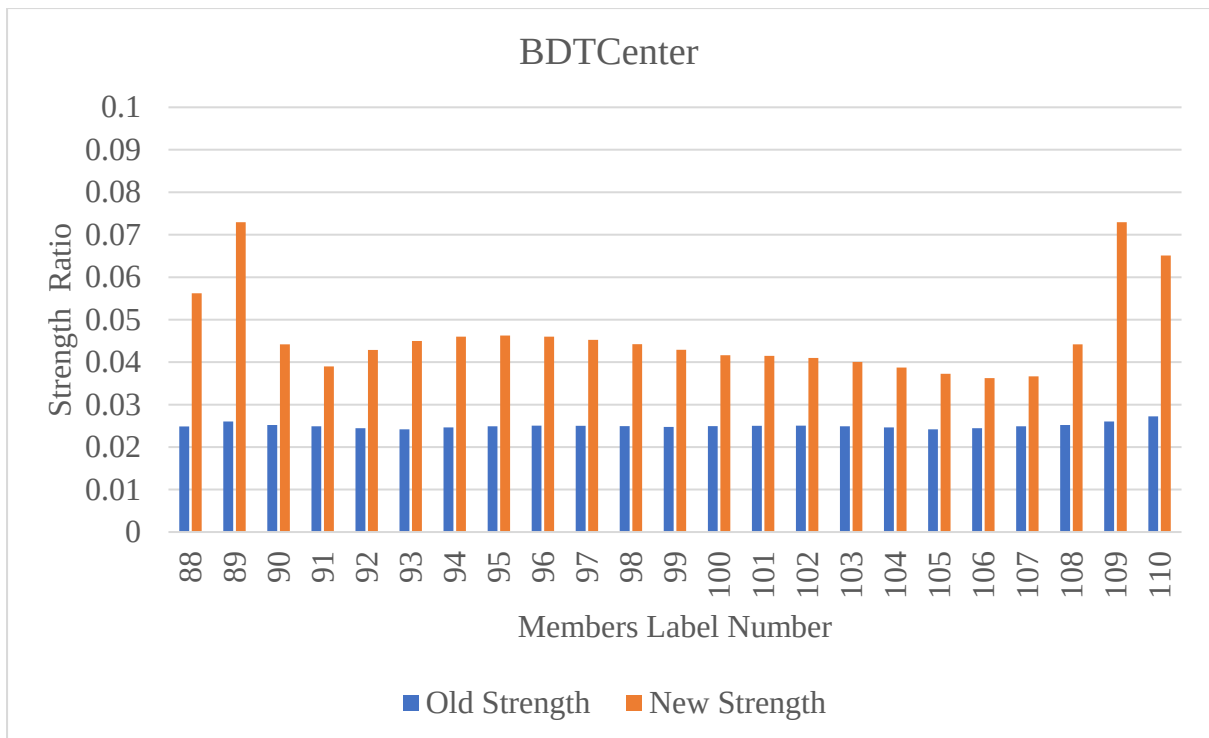


Figure 4-13 BDTCenter Strength Ratio Before & After Optimization

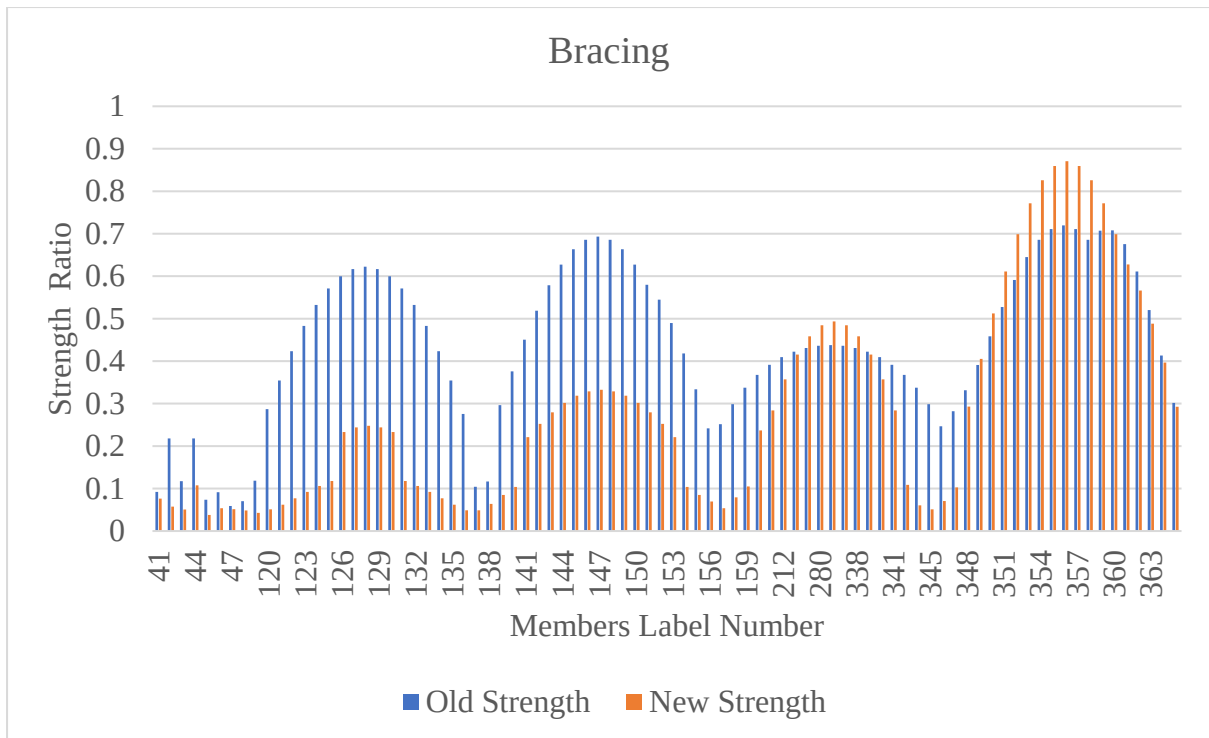


Figure 4-14 Bracing Strength Ratio Before & After Optimization

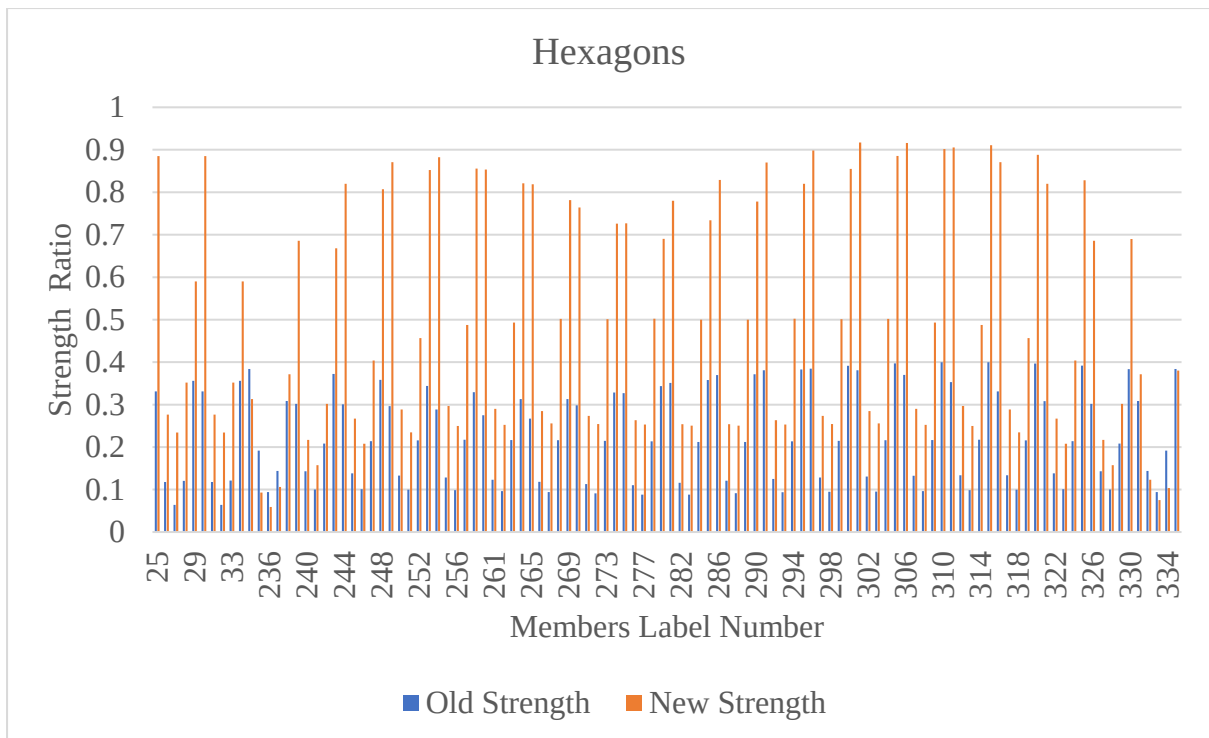


Figure 4-15 Hexagons Strength Ratio Before & After Optimization

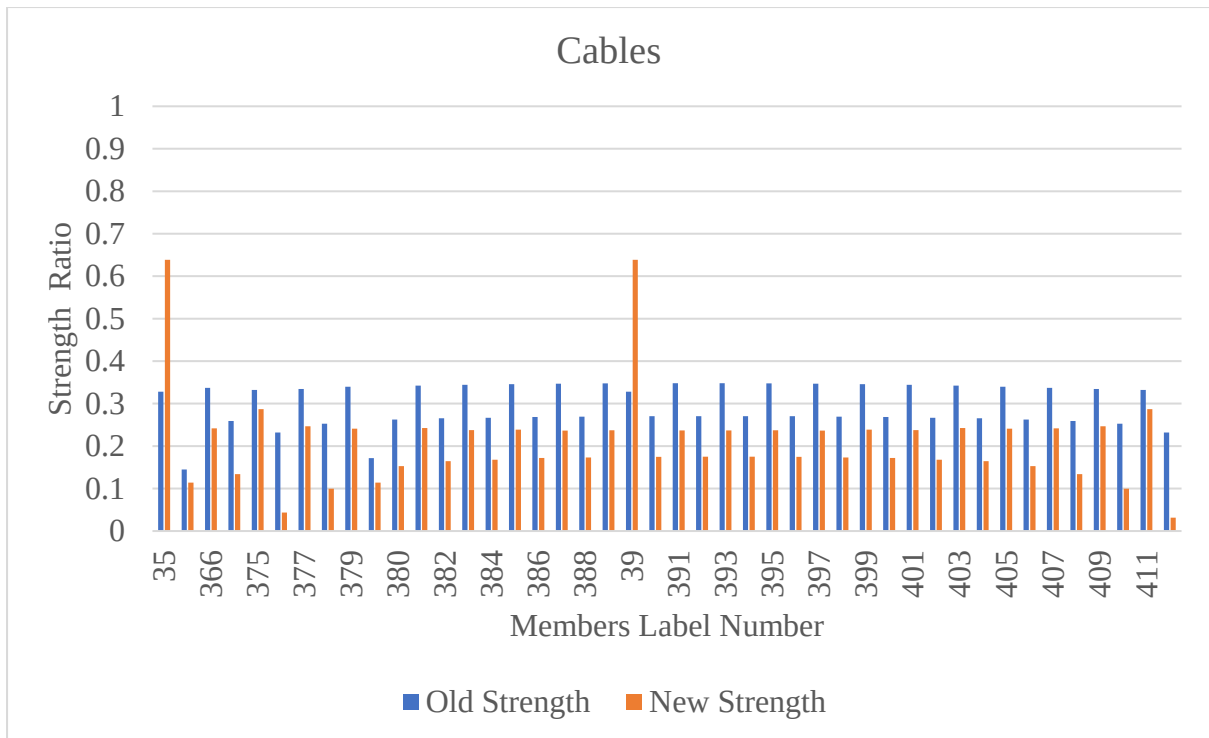


Figure 4-16 Cables Strength Ratio Before & After Optimization

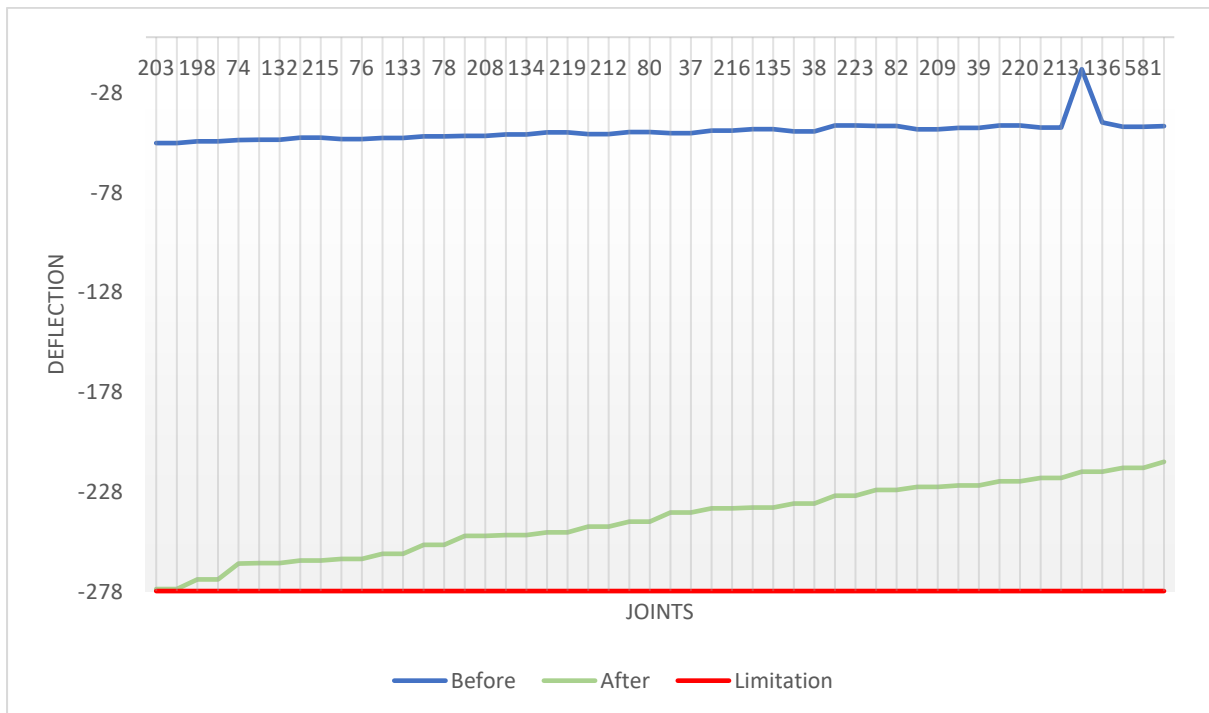


Figure 4-17 Largest Vertical Deflection of 50 Joints Before & After Optimization

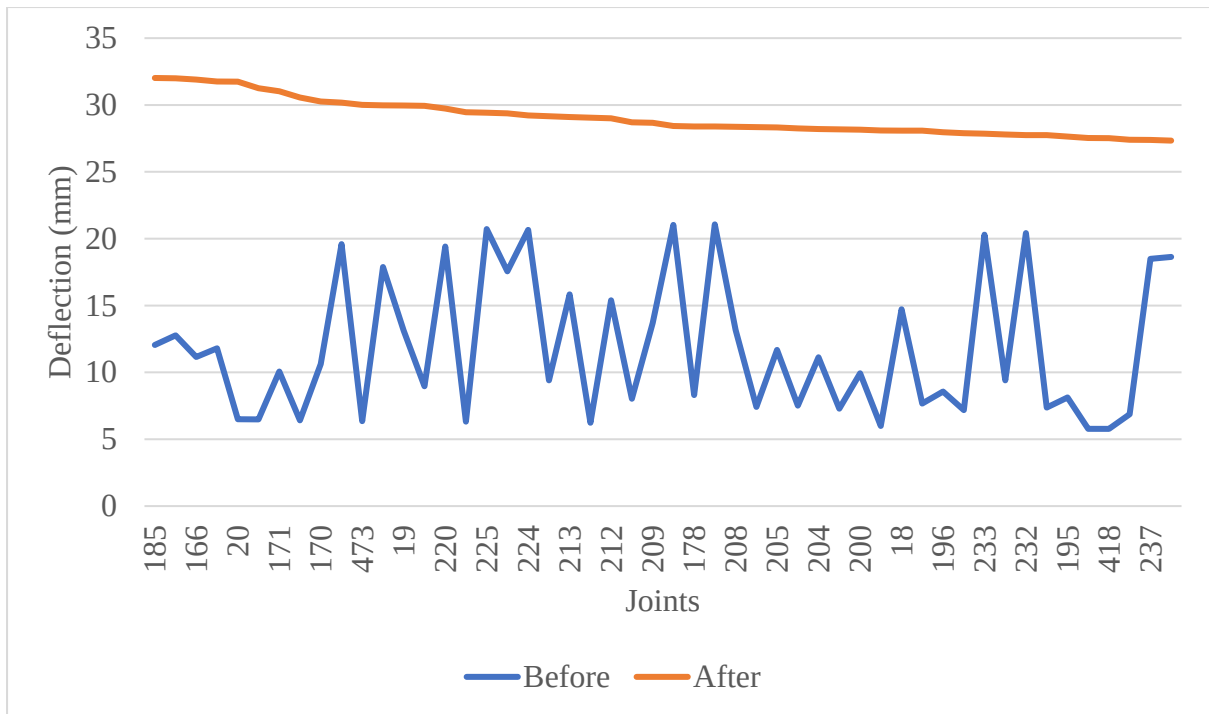


Figure 4-18 Largest Horizontal Deflection of 50 Joints Before & After Optimization

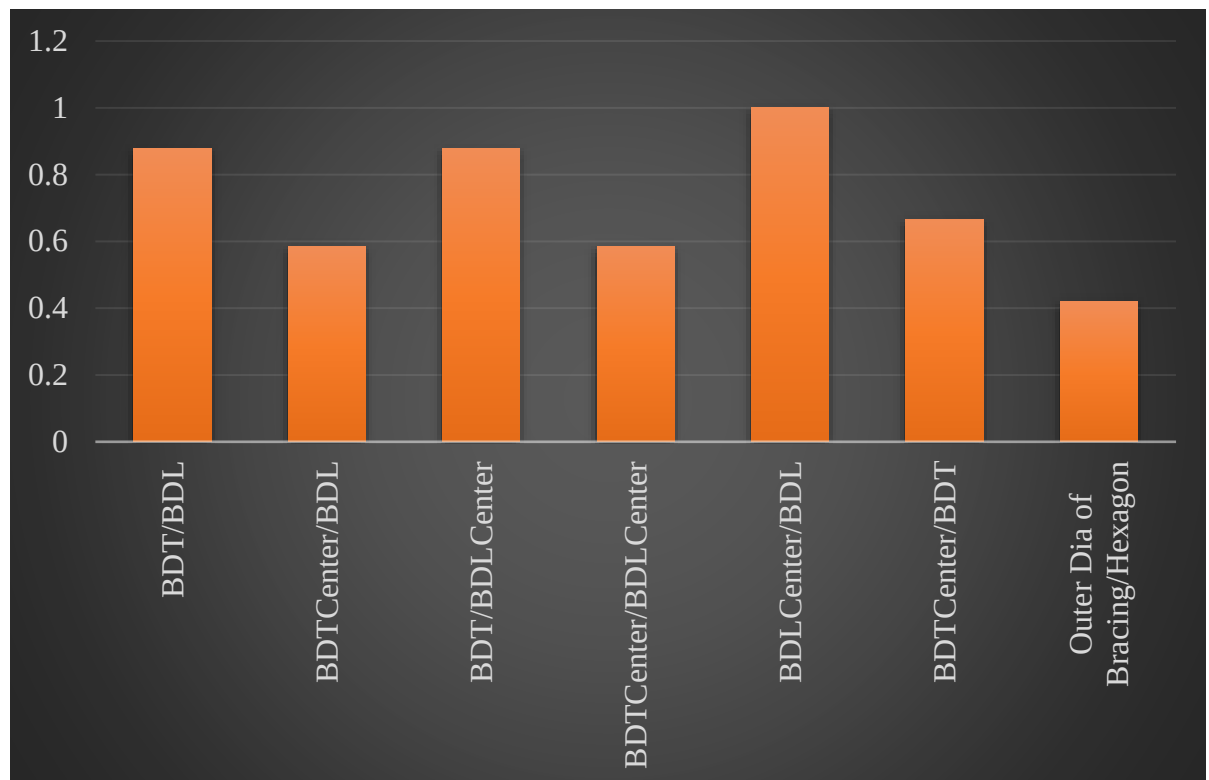


Figure 4-19 Geometry Constraints between Sections as per Equations 3-18 & 3-19

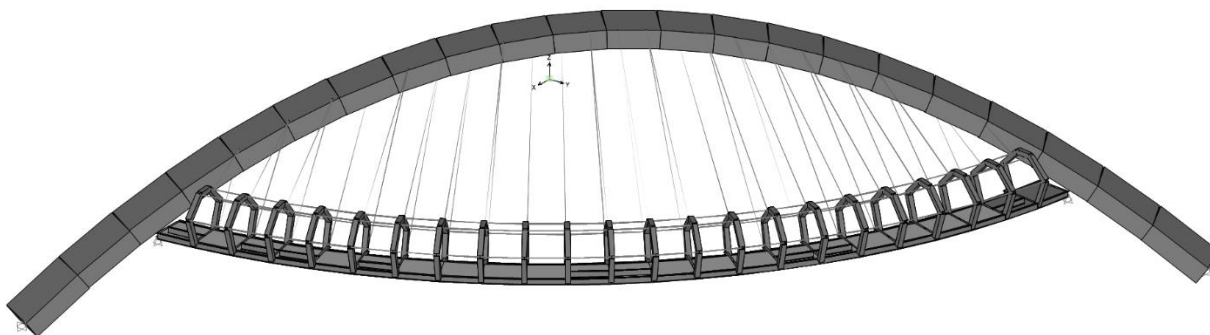


Figure 4-20 Footbridge Structure Before Optimization

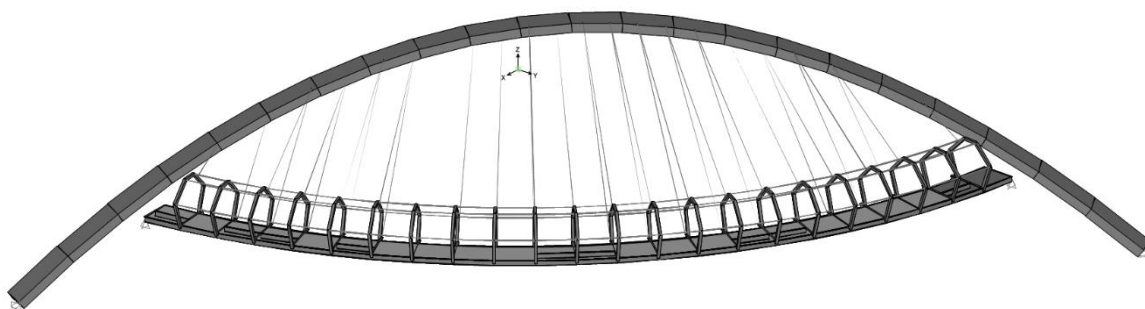


Figure 4-21 Footbridge Structure After Optimization

CHAPTER FIVE

CONCLUSION

Chapter 5 Conclusion

This chapter clears the research works implantation for achieving its objective; however, it discusses further work that can be performed and recommendations and guidelines that has been executed in this research.

5.1 Main Research Fulfilments

This section explains the accomplishing of research objectives as follows:

- ✓ **Design the old concept of the I-4 Maitland pedestrian bridge in Florida State according to provisions of AASHTO LRFD Guide Specifications.**

The footbridge is modeled to resemble the old concept of the I-4 Maitland pedestrian bridge. The footbridge structure consists of a 100 m curved steel frame deck hanging by an arch through steel cables. The frame deck contains three parallel lines along the deck and a row of transverse beams. There are 22 hexagons constructed perpendicularly on the deck frame. The whole frame structure is made of S355 Steel. The arch is 24.5 m in height and inclined by 20° from the vertical line against the bridge deck location. The member sections are defined as a W-section for the frame deck, an HSS section for hexagons, a built-up HSS section for the arch, a pipe section for bracing members among the hexagons, and a circular section for the cables.

In addition, the footbridge is designated to bear only static loads represented in a safety handrail with 2.92 kN/m weight as dead load with 4.31Kpa pedestrian loads and wind load of 105mph speed. The wind load is assumed to cover all directions considering its angles of 0 to 315 degrees with a 45-degree step, and the exposure category of the bridge area is C. The structure is analyzed nonlinearly (P-Delta) under three load combinations: strength-I, strength-III, and service-I to satisfy the AASHTO requirement. Furthermore, SAP2000 software is used for modeling, analysis, and checking the constraints of the structure.

- ✓ **Achieve an eligible safe, optimum design for the mentioned pedestrian bridge as per AISC360-16 specifications.**

The desired pedestrian bridge is optimized to reduce the total weight. The total weight decrement relates to the reduction of the cross sections of the structure members. The footbridge constraints are estimated concerning AISC 360-16 specifications. As mentioned earlier, the structure is checked by SAP2000, which doesn't have AASHTO standards in its database and has only AISC 360 LRFD library; however, AISC 360 and AASHTO codes are almost the same.

The program was initiated to run using 1000 iterations for each algorithm to minimize required iteration for each which decrease the time consumption for run. In each algorithm, the program is run 5 times with different random number to measure the efficiency of each algorithm. After the optimization process completion, the final cross-sections of the members are reduced, fulfilling the constraints conditions and decreasing the total weight to 502.76 Ton (4932 KN).

Table 5-1 Optimum Sections are Developed by DE Algorithm

Member Name	Section Shape	Section Name	Depth (mm)	Width (mm)	Flange Thick. (mm)	Web Thick. (mm)
Arch	HSS (Hollow Tube)	Built-Up Section	1000	3000	65	50
Bridge Deck Long	W (I-section)	W530 X 66	526	165	11.4	8.89
Bridge Deck Long (Intermediate)	W (I-section)	W530 X 66	526	165	11.4	8.89
Bridge Deck Trans.	W (I-section)	W460 X 113	462	279	17.3	10.8
Bridge Deck Trans. (Intermediate)	W (I-section)	W 310 X 67	307	204	14.6	8.51
Bracing	Pipe	Pipe100STD	Outer Diameter=114.3 mm		Wall Thickness =6.02 mm	
Hexagons	HSS (Hollow Tube)	HSS 273.1 X 12.7	273	273	12.7	12.7
Cable	Circle	Diameter=37mm				

✓ **Evaluate the quality of each algorithm executed in the research.**

The optimization is carried out through three metaheuristic algorithms: ABC, TLBO, and DE and DE algorithm who surpasses the others in obtaining the best results because DE minimize the weight to 505.76 Tons (4932 KN) in 11.59 days while ABC obtain 636.57 Tons (6244.75 KN) in

21 days (3 weeks) and TLBO reach 522.48 Tons (5125.54 KN) with 30.89 days (1 month).

5.2 The Research Further work

This thesis opens many horizons for future works can be done such as

- Evaluate optimization design to contain dynamic loads due to pedestrian movements or seismic loads.
- Optimize the structure considering the vibration of pedestrian movements.
- Enhance used algorithms (ABC, TLBO, and DE) to improve the results obtained for such problems.
- Add the arch height or its inclination angle as a design variable in the optimization process.
- Use more metaheuristic algorithms to test their performance in such problems.
- Study different materials for the cables to handle this pedestrian bridge.
- Develop SAP2000 software to be able to optimize the modeled structure using metaheuristic algorithms by defining the parameters of the used algorithm and selecting the design variables. The user will specify the desired structure members into groups to set them as design variables in the optimization process. This development will make a new revolution in the structure design field.

5.3 The Recommendations and Guidelines for this research

This research provides some recommendations and guidelines can be concerned as:

- The optimized design of this footbridge can be constructed in real life in addition to consider seismic load.

- MATLAB commands are created to be a general concept for any optimization design of steel structure, even is not a bridge by suiting the parameters of the desired structure and additional required constraints.

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APPENDIX-A

Design Pool Schedules

APPENDIX-A Design Pool Schedules

The Design Pool for each Variable

Table A- 1 the design pool of A1 ~ A4 (W-section)

Sl. NO.	Section Name (AISC)	Depth (d) (mm)	Width (b) (mm)	Web thickness (t _w) (mm)	flange thickness (t _f) (mm)	Area (a) (mm ²)
1	W530X66	526	165	8.89	11.4	8390
2	W310X67	307	204	8.51	14.6	8450
3	W410X67	409	179	8.76	14.4	8580
4	W250X67	257	204	8.89	15.7	8580
5	W460X68	460	154	9.14	15.4	8710
6	W200X71	216	206	10.2	17.4	9100
7	W530X72	523	207	8.89	10.9	9100
8	W360X72	351	204	8.64	15.1	9100
9	W250X73	254	254	8.64	14.2	9290
10	W310X74	310	205	9.40	16.3	9420
11	W530X74	528	166	9.65	13.6	9480
12	W460X74	457	191	9.02	14.5	9480
13	W410X75	414	180	9.65	16.0	9480
14	W360X79	353	205	9.40	16.8	10100
15	W310X79	307	254	8.76	14.6	10100
16	W250X80	257	254	9.40	15.6	10200
17	W610X82	599	178	10.0	12.8	10500
18	W530X82	528	209	9.53	13.3	10500
19	W460X82	460	191	9.91	16.0	10500
20	W530X85	536	167	10.3	16.5	10800

21	W410X85	417	181	10.9	18.2	10800
22	W310X86	310	254	9.14	16.3	11000
23	W200X86	222	209	13.0	20.6	11000
24	W460X89	462	192	10.5	17.7	11400
25	W250X89	259	257	10.7	17.3	11400
26	W360X91	353	254	9.53	16.4	11500
27	W610X92	602	179	10.9	15.0	11700
28	W530X92	533	209	10.2	15.6	11800
29	W460X97	467	193	11.4	19.1	12300
30	W310X97	307	305	9.91	15.4	12300
31	W410X100	414	259	10.0	16.9	12600
32	W200X100	229	210	14.5	23.7	12700
33	W250X101	264	257	11.9	19.6	12800
34	W530X101	536	210	10.9	17.4	12900
35	W360X101	356	254	10.5	18.3	12900
36	W610X101	602	228	10.5	14.9	13000
37	W460X106	470	194	12.6	20.6	13500
38	W310X107	312	305	10.9	17.0	13600
39	W530X109	538	211	11.6	18.8	13900
40	W360X110	361	257	11.4	19.9	14100
41	W460X113	462	279	10.8	17.3	14400
42	W610X113	607	228	11.2	17.3	14500
43	W410X114	419	262	11.6	19.3	14600
44	W250X115	269	259	13.5	22.1	14600
45	W310X117	315	307	11.9	18.7	15000
46	W360X122	363	257	13.0	21.7	15500
47	W530X123	544	212	13.1	21.2	15700
48	W690X125	678	254	11.7	16.3	15900

49	W610X125	612	229	11.9	19.6	15900
50	W460X128	467	282	12.2	19.6	16300
51	W310X129	318	307	13.1	20.6	16500
52	W250X131	274	262	15.4	25.1	16800
53	W410X132	427	264	13.3	22.2	16900
54	W760X134	749	264	11.9	15.5	17000
55	W360X134	356	368	11.2	18.0	17100
56	W530X138	549	214	14.7	23.6	17600
57	W690X140	683	254	12.4	18.9	17800
58	W610X140	617	230	13.1	22.2	17900
59	W310X143	323	310	14.0	22.9	18200
60	W460X144	472	282	13.6	22.1	18400
61	W760X147	754	267	13.2	17.0	18700
62	W360X147	361	371	12.3	19.8	18800
63	W250X149	282	262	17.3	28.4	18900
64	W410X149	432	264	14.9	25.0	19000
65	W530X150	544	312	12.7	20.3	19200
66	W690X152	688	254	13.1	21.1	19400
67	W610X153	622	229	14.0	24.9	19500
68	W610X155	612	325	12.7	19.1	19800
69	W460X158	475	284	15.0	23.9	20100
70	W310X158	328	310	15.5	25.1	20100
71	W760X161	757	267	13.8	19.3	20500
72	W360X162	363	371	13.3	21.8	20600
73	W530X165	546	312	14.0	22.2	21000
74	W250X167	290	264	19.2	31.8	21200
75	W690X170	693	257	14.5	23.6	21700
76	W760X173	762	267	14.4	21.6	22100

77	W610X174	617	325	14.0	21.6	22200
78	W840X176	836	292	14.0	18.8	22400
79	W460X177	483	287	16.6	26.9	22600
80	W310X179	333	312	18.0	28.2	22700
81	W360X179	368	373	15.0	23.9	22800
82	W530X182	551	315	15.2	24.4	23200
83	W760X185	767	267	14.9	23.6	23500
84	W690X192	701	254	15.5	27.9	24400
85	W840X193	841	292	14.7	21.7	24700
86	W460X193	490	284	17.0	30.5	24700
87	W610X195	622	328	15.4	24.4	24900
88	W760X196	770	267	15.6	25.4	25000
89	W530X196	554	315	16.5	26.4	25000
90	W360X196	373	373	16.4	26.2	25000
91	W920X201	904	305	15.2	20.1	25700
92	W310X202	340	315	20.1	31.8	25700
93	W840X210	846	292	15.4	24.4	26800
94	W460X213	495	284	18.5	33.5	27100
95	W360X216	376	394	17.3	27.7	27500
96	W610X217	627	328	16.5	27.7	27700
97	W690X217	696	356	15.4	24.8	27900
98	W530X219	561	318	18.3	29.2	27900
99	W760X220	780	267	16.5	30.0	28100
100	W1000X222	970	300	16.0	21.1	28300
101	W920X223	912	305	15.9	23.9	28600

Table A- 2 The design pool of A5 (Pipe-section)

Sl. NO.	Section Name (AISC)	Outer Diameter (OD) (mm)	Wall Thickness (wt) (mm)	Area (a) (mm ²)
1	Pipe15STD	21.3	2.77	151
2	Pipe15XS	21.3	3.73	195
3	Pipe20STD	26.7	2.87	201
4	Pipe20XS	26.7	3.91	263
5	Pipe25STD	33.4	3.38	303
6	Pipe25XS	33.5	4.55	388
7	Pipe32STD	42.2	3.56	403
8	Pipe40STD	48.3	3.68	483
9	Pipe32XS	42.2	4.85	540
10	Pipe40XS	48.3	5.08	645
11	Pipe50STD	60.3	3.91	658
12	Pipe50XS	60.3	5.54	903
13	Pipe65STD	73.0	5.16	1040
14	Pipe80STD	88.9	5.49	1340
15	Pipe65XS	73.0	7.01	1350
16	Pipe90STD	101.6	5.74	1610
17	Pipe50XXS	60.3	11.1	1620
18	Pipe80XS	88.9	7.62	1830
19	Pipe100STD	114.3	6.02	1910
20	Pipe90XS	101.6	8.08	2210
21	Pipe65XXS	73.0	14.0	2470
22	Pipe125STD	141.3	6.55	2590
23	Pipe100XS	114.3	8.56	2670
24	Pipe80XXS	88.9	15.2	3340

25	Pipe150STD	168.3	7.11	3350
26	Pipe125XS	141.3	9.53	3700
27	Pipe100XXS	114.3	17.1	4940
28	Pipe150XS	168.3	11.0	5050
29	Pipe200STD	219.1	8.18	5060
30	Pipe125XXS	141.3	19.1	6900
31	Pipe250STD	273.0	9.27	7420
32	Pipe200XS	219.1	12.7	7680
33	Pipe300STD	323.8	9.53	8840
34	Pipe150XXS	168.3	21.9	9480
35	Pipe350STD	355.6	9.53	9680
36	Pipe250XS	273.0	12.7	9740
37	Pipe400STD	406.4	9.53	11100
38	Pipe300XS	323.8	12.7	11300
39	Pipe350XS	355.6	12.7	12400
40	Pipe450STD	457	9.53	12500
41	Pipe200XXS	219.1	22.2	12900
42	Pipe500STD	508	9.53	13900
43	Pipe400XS	406.4	12.7	14200
44	Pipe450XS	457	12.7	16000
45	Pipe600STD	610	9.53	16800
46	Pipe500XS	508	12.7	17800
47	Pipe650STD	660	9.53	18200
48	Pipe250XXS	273.0	25.4	18600
49	Pipe600XS	610	12.7	21500
50	Pipe300XXS	323.8	25.4	22800
51	Pipe650XS	660	12.7	23300

Table A- 3 The design pool of A6 (HSS-section)

Sl. NO.	Section Name (AISC)	Depth (d) (mm)	Width (b) (mm)	Thickness (t) (mm)	Area (a) (mm ²)
1	HSS228.6X177.8X12.7	229	178.0	12.7	8710
2	HSS203.2X203.2X12.7	203	203.0	12.7	8710
3	HSS323.9X9.5	324	324.0	9.53	8770
4	HSS254X12.7	254	254.0	12.7	8970
5	HSS254X101.6X15.9	254	102.0	15.9	9030
6	HSS228.6X127X15.9	229	127.0	15.9	9030
7	HSS203.2X152.4X15.9	203	152.0	15.9	9030
8	HSS177.8X177.8X15.9	178	178.0	15.9	9030
9	HSS406.4X7.9	406	406.0	7.94	9290
10	HSS304.8X254X9.5	305	254.0	9.53	9420
11	HSS219.1X15.9	219	219.0	15.9	9480
12	HSS355.6X9.5	356	356.0	9.53	9680
13	HSS273.1X12.7	273	273.0	12.7	9680
14	HSS355.6X101.6X12.7	356	102.0	12.7	9870
15	HSS304.8X152.4X12.7	305	152.0	12.7	9870
16	HSS254X203.2X12.7	254	203.0	12.7	9870
17	HSS228.6X228.6X12.7	229	229.0	12.7	9870
18	HSS508X203.2X7.9	508	203.0	7.94	10100
19	HSS406.4X304.8X7.9	406	305.0	7.94	10100
20	HSS355.6X355.6X7.9	356	356.0	7.94	10100
21	HSS508X101.6X9.5	508	102.0	9.53	10300
22	HSS457.2X152.4X9.5	457	152.0	9.53	10300
23	HSS406.4X203.2X9.5	406	203.0	9.53	10300
24	HSS355.6X254X9.5	356	254.0	9.53	10300

25	HSS304.8X304.8X9.5	305	305.0	9.53	10300
26	HSS304.8X101.6X15.9	305	102.0	15.9	10600
27	HSS254X152.4X15.9	254	152.0	15.9	10600
28	HSS228.6X177.8X15.9	229	178.0	15.9	10600
29	HSS203.2X203.2X15.9	203	203.0	15.9	10600
30	HSS406.4X101.6X12.7	406	102.0	12.7	11100
31	HSS355.6X152.4X12.7	356	152.0	12.7	11100
32	HSS304.8X203.2X12.7	305	203.0	12.7	11100
33	HSS254X254X12.7	254	254.0	12.7	11100
34	HSS406.4X9.5	406	406.0	9.53	11100
35	HSS254X15.9	254	254.0	15.9	11100
36	HSS323.9X12.7	324	324.0	12.7	11500
37	HSS508X304.8X7.9	508	305.0	7.94	11700
38	HSS406.4X406.4X7.9	406	406.0	7.94	11700
39	HSS508X203.2X9.5	508	203.0	9.53	12100
40	HSS406.4X304.8X9.5	406	305.0	9.53	12100
41	HSS355.6X355.6X9.5	356	356.0	9.53	12100
42	HSS355.6X101.6X15.9	356	102.0	15.9	12100
43	HSS304.8X152.4X15.9	305	152.0	15.9	12100
44	HSS254X203.2X15.9	254	203.0	15.9	12100
45	HSS228.6X228.6X15.9	229	229.0	15.9	12100
46	HSS304.8X254X12.7	305	254.0	12.7	12300
47	HSS457.2X9.5	457	457.0	9.53	12500
48	HSS406.4X11.1	406	406.0	11.1	12800
49	HSS355.6X12.7	356	356.0	12.7	12800
50	HSS508X101.6X12.7	508	102.0	12.7	13500
51	HSS457.2X152.4X12.7	457	152.0	12.7	13500
52	HSS406.4X203.2X12.7	406	203.0	12.7	13500

53	HSS406.4X101.6X15.9	406	102.0	15.9	13500
54	HSS355.6X254X12.7	356	254.0	12.7	13500
55	HSS355.6X152.4X15.9	356	152.0	15.9	13500
56	HSS304.8X304.8X12.7	305	305.0	12.7	13500
57	HSS304.8X203.2X15.9	305	203.0	15.9	13500
58	HSS254X254X15.9	254	254.0	15.9	13500
59	HSS508X304.8X9.5	508	305.0	9.53	13900
60	HSS406.4X406.4X9.5	406	406.0	9.53	13900
61	HSS508X9.5	508	508.0	9.53	13900
62	HSS406.4X12.7	406	406.0	12.7	14600
63	HSS355.6X15.9	356	356.0	15.9	15800
64	HSS508X203.2X12.7	508	203.0	12.7	15900
65	HSS406.4X304.8X12.7	406	305.0	12.7	15900
66	HSS355.6X355.6X12.7	356	356.0	12.7	15900
67	HSS254X254X19	254	254.0	19.1	15900
68	HSS457.2X12.7	457	457.0	12.7	16500
69	HSS457.2X152.4X15.9	457	152.0	15.9	16600
70	HSS406.4X203.2X15.9	406	203.0	15.9	16600
71	HSS355.6X254X15.9	356	254.0	15.9	16600
72	HSS304.8X304.8X15.9	305	305.0	15.9	16600
73	HSS406.4X15.9	406	406.0	15.9	18100
74	HSS508X304.8X12.7	508	305.0	12.7	18300
75	HSS406.4X406.4X12.7	406	406.0	12.7	18300
76	HSS508X12.7	508	508.0	12.7	18400
77	HSS508X203.2X15.9	508	203.0	15.9	19500
78	HSS406.4X304.8X15.9	406	305.0	15.9	19500
79	HSS355.6X355.6X15.9	356	356.0	15.9	19500
80	HSS304.8X304.8X19	305	305.0	19.1	19500

81	HSS609.6X304.8X12.7	610	305.0	12.7	20700
82	HSS457.2X457.2X12.7	457	457.0	12.7	20700
83	HSS508X304.8X15.9	508	305.0	15.9	22600
84	HSS406.4X406.4X15.9	406	406.0	15.9	22600
85	HSS508X508X12.7	508	508.0	12.7	23100
86	HSS406.4X304.8X19	406	305.0	19.1	23200
87	HSS355.6X355.6X19	356	356.0	19.1	23200
88	HSS609.6X304.8X15.9	610	305.0	15.9	25500
89	HSS457.2X457.2X15.9	457	457.0	15.9	25500
90	HSS355.6X355.6X22.2	356	356.0	22.2	26600
91	HSS508X304.8X19	508	305.0	19.1	26800
92	HSS406.4X406.4X19.0	406	406.0	19.1	26800
93	HSS508X508X15.9	508	508.0	15.9	28600
94	HSS609.6X304.8X19	610	305.0	19.1	30400
95	HSS457.2X457.2X19	457	457.0	19.1	30400
96	HSS406.4X406.4X22.2	406	406.0	22.2	30800
97	HSS508X508X19	508	508.0	19.1	33900
98	HSS457.2X457.2X22.2	457	457.0	22.2	35000
99	HSS558.8X558.8X19	559	559.0	19.1	37600
100	HSS508X508X22.2	508	508.0	22.2	39200
101	HSS558.8X558.8X22.2	559	559.0	22.2	43400

Table A- 4 Design Pool of Built-up Sections (Arch & Cables)

Interval	Arch Dimension Vectors (mm)				Cable (mm)
	Depth (D)	Width (B)	Flange thick. (FT)	Web Thick. (WT)	Diameter (Dia.)
	I ₇	I ₈	I ₉	I ₁₀	I ₁₁
Start	1000	1000	50	50	10
End	3500	3500	150	150	110
Increment	25	25	1	1	1

APPENDIX-B

MATLAB Scripts & Functions

APPENDIX-B MATLAB Scripts & Functions

Main MATLAB Script

Main MATLAB script is classified to six sections as follows:

Section One “Opening SAP2000 and Reset the model”:

```
%Opening SAP2000 V20
clc;
clear;
close all;
SM.App( 'sap' );
SM.Ver( '20' );
%create Sap2000 object
APIDLPath ='C:\Program Files\Computers and Structures\SAP2000
20\SAP2000v20.dll';
ProgramPath =' "E:\Master Course\1-Master Thesis\Program\runasdate-
x64\RunAsDate.exe" /movetime 01\01\2018 00:00:00 "C:\Program
Files\Computers and Structures\SAP2000 20\SAP2000.exe" ';
[Sobj] = SM.Helper.CreateObject( ProgramPath,APIDLPath );
%create SapModel object
[ Smdl ]=SM.SapModel();
%start Sap2000 application
SM.ApplicationStart;
%initialize model
ret = SM.InitializeNewModel;
ModelName = 'Model (1)_V16.sdb';
ModelPath = fullfile('E:\Master Course\1-Master Thesis\Final Model for
API\1. Final Model',ModelName);
ret = SM.File.OpenFile(ModelPath);
ret = SM.SetPresentUnits(SM.eUnits.kN_mm_C); %Defining units
ret = SM.DesignSteel.DeleteResults; %Reset all pervious results
ret = SM.SetModelIsLocked(false); %Reset all pervious analyzing
```

Section Two “Identify Variables”:

```
nVar = 11; % D Number of Unknown Variables
VarSize = [1 nVar]; % Unknown Variables Matrix Size (NOT Change)
% VarMin=[Wmin4 Bracing Hexagons Archd Archb Archtf Archtw Cablemin]
VarMin =[50 50 50 50 1 416 1 1 1 1 1];
```

```

% VarMax=[Wmax4 Bracing Hexagons Archd Archb Archtf Archtw Cablemax]
VarMax =[150 150 150 150 51 516 100 100 100 100 100];

MaxIt=600;           % Maximum Number of Iterations
nPop=50;             % Population Size
rng(1);             % Random values controller

```

Section Three “Metaheuristic Algorithm Approach”:

ABC Algorithm

```

nOnlooker=nPop;      % Number of Onlooker Bees
L=100; %round(0.5*nVar*nPop); % Abandonment Limit Parameter (Trial Limit)
a=1;                 % Acceleration Coefficient Upper Bound
% Empty Bee Structure
empty_bee.Var=[];
empty_bee.Weight=[];
% Initialize Population Array
pop=repmat(empty_bee,nPop,1);
% Initialize Best Solution Ever Found
BestSol.Weight=inf;
% Create Initial Population
for i=1:nPop
    pop(i).Var = ceil(unifrnd(VarMin, VarMax));
    [pop(i).Weight] = WeightFunction(pop(i).Var);
    if pop(i).Weight < BestSol.Weight
        BestSol = pop(i);
    end
end
% Abandonment Counter
C=zeros(nPop,1);
% Array to Hold Best Cost Values
BestWeight=zeros(MaxIt,1);
%% ABC Main Loop
for it=1:MaxIt
    % Recruited Bees
    for i=1:nPop
        % Choose k randomly, not equal to i
        K=[1:i-1 i+1:nPop];
        k=K(randi([1 numel(K)]));
    end
end

```

```

% Define Acceleration Coeff.
phi=a*unifrnd(-1,+1,VarSize);
% New Bee Position
newbee.Var=ceil(pop(i).Var+phi.*(pop(i).Var-pop(k).Var));
% Clipping
newbee.Var = max(newbee.Var, VarMin);
newbee.Var = min(newbee.Var, VarMax);
% Evaluation
[newbee.Weight] = WeightFunction(newbee.Var);
% Comparision
if newbee.Weight<=pop(i).Weight
    pop(i)=newbee;
else
    C(i)=C(i)+1;
end
end
% Calculate Fitness Values and Selection Probabilities
F=zeros(nPop,1);
MeanWeight = mean([pop.Weight]);
for i=1:nPop
    F(i) = exp(-pop(i).Weight/MeanWeight); % Convert Cost to Fitness
end
P=F/sum(F);
% Onlooker Bees
for m=1:nOnlooker
    % Select Source Site
    i=RouletteWheelSelection(P);

```

```

% RouletteWheelSelection Function

function i = RouletteWheelSelection(P)

    r = rand;

    C = cumsum(P);

    i = find(r <= C, 1, 'first');

end

```

```

% Choose k randomly, not equal to i
K=[1:i-1 i+1:nPop];

```

```

k=K(randi([1 numel(K)]));
% Define Acceleration Coeff.
phi=a*unifrnd(-1,+1,VarSize);
% New Bee Position
newbee.Var=ceil(pop(i).Var+phi.*(pop(i).Var-pop(k).Var));
% Clipping
newbee.Var = max(newbee.Var, VarMin);
newbee.Var = min(newbee.Var, VarMax);
% Evaluation
[newbee.Weight] = WeightFunction(newbee.Var);
% Comparision
if newbee.Weight<=pop(i).Weight
    pop(i)=newbee;
else
    C(i)=C(i)+1;
end
end
% Scout Bees
for i=1:nPop
    if C(i)>=L
        pop(i).Var = ceil(unifrnd(VarMin, VarMax));
        [pop(i).Weight] = WeightFunction(pop(i).Var);
        C(i)=0;
    end
end
% Update Best Solution Ever Found
for i=1:nPop
    if pop(i).Weight<=BestSol.Weight
        BestSol=pop(i);
    end
end
% Store Record for Current Iteration
BestWeight(it) = BestSol.Weight;
[WEIGHT,C,sc,dc,gc] = WeightFunction(BestSol.Var);
% Show Iteration Information and each constraint
disp(['Iteration ' num2str(it) ': Best Weight = '
num2str(BestWeight(it)) ': C = ' num2str(C) ', SC = ' num2str(sc) ', DC = '
num2str(dc) ', GC = ' num2str(gc)]);
end

```

TLBO Algorithm

```
% Empty Structure for Individuals
empty_individual.Var = [];
empty_individual.Weight = [];
% Initialize Population Array
pop = repmat(empty_individual, nPop, 1);
% Initialize Best Solution
BestSol.Weight = inf;
% Initialize Population Members
for i=1:nPop
    pop(i).Var = ceil(unifrnd(VarMin, VarMax));
    [pop(i).Weight] = WeightFunction(pop(i).Var);
    if pop(i).Weight < BestSol.Weight
        BestSol = pop(i);
    end
end
% Initialize Best Cost Record
BestWeight = zeros(MaxIt,1);
%% TLBO Main Loop
for it=1:MaxIt
    % Calculate Population Mean
    Mean = 0;
    for i=1:nPop
        Mean = Mean + pop(i).Var;
    end
    Mean = Mean/nPop;
    % Select Teacher
    Teacher = pop(1);
    for i=2:nPop
        if pop(i).Weight < Teacher.Weight
            Teacher = pop(i);
        end
    end
    % Teacher Phase
    for i=1:nPop
        % Create Empty Solution
        newsol = empty_individual;
```

```

    % Teaching Factor
    TF = randi([1 2]);
    % Teaching (moving towards teacher)
    newsol.Var = ceil( pop(i).Var + rand(VarSize).*(Teacher.Var -
TF*Mean));
    % Clipping
    newsol.Var = max(newsol.Var, VarMin);
    newsol.Var = min(newsol.Var, VarMax);
    % Evaluation
    newsol.Weight = WeightFunction(newsol.Var);
    % Comparision
    if newsol.Weight < pop(i).Weight
        pop(i) = newsol;
        if pop(i).Weight < BestSol.Weight
            BestSol = pop(i);
        end
    end
end
% Learner Phase
for i=1:nPop
    A = 1:nPop;
    A(i)=[];
    j = A(randi(nPop-1));
    Step = pop(i).Var - pop(j).Var;
    if pop(j).Weight < pop(i).Weight
        Step = -Step;
    end
    % Create Empty Solution
    newsol = empty_individual;
    % Teaching (moving towards teacher)
    newsol.Var = ceil( pop(i).Var + rand(VarSize).*Step);
    % Clipping
    newsol.Var = max(newsol.Var, VarMin);
    newsol.Var = min(newsol.Var, VarMax);
    % Evaluation
    newsol.Weight = WeightFunction(newsol.Var);
    % Comparision
    if newsol.Weight < pop(i).Weight
        pop(i) = newsol;
        if pop(i).Weight < BestSol.Weight
            BestSol = pop(i);
        end
    end
end

```

```

        end
    end
end

% Store Record for Current Iteration
BestWeight(it) = BestSol.Weight;
[WEIGHT,C,sc,dc,gc] = WeightFunction(BestSol.Var);
% Show Iteration Information
disp(['Iteration ' num2str(it) ': Best Weight = '
num2str(BestWeight(it)) ': C = ' num2str(C) ', SC = ' num2str(sc) ', DC = '
num2str(dc) ', GC = ' num2str(gc)]);
end

```

DE Algorithm

```

beta_min=0.2; % Lower Bound of Scaling Factor
beta_max=0.8; % Upper Bound of Scaling Factor
pCR=0.2; % Crossover Probability
empty_individual.Var=[];
empty_individual.Weight=[];
BestSol.Weight=inf;
pop= repmat(empty_individual,nPop,1);
for i=1:nPop
    pop(i).Var = ceil(unifrnd(VarMin, VarMax));
    [pop(i).Weight] = WeightFunction(pop(i).Var);
    if pop(i).Weight < BestSol.Weight
        BestSol = pop(i);
    end
end
BestWeight=zeros(MaxIt,1);
%% DE Main Loop
for it=1:MaxIt
    for i=1:nPop
        x=pop(i).Var;
        A=randperm(nPop);
        A(A==i)=[];
        a=A(1);
        b=A(2);
        c=A(3);

```

```

% Mutation
%beta=unifrnd(beta_min,beta_max);
beta=unifrnd(beta_min,beta_max,VarSize);
y=ceil(pop(a).Var+beta.*(pop(b).Var-pop(c).Var));
y = max(y, VarMin);
y = min(y, VarMax);

% Crossover
z=zeros(size(x));
j0=randi([1 numel(x)]);
for j=1:numel(x)
    if j==j0 || rand<=pCR
        z(j)=y(j);
    else
        z(j)=x(j);
    end
end
NewSol.Var=z;
NewSol.Weight=WeightFunction(NewSol.Var);
if NewSol.Weight < pop(i).Weight
    pop(i)=NewSol;
    if pop(i).Weight < BestSol.Weight
        BestSol=pop(i);
    end
end

% Store Record for Current Iteration
BestWeight(it) = BestSol.Weight;
[WEIGHT,C1,sc,dc,gc] = WeightFunction(BestSol.Var);
% Show Iteration Information
disp(['Iteration ' num2str(it) ': Best Weight = '
num2str(BestWeight(it)) ': C = ' num2str(C1) ', SC = ' num2str(sc) ', DC =
' num2str(dc) ', GC = ' num2str(gc)']);

end

```

Section Four “Display the Results and Plot”:

```

figure;
%plot(BestWeights, 'LineWidth', 2);
semilogy(BestWeight, 'LineWidth', 2);
xlabel('Iteration');
ylabel('Best Weight');
grid on;
fname=["BDL" "BDLCenter" "BDT" "BDTCenter" "Bracing" "Hexagons" "Arch"
"Cable"];
BestSol

```

```

for i=1:11
    if i<5
        [a,d,b,f,w,n] = Wsection(BestSol.Var(i));
        disp([num2str(frname(i)) 'Section is' num2str(n) '= [depth('
num2str(d) '), width(' num2str(b) '), flangethick.( ' num2str(f) '),
webthick.( ' num2str(w) '), Area( ' num2str(a) ')]'])
        disp([' '])
    elseif i<6
        [a,od,wt,n] = Pipe(BestSol.Var(i));
        disp([num2str(frname(i)) 'Section is' num2str(n) '= [outer dia.( '
num2str(od) '), wall thick.( ' num2str(wt) '), Area( ' num2str(a) ')]'])
        disp([' '])
    elseif i<7
        [a,d,b,t,n] = Hsection(BestSol.Var(i));
        disp([num2str(frname(i)) 'Section is' num2str(n) '= [depth('
num2str(d) '), width( ' num2str(b) '), thickness( ' num2str(t) '), Area( '
num2str(a) ')]'])
        disp([' '])
    elseif i==7
        dpool=1000:25:3500;
        d=dpool(BestSol.Var(i));
    elseif i==8
        bpool=1000:25:3500;
        b=bpool(BestSol.Var(i));
    elseif i==9
        tfpool=50:1:150;
        tf=tfpool(BestSol.Var(i));
    elseif i==10
        twpool=50:1:150;
        tw=twpool(BestSol.Var(i));
        B =b-2*tw;
        D =d-2*tf;
        a=d.*b-D.*B;
        disp([num2str(frname(i-3)) 'Section is
(Depth,Width,flangethick.,webthick.) =( ' num2str(d) ', ' num2str(b) ', '
num2str(tf) ', ' num2str(tw) ', ' num2str(a) ')]'])
        disp([' '])
    else
        diapool=10:1:110;
        dia=diapool(BestSol.Var(i));
        a=pi()/4.*dia.^2;
        disp([num2str(frname(i-3)) 'Section is (Diameter) =( ' num2str(dia)
', ' num2str(a) ')]'])
        disp([' '])
    end
end

end

```

Section Five “Save and Close SAP2000”:

```

% Upload Final result on SAP2000 and save
[WEIGHT,C,sc,dc,gc] = WeightFunction(BestSol.Var);
disp([': C = ' num2str(C) ', SC = ' num2str(sc) ', DC = ' num2str(dc) ', GC
= ' num2str(gc)'])
ret=SM.File.Save();
SM.ApplicationExit (false);

```

MATLAB Functions

W Section Function

```
function [a,d,b,f,w,n] = Wsection(i)
```

```
%unit is mm
```

```
warea=[1630 1730    1910    2280    2290    2470    2480    2680    2850
2860    2860    3040    3040    3060    3220    3390    3590    3590
3630    3790    3970    4180    4190    4190    4570    4740    4910
4940    4950    4960    5320    5670    5700    5710    5890    5890
6260    6450    6650    6650    6650    6840    7230    7420    7550
7550    7610    7610    8130    8390    8450    8580    8580    8710
9100    9100    9100    9290    9420    9480    9480    9480    10100
10100    10200    10500    10500    10500    10800    10800    11000    11000
11400    11400    11500    11700    11800    12300    12300    12600    12700
12800    12900    12900    13000    13500    13600    13900    14100    14400
14500    14600    14600    15000    15500    15700    15900    15900    16300
16500    16800    16900    17000    17100    17600    17800    17900    18200
18400    18700    18800    18900    19000    19200    19400    19500    19800
20100    20100    20500    20600    21000    21200    21700    22100    22200
22400    22600    22700    22800    23200    23500    24400    24700    24700
24900    25000    25000    25000    25700    25700    26800    27100    27500
27700    27900    27900    28100    28300    28600    28800    29000    29900
30100    30300    30700    30800    31500    31800    31900    32300    32300
32800    33200    33400    33400    33900    34400    34600    34600    36100
36200    36300    36500    36600    36800    36800    37900    38100    38300
39200    39900    39900    40000    40100    40200    40200    41000    41200
42100    42900    43400    43700    43700    43900    44000    44200    44300
44600    44700    44800    45900    46800    47400    47400    47600    47800
48600    48800    49000    49100    49700    49800    49800    49900    49900
52600    52800    52800    52800    53100    53500    53600    53700    53700
55100    55200    55500    55600    56300    57400    57700    57900    58200
59000    59100    60500    61500    61900    61900    62500    63000    63400
63500    63800    64000    65200    67100    67700    68400    68400    70300
70300    70300    71000    73500    74200    74800    74800    75500    75500
80600    81900    83900    86500    92300    94800    95500    101000    103000
105000    112000    115000    124000    125000    126000    137000    139000    152000
154000    162000    166000    175000];
```

```

wdepth=[148 150 200 251 153 106 203 302 254 206 152 305 127 160 257 207 131
310 259 157 210 312 259 348 201 162 262 310 399 353 205 312 267 351 404 203
247 356 450 318 206 404 358 252 210 302 455 406 348 526 307 409 257 460 216
523 351 254 310 528 457 414 353 307 257 599 528 460 536 417 310 222 462 259
353 602 533 467 307 414 229 264 536 356 602 470 312 538 361 462 607 419 269
315 363 544 678 612 467 318 274 427 749 356 549 683 617 323 472 754 361 282
432 544 688 622 612 475 328 757 363 546 290 693 762 617 836 483 333 368 551
767 701 841 490 622 770 554 373 904 340 846 495 376 627 696 561 780 970 912
348 851 500 381 914 701 635 572 980 859 919 356 772 508 640 386 706 991 922
577 366 780 518 648 394 927 714 983 856 584 653 932 373 399 1000 785 526
991 721 861 594 660 384 1090 943 927 406 536 1010 795 729 869 932
1000 668 602 391 951 417 546 737 803 1100 937 876 1020 1010 612
678 404 1020 942 744 556 424 1110 884 813 1030 1010 947 414 688
752 434 566 894 1020 823 1040 958 1040 699 1120 427 762 445 904
833 965 1030 772 711 455 1030 914 843 1060 975 1040 465 475
1050 988 483 998 498 1070 1010 826 513 1090 531 1040 1110
549 1060 569 1080 579 1090 599 1090];

width=[100 100 100 101 102 103 102 101 102 102 152 101 127 102 102 133 128
102 102 153 134 102 146 127 165 154 147 165 140 128 166 166 148 171 140 203
202 171 152 167 204 178 172 203 205 203 153 178 203 165 204 179 204 154 206
207 204 254 205 166 191 180 205 254 254 178 209 191 167 181 254 209 192 257
254 179 209 193 305 259 210 257 210 254 228 194 305 211 257 279 228 262 259
307 257 212 254 229 282 307 262 264 264 368 214 254 230 310 282 267 371 262
264 312 254 229 325 284 310 267 371 312 264 257 267 325 292 287 312 373 315
267 254 292 284 328 267 315 373 305 315 292 284 394 328 356 318 267 300 305
318 295 287 396 305 356 330 315 300 292 305 320 381 290 328 399 358 300 307
318 323 381 292 330 399 307 356 401 399 320 330 310 325 401 300 384 295 401
358 401 323 333 328 401 307 419 404 297 302 384 361 404 419 401 335 325 330
310 406 300 363 386 401 422 401 302 401 328 338 333 305 422 366 302 409 401
404 389 305 401 424 335 340 366 411 305 406 404 391 307 422 310 343 404 340
371 417 409 394 424 406 373 348 419 409 411 396 315 427 409 422 424 411 432
427 434 432 417 437 389 437 424 442 447 429 450 452 455 457 472 462 478
472];

```

```

webt=[4.32 4.32 4.32 4.83 5.84 7.11 5.84 5.08 5.84
6.22 5.84 5.59 6.10 6.60 6.10 5.84 6.86 5.97
6.35 6.60 6.35 6.60 6.10 5.84 6.22 8.13 6.60
5.84 6.35 6.48 7.24 6.60 7.62 6.86 6.99 7.24
7.37 7.24 7.62 7.62 7.87 7.49 7.87 8.00 9.14
7.49 8.00 7.75 7.75 8.89 8.51 8.76 8.89 9.14
10.2 8.89 8.64 8.64 9.40 9.65 9.02 9.65 9.40

```

8.76	9.40	10.0	9.53	9.91	10.3	10.9	9.14	13.0
10.5	10.7	9.53	10.9	10.2	11.4	9.91	10.0	14.5
11.9	10.9	10.5	10.5	12.6	10.9	11.6	11.4	10.8
11.2	11.6	13.5	11.9	13.0	13.1	11.7	11.9	12.2
13.1	15.4	13.3	11.9	11.2	14.7	12.4	13.1	14.0
13.6	13.2	12.3	17.3	14.9	12.7	13.1	14.0	12.7
15.0	15.5	13.8	13.3	14.0	19.2	14.5	14.4	14.0
14.0	16.6	18.0	15.0	15.2	14.9	15.5	14.7	17.0
15.4	15.6	16.5	16.4	15.2	20.1	15.4	18.5	17.3
16.5	15.4	18.3	16.5	16.0	15.9	22.1	16.1	20.6
18.9	16.5	16.8	17.9	19.1	16.5	17.0	17.3	24.4
16.6	22.6	19.1	21.1	18.4	16.5	18.4	21.1	26.9
18.0	24.4	20.6	22.6	19.4	19.1	16.5	18.2	23.1
22.1	21.1	30.0	24.9	19.1	19.7	26.9	16.5	21.1
19.7	25.4	24.4	32.8	18.0	22.1	19.3	27.2	29.5
21.1	21.1	23.1	21.1	20.3	19.1	26.4	27.9	35.6
24.4	30.0	32.5	24.9	23.6	19.9	21.3	22.1	24.4
21.1	31.0	29.5	38.9	26.2	22.5	26.9	35.6	32.8
22.0	24.4	25.9	26.9	23.6	24.0	41.4	32.0	29.5
35.8	38.6	26.4	25.4	29.0	30.0	25.9	31.0	35.1
26.2	45.2	32.0	39.1	29.5	31.5	28.4	28.4	35.1
38.6	42.2	29.5	32.0	34.5	36.1	31.0	31.0	45.0
47.8	34.0	34.5	51.3	38.1	55.6	39.1	40.9	50.0
60.5	45.5	66.0	50.0	50.0	71.9	55.1	78.0	60.5
95.0	64.0	100	76.7];					

wflanget=[4.95	5.46	5.21	5.33	7.11	8.76	6.48	5.72	
6.86	8.00	6.60	6.73	9.14	10.3	8.38	8.38	10.9
8.89	10.0	9.27	10.2	10.8	9.14	8.51	10.2	11.6
11.2	9.65	8.76	10.7	11.8	11.2	13.0	9.78	11.2
11.0	11.0	11.6	10.8	13.2	12.6	10.9	13.1	13.5
14.2	13.1	13.3	12.8	13.5	11.4	14.6	14.4	15.7
15.4	17.4	10.9	15.1	14.2	16.3	13.6	14.5	16.0
16.8	14.6	15.6	12.8	13.3	16.0	16.5	18.2	16.3
20.6	17.7	17.3	16.4	15.0	15.6	19.1	15.4	16.9
23.7	19.6	17.4	18.3	14.9	20.6	17.0	18.8	19.9
17.3	17.3	19.3	22.1	18.7	21.7	21.2	16.3	19.6
19.6	20.6	25.1	22.2	15.5	18.0	23.6	18.9	22.2
22.9	22.1	17.0	19.8	28.4	25.0	20.3	21.1	24.9
19.1	23.9	25.1	19.3	21.8	22.2	31.8	23.6	21.6
21.6	18.8	26.9	28.2	23.9	24.4	23.6	27.9	21.7

30.5	24.4	25.4	26.4	26.2	20.1	31.8	24.4	33.5
27.7	27.7	24.8	29.2	30.0	21.1	23.9	35.6	26.9
36.6	30.2	25.9	27.4	31.0	34.5	26.2	31.0	27.9
39.6	27.2	40.4	34.0	33.3	30.2	30.5	30.0	37.6
44.2	30.2	44.5	37.1	36.6	32.0	34.0	27.2	29.2
41.4	39.9	34.5	48.3	39.6	36.1	33.5	48.5	31.0
38.1	32.5	45.5	43.9	52.6	31.0	39.9	32.0	43.7
53.6	40.1	38.1	40.9	35.6	34.3	36.1	48.0	50.5
57.2	43.9	48.0	58.4	45.0	41.9	36.1	36.6	39.9
43.9	40.1	55.6	53.1	62.7	46.0	39.9	49.0	63.5
52.6	40.1	43.9	47.0	49.0	41.9	42.7	68.8	57.9
53.1	57.4	69.6	48.0	46.0	52.1	54.1	47.0	54.1
63.0	45.0	75.2	57.9	62.7	53.1	56.9	51.1	51.1
63.0	69.1	67.6	52.1	57.9	62.0	64.0	55.9	55.9
72.4	77.2	59.9	62.0	81.5	68.1	88.9	70.1	73.9
89.9	97.0	82.0	106	89.9	89.9	115	99.1	125
109	130	115	140					

115];

wname=["W150X13" "W150X13.5" "W200X15" "W250X17.9" "W150X18"

"W100X19.3" "W200X19.3" "W310X21" "W250X22.3" "W200X22.5" "W150X22.5"

"W310X23.8" "W130X23.8" "W150X24" "W250X25.3" "W200X26.6" "W130X28.1"

"W310X28.3" "W250X28.4" "W150X29.8" "W200X31.3" "W310X32.7" "W250X32.7"

"W360X32.9" "W200X35.9" "W150X37.1" "W250X38.5" "W310X38.7" "W410X38.8"

"W360X39" "W200X41.7" "W310X44.5" "W250X44.8" "W360X44" "W410X46.1"

"W200X46.1" "W250X49.1" "W360X51" "W460X52" "W310X52" "W200X52"

"W410X53" "W360X57.8" "W250X58" "W200X59" "W310X60" "W460X60"

"W410X60" "W360X64" "W530X66" "W310X67" "W410X67" "W250X67"

"W460X68" "W200X71" "W530X72" "W360X72" "W250X73" "W310X74"

"W530X74" "W460X74" "W410X75" "W360X79" "W310X79" "W250X80"

"W610X82" "W530X82" "W460X82" "W530X85" "W410X85" "W310X86"

"W200X86" "W460X89" "W250X89" "W360X91" "W610X92" "W530X92"

"W460X97" "W310X97" "W410X100" "W200X100" "W250X101" "W530X101"

"W360X101" "W610X101" "W460X106" "W310X107" "W530X109" "W360X110"

"W460X113" "W610X113" "W410X114" "W250X115" "W310X117" "W360X122"

"W530X123" "W690X125" "W610X125" "W460X128" "W310X129" "W250X131"

"W410X132" "W760X134" "W360X134" "W530X138" "W690X140" "W610X140"

"W310X143" "W460X144" "W760X147" "W360X147" "W250X149" "W410X149"

"W530X150" "W690X152" "W610X153" "W610X155" "W460X158" "W310X158"

"W760X161" "W360X162" "W530X165" "W250X167" "W690X170" "W760X173"

"W610X174" "W840X176" "W460X177" "W310X179" "W360X179" "W530X182"

"W760X185" "W690X192" "W840X193" "W460X193" "W610X195" "W760X196"

```

"W530X196" "W360X196" "W920X201" "W310X202" "W840X210" "W460X213"
"W360X216" "W610X217" "W690X217" "W530X219" "W760X220" "W1000X222"
"W920X223" "W310X226" "W840X226" "W460X235" "W360X237" "W920X238"
"W690X240" "W610X241" "W530X248" "W1000X249" "W840X251" "W920X253"
"W310X253" "W760X257" "W460X260" "W610X262" "W360X262" "W690X265"
"W1000X272" "W920X271" "W530X272" "W310X283" "W760X284" "W460X286"
"W610X285" "W360X287" "W920X289" "W690X289" "W1000X296" "W840X299"
"W530X300" "W610X307" "W920X313" "W310X313" "W360X314" "W1000X314"
"W760X314" "W460X315" "W1000X321" "W690X323" "W840X329" "W530X332"
"W610X341" "W310X342" "W1100X343" "W920X345" "W920X344" "W360X347"
"W460X349" "W1000X350" "W760X350" "W690X350" "W840X359" "W920X368"
"W1000X371" "W610X372" "W530X369" "W310X375" "W920X381" "W360X382"
"W460X384" "W690X384" "W760X389" "W1100X390" "W920X390" "W840X392"
"W1000X393" "W1000X412" "W530X409" "W610X415" "W310X415" "W1000X415"
"W920X420" "W690X419" "W460X421" "W360X421" "W1100X433" "W840X433"
"W760X434" "W1000X438" "W1000X443" "W920X449" "W310X454" "W610X455"
"W690X457" "W360X463" "W460X464" "W840X473" "W1000X483" "W760X484"
"W1000X486" "W920X491" "W1000X494" "W610X498" "W1100X499" "W310X500"
"W690X500" "W360X509" "W840X527" "W760X531" "W920X537" "W1000X539"
"W690X548" "W610X551" "W360X551" "W1000X554" "W840X576" "W760X582"
"W1000X584" "W920X588" "W1000X591" "W360X592" "W360X634" "W1000X642"
"W920X656" "W360X677" "W920X725" "W360X744" "W1000X748" "W920X787"
"W690X802" "W360X818" "W1000X883" "W360X900" "W920X970" "W1000X976"
"W360X990" "W920X1077" "W360X1086" "W920X1194" "W360X1202" "W920X1269"
"W360X1299" "W920X1377"]];

```

```

a=warea(i);
d=wdepth(i);
b=width(i);
f=wflanget(i);
w=webt(i);
n=wname(i);

```

```
end
```

Pipe Section Function

```

function [a,od,wt,n] = Pipe(i)
%unit is mm

```

```

area=[151    195 201 263 303 388 403 483 540 645 658 903 1040    1340
1350    1610    1620    1830    1910    2210    2470    2590    2670
3340    3350    3700    4940    5050    5060    6900    7420    7680
8840    9480    9680    9740    11100    11300    12400    12500    12900
13900    14200    16000    16800    17800    18200    18600    21500    22800
23300];

outerdia=[21.3  21.3    26.7    26.7    33.4    33.5    42.2    48.3
42.2    48.3    60.3    60.3    73.0    88.9    73.0    101.6    60.3
88.9    114.3    101.6    73.0    141.3    114.3    88.9    168.3    141.3
114.3    168.3    219.1    141.3    273.0    219.1    323.8    168.3    355.6
273.0    406.4    323.8    355.6    457 219.1    508 406.4    457 610 508 660
273.0    610 323.8    660];

wallthick=[2.77 3.73    2.87    3.91    3.38    4.55    3.56    3.68
4.85    5.08    3.91    5.54    5.16    5.49    7.01    5.74    11.1
7.62    6.02    8.08    14.0    6.55    8.56    15.2    7.11    9.53
17.1    11.0    8.18    19.1    9.27    12.7    9.53    21.9    9.53
12.7    9.53    12.7    12.7    9.53    22.2    9.53    12.7    12.7
9.53    12.7    9.53    25.4    12.7    25.4    12.7];

name=["Pipe15STD"  "Pipe15XS"  "Pipe20STD" "Pipe20XS"  "Pipe25STD"
"Pipe25XS"  "Pipe32STD" "Pipe40STD" "Pipe32XS"  "Pipe40XS"  "Pipe50STD"
"Pipe50XS"  "Pipe65STD" "Pipe80STD" "Pipe65XS"  "Pipe90STD" "Pipe50XXS"
"Pipe80XS"  "Pipe100STD"    "Pipe90XS"  "Pipe65XXS" "Pipe125STD"
"Pipe100XS" "Pipe80XXS" "Pipe150STD"    "Pipe125XS" "Pipe100XXS"
"Pipe150XS" "Pipe200STD"    "Pipe125XXS"    "Pipe250STD"    "Pipe200XS"
"Pipe300STD"    "Pipe150XXS"    "Pipe350STD"    "Pipe250XS" "Pipe400STD"
"Pipe300XS" "Pipe350XS" "Pipe450STD"    "Pipe200XXS"    "Pipe500STD"
"Pipe400XS" "Pipe450XS" "Pipe600STD"    "Pipe500XS" "Pipe650STD"
"Pipe250XXS"    "Pipe600XS" "Pipe300XXS"    "Pipe650XS"];

a=area(i);
od=outerdia(i);
wt=wallthick(i);
n=name(i);

end

```

HSS Section Function

```
function [a,d,b,t,n] = Hsection(i)
```

```
%unit is mm
```

```
harea=[392  403 403 467 467 483 531 542 542 542 545 561 579 608 617 617 617
645 652 658 658 677 690 690 690 723 768 768 768 768 768 774 794 819 819 826
839 839 839 884 884 884 897 916 916 955 974 974 994 994 994 994 994 994 994
1010  1030  1030  1060  1070  1080  1100  1100  1120
1120  1120  1140  1140  1140  1140  1150  1170  1220
1220  1220  1250  1270  1270  1270  1270  1290  1290
1290  1290  1310  1330  1340  1350  1370  1380  1430
1430  1440  1440  1440  1440  1450  1450  1450  1520
1520  1520  1530  1540  1550  1570  1570  1570  1570
1590  1590  1590  1590  1610  1620  1660  1660  1660
1680  1700  1700  1720  1740  1740  1740  1740  1780
1820  1880  1880  1880  1890  1890  1890  1890  1890
1890  1900  1900  1900  1900  1910  1960  2030  2040
2040  2050  2080  2120  2120  2120  2120  2170  2170
2170  2190  2190  2190  2190  2250  2270  2270  2270
2280  2320  2340  2340  2340  2340  2340  2360  2410
2410  2480  2480  2480  2480  2560  2570  2570  2570
2570  2570  2580  2590  2640  2640  2640  2640  2650
2650  2650  2660  2720  2770  2770  2770  2770  2770
2790  2900  2940  2980  3010  3010  3010  3010  3010
3020  3020  3020  3020  3030  3080  3080  3080  3080
3080  3080  3080  3140  3190  3240  3240  3290  3340
3350  3370  3380  3380  3380  3380  3380  3390  3390
3390  3390  3430  3460  3460  3460  3460  3460  3540
3540  3540  3650  3680  3690  3740  3770  3770  3770
3770  3830  3880  3880  3880  3910  3910  3910  3910
3950  3960  3980  3980  3980  3980  3980  3990  3990
3990  3990  4000  4150  4150  4150  4150  4150  4250
4270  4280  4280  4360  4360  4360  4360  4430  4440
4440  4440  4440  4440  4480  4480  4480  4520  4520
4580  4580  4580  4580  4610  4620  4700  4710  4750
4810  4890  4890  4890  4890  4890  4900  4900  4900
4900  4900  4970  5060  5060  5070  5080  5080  5080
5150  5180  5180  5180  5180  5220  5260  5270  5270
5340  5460  5500  5560  5650  5650  5650  5650  5680
5680  5680  5730  5780  5780  5780  5780  5790  5790
```

5790	5790	5810	5850	5910	6040	6160	6240	6280
6280	6280	6280	6390	6400	6400	6400	6400	6450
6520	6580	6650	6710	6710	6710	6710	6840	6970
6970	6970	6970	6970	7160	7160	7160	7160	7160
7350	7420	7480	7480	7480	7480	7550	7550	7610
7610	7610	7610	7680	7870	8060	8520	8520	8520
8520	8650	8650	8650	8650	8650	8650	8710	8710
8710	8710	8770	8970	9030	9030	9030	9030	9290
9420	9480	9680	9680	9870	9870	9870	9870	10100
10100	10100	10300	10300	10300	10300	10300	10600	10600
10600	10600	11100	11100	11100	11100	11100	11100	11500
11700	11700	12100	12100	12100	12100	12100	12100	12100
12300	12500	12800	12800	13500	13500	13500	13500	13500
13500	13500	13500	13500	13900	13900	13900	14600	15800
15900	15900	15900	15900	16500	16600	16600	16600	16600
18100	18300	18300	18400	19500	19500	19500	19500	20700
20700	22600	22600	23100	23200	23200	25500	25500	26600
26800	26800	28600	30400	30400	30800	33900	35000	37600
39200	43400	];						

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hwidth=[50.8    48.3    42.2    63.5    50.8    48.3    60.3    76.2
63.5    50.8    50.8    63.5    57.2    48.3    76.2    63.5    57.2
60.3    73   63.5    50.8    76.2    88.9    76.2    63.5    76.2    88.9
76.2    76.2    63.5    50.8    60.3    88.9    76.2    63.5    57.2    102
88.9    76.2    76.2    63.5    57.2    60.3    102 102 73   63.5    50.8
127 102 88.9    88.9    76.2    63.5    76.2    60.3    114 73   127 63.5
76.2    88.9    76.2    76.2    63.5    57.2    152 127 102 76.2    127
88.9    102 88.9    76.2    73   88.9    76.2    63.5    88.9    178 152 127
114 76.2    102 88.9    102 141 152 88.9    76.2    203 178 152 127 127 102
88.9    76.2    63.5    114 168 88.9    127 102 88.9    76.2    102 203 178
152 140 102 178 152 127 102 102 76.2    127 102 254 203 178 152 102 88.9
127 102 88.9    254 178 152 127 114 88.9    102 88.9    76.2    141 114 254
127 254 178 152 102 203 178 152 127 152 127 102 102 88.9    76.2    102 127
127 102 88.9    168 127 203 203 178 152 140 175 102 178 178 152 127 114 140
254 229 203 178 152 191 141 229 127 102 88.9    152 127 102 114 152 203 178
152 127 127 254 254 114 219 305 254 229 203 178 152 127 114 168 152 203 178
152 152 140 127 102 175 178 305 254 127 244 168 152 254 229 203 178 152 203
178 152 127 191 305 254 229 203 254 152 127 114 140 254 141 168 203 178 152
140 254 127 102 175 356 305 254 229 178 219 305 254 229 203 178 203 178 152
127 152 254 229 203 178 152 191 127 305 254 406 356 305 254 244 203 178 152
140 168 152 127 114 254 194 305 254 229 203 254 175 178 254 140 141 254 229

```

203 178 152 305 254 229 203 178 273 219 191 168 178 152 127 194 356 305 254
229 152 305 305 254 254 305 244 254 305 254 229 203 203 178 152 254 406 356
305 254 254 229 203 178 168 219 324 175 178 254 229 203 178 152 305 356 305
254 229 305 356 244 191 305 254 229 203 254 508 457 406 356 305 406 356 305
254 254 273 406 254 229 203 178 203 152 356 305 254 229 219 305 356 406 356
305 254 508 457 406 356 305 244 305 254 229 203 324 254 254 229 203 178 406
305 219 356 273 356 305 254 229 508 406 356 508 457 406 356 305 305 254 229
203 406 356 305 254 406 254 324 508 406 508 406 356 356 305 254 229 305 457
406 356 508 457 406 406 356 356 305 305 254 508 406 508 406 356 508 406 356
254 457 457 406 356 305 406 508 406 508 508 406 356 305 610 457 508 406 508
406 356 610 457 356 508 406 508 610 457 406 508 457 559 508 559];

hdepth=[25.4 48.3 42.2 25.4 38.1 48.3 60.3 25.4
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50.8 63.5 25.4 38.1 50.8 60.3 88.9 76.2 63.5
50.8 50.8 63.5 76.2 38.1 50.8 57.2 60.3 63.5
102.0 73.0 38.1 50.8 50.8 76.2 88.9 38.1 50.8
63.5 76.2 60.3 114.0 73.0 63.5 63.5 76.2 50.8
63.5 38.1 50.8 57.2 50.8 76.2 102.0 76.2 127.0
88.9 50.8 63.5 76.2 73.0 38.1 50.8 63.5 88.9
50.8 76.2 102.0 114.0 76.2 63.5 88.9 102.0 141.0
152.0 50.8 63.5 50.8 76.2 102.0 127.0 50.8 76.2
88.9 50.8 63.5 114.0 168.0 88.9 63.5 50.8 63.5
76.2 102.0 76.2 102.0 127.0 140.0 102.0 178.0 50.8
76.2 102.0 102.0 63.5 127.0 63.5 50.8 102.0 127.0
152.0 102.0 88.9 50.8 76.2 88.9 76.2 50.8 76.2
102.0 114.0 88.9 50.8 63.5 76.2 141.0 114.0 88.9
63.5 102.0 178.0 152.0 63.5 50.8 76.2 102.0 127.0
50.8 76.2 102.0 50.8 63.5 76.2 102.0 127.0 50.8
76.2 88.9 168.0 127.0 203.0 76.2 102.0 127.0 140.0
175.0 63.5 178.0 50.8 76.2 102.0 114.0 140.0 50.8
76.2 102.0 127.0 152.0 191.0 141.0 229.0 50.8 76.2
88.9 50.8 76.2 102.0 114.0 152.0 50.8 76.2 102.0
127.0 127.0 76.2 88.9 114.0 219.0 50.8 102.0 127.0
152.0 178.0 76.2 102.0 114.0 168.0 152.0 76.2 102.0
127.0 50.8 140.0 76.2 102.0 175.0 178.0 76.2 127.0
127.0 244.0 168.0 152.0 50.8 76.2 102.0 127.0 152.0
50.8 76.2 102.0 127.0 191.0 102.0 152.0 178.0 203.0
254.0 76.2 102.0 114.0 140.0 76.2 141.0 168.0 76.2
102.0 127.0 140.0 88.9 76.2 102.0 175.0 102.0 152.0

203.0	229.0	178.0	219.0	50.8	102.0	127.0	152.0	178.0
50.8	76.2	102.0	127.0	152.0	50.8	76.2	102.0	127.0
152.0	191.0	127.0	76.2	127.0	102.0	152.0	203.0	254.0
244.0	76.2	102.0	127.0	140.0	168.0	76.2	102.0	114.0
76.2	194.0	102.0	152.0	178.0	203.0	254.0	175.0	178.0
88.9	140.0	141.0	50.8	76.2	102.0	127.0	152.0	50.8
102.0	127.0	152.0	178.0	273.0	219.0	191.0	168.0	76.2
102.0	127.0	194.0	102.0	152.0	203.0	229.0	152.0	305.0
76.2	127.0	76.2	88.9	244.0	88.9	102.0	152.0	178.0
203.0	76.2	102.0	127.0	254.0	102.0	152.0	203.0	254.0
102.0	127.0	152.0	178.0	168.0	219.0	324.0	175.0	178.0
127.0	76.2	102.0	127.0	152.0	254.0	102.0	152.0	203.0
229.0	88.9	356.0	244.0	191.0	102.0	152.0	178.0	203.0
254.0	102.0	152.0	203.0	254.0	305.0	102.0	152.0	203.0
254.0	88.9	273.0	406.0	102.0	127.0	152.0	178.0	102.0
152.0	102.0	152.0	203.0	229.0	219.0	254.0	356.0	102.0
152.0	203.0	254.0	102.0	152.0	203.0	254.0	305.0	244.0
102.0	152.0	178.0	203.0	324.0	254.0	102.0	127.0	152.0
178.0	406.0	254.0	219.0	356.0	273.0	102.0	152.0	203.0
229.0	203.0	305.0	356.0	102.0	152.0	203.0	254.0	305.0
102.0	152.0	178.0	203.0	102.0	152.0	203.0	254.0	406.0
254.0	324.0	305.0	406.0	203.0	305.0	356.0	102.0	152.0
203.0	229.0	254.0	457.0	406.0	356.0	102.0	152.0	203.0
102.0	254.0	152.0	305.0	203.0	254.0	305.0	406.0	508.0
406.0	356.0	203.0	305.0	356.0	254.0	457.0	152.0	203.0
254.0	305.0	406.0	305.0	406.0	508.0	203.0	305.0	356.0
305.0	305.0	457.0	305.0	406.0	508.0	305.0	356.0	305.0
457.0	356.0	305.0	406.0	508.0	305.0	457.0	406.0	508.0
457.0	559.0	508.0	559.0];					

hthick=[3.18	3.05	3.56	3.18	3.18	3.68	3.18	3.18
3.18	3.18	4.76	3.18	3.18	4.78	3.18	3.18
3.91	3.18	4.76	4.76	3.18	3.18	3.18	3.40
3.18	3.18	4.76	4.76	4.76	4.78	3.18	3.86
4.76	3.18	3.18	3.18	4.76	4.76	4.76	5.54
3.18	4.78	6.35	6.35	3.18	3.18	3.18	4.76
4.76	4.78	6.35	3.18	5.16	3.18	6.35	5.16
4.76	6.35	6.35	6.35	3.18	3.18	3.18	5.49
4.78	4.76	4.76	4.76	6.35	6.35	6.35	6.35
3.18	3.18	3.18	3.18	6.35	4.76	5.49	4.78
3.18	6.35	6.35	3.18	3.18	3.18	3.18	4.76

4.76	7.94	7.94	4.78	3.18	6.35	4.76	6.35	6.35
6.35	5.59	3.18	3.18	3.18	3.18	5.74	3.18	4.76
4.76	4.76	6.02	7.94	4.78	6.35	3.18	3.18	3.18
3.18	6.35	7.62	6.35	6.35	6.35	3.18	4.76	4.76
4.76	4.76	7.95	7.94	7.94	7.94	4.78	6.02	3.18
6.35	3.18	3.18	4.78	7.94	4.76	4.76	4.76	4.76
6.35	6.35	6.35	9.53	9.53	9.53	7.94	6.35	7.94
7.94	7.94	4.78	6.55	3.18	4.76	4.76	4.76	4.76
4.78	9.53	4.78	6.35	6.35	6.35	6.35	6.55	4.76
4.76	4.76	4.76	4.76	4.78	6.55	3.18	9.53	9.53
9.53	7.94	7.94	7.94	8.56	6.35	6.35	6.35	6.35
6.35	7.94	4.76	4.76	9.53	4.78	4.76	4.76	4.76
4.76	4.76	7.94	7.94	7.94	6.35	7.11	6.35	6.35
6.35	9.53	6.35	9.53	9.53	6.35	6.35	4.76	4.76
9.53	4.78	7.11	7.94	6.35	6.35	6.35	6.35	6.35
7.94	7.94	7.94	7.94	6.35	4.76	4.76	4.76	4.76
4.78	9.53	9.53	9.53	9.53	6.35	9.53	7.94	7.94
7.94	7.94	7.94	6.35	12.7	12.7	7.94	4.76	4.76
4.76	4.76	7.94	6.35	6.35	6.35	6.35	6.35	6.35
9.53	9.53	9.53	9.53	9.53	7.94	7.94	7.94	7.94
7.94	7.94	12.7	6.35	6.35	4.76	4.76	4.77	4.76
6.35	9.53	9.53	9.53	9.53	9.53	12.7	12.7	12.7
7.94	8.33	6.35	6.35	6.35	6.35	6.35	9.53	9.53
7.94	12.7	12.7	9.53	9.53	9.53	9.53	9.53	7.94
7.94	7.94	7.94	7.94	6.35	8.18	9.53	11.1	12.7
12.7	12.7	9.53	6.35	6.35	6.35	6.35	12.7	4.76
7.94	7.94	9.53	7.94	7.94	9.53	7.94	7.94	7.94
7.94	12.7	12.7	12.7	7.94	6.35	6.35	6.35	6.35
9.53	9.53	9.53	9.53	12.7	9.53	6.35	12.7	12.7
9.53	12.7	12.7	12.7	12.7	6.35	7.94	7.94	7.94
7.94	9.53	6.35	9.53	12.7	9.53	9.53	9.53	9.53
9.53	6.35	6.35	6.35	6.35	6.35	7.94	7.94	7.94
7.94	12.7	9.53	6.35	12.7	12.7	12.7	12.7	15.9
15.9	9.53	9.53	9.53	9.53	12.7	7.94	7.94	9.53
9.53	9.53	9.53	7.94	7.94	7.94	7.94	7.94	12.7
12.7	12.7	12.7	12.7	9.53	12.7	15.9	15.9	15.9
15.9	7.94	9.53	15.9	9.53	12.7	12.7	12.7	12.7
12.7	7.94	7.94	7.94	9.53	9.53	9.53	9.53	9.53
15.9	15.9	15.9	15.9	12.7	12.7	12.7	12.7	9.53
15.9	12.7	7.94	7.94	9.53	9.53	9.53	15.9	15.9
15.9	15.9	12.7	9.53	11.1	12.7	12.7	12.7	12.7

15.9	12.7	15.9	12.7	15.9	15.9	9.53	9.53	9.53
12.7	15.9	12.7	12.7	12.7	19.1	12.7	15.9	15.9
15.9	15.9	15.9	12.7	12.7	12.7	15.9	15.9	15.9
19.1	12.7	12.7	15.9	15.9	12.7	19.1	19.1	15.9
15.9	22.2	19.1	19.1	15.9	19.1	19.1	22.2	19.1
22.2	19.1	22.2	22.2];					

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"HSS76.2X25.4X3.2"    "HSS63.5X38.1X3.2"    "HSS50.8X50.8X3.2"
"HSS50.8X25.4X4.8"    "HSS63.5X3.2"    "HSS57.2X50.8X3.2"    "HSS48.3X4.8"
"HSS76.2X38.1X3.2"    "HSS63.5X50.8X3.2"    "HSS57.2X57.2X3.2"    "HSS60.3X3.9"
"HSS73X3.2"    "HSS63.5X25.4X4.8"    "HSS50.8X38.1X4.8"    "HSS76.2X3.2"
"HSS88.9X38.1X3.2"    "HSS76.2X50.8X3.2"    "HSS63.5X63.5X3.2"    "HSS76.2X3.4"
"HSS88.9X50.8X3.2"    "HSS76.2X63.5X3.2"    "HSS76.2X25.4X4.8"
"HSS63.5X38.1X4.8"    "HSS50.8X50.8X4.8"    "HSS60.3X4.8"    "HSS88.9X3.2"
"HSS76.2X3.9"    "HSS63.5X4.8"    "HSS57.2X50.8X4.8"    "HSS101.6X50.8X3.2"
"HSS88.9X63.5X3.2"    "HSS76.2X76.2X3.2"    "HSS76.2X38.1X4.8"
"HSS63.5X50.8X4.8"    "HSS57.2X57.2X4.8"    "HSS60.3X5.5"    "HSS101.6X63.5X3.2"
"HSS101.6X3.2"    "HSS73X4.8"    "HSS63.5X38.1X6.4"    "HSS50.8X50.8X6.4"
"HSS127X50.8X3.2"    "HSS101.6X76.2X3.2"    "HSS88.9X88.9X3.2"
"HSS88.9X38.1X4.8"    "HSS76.2X50.8X4.8"    "HSS63.5X63.5X4.8"    "HSS76.2X4.8"
"HSS60.3X6.4"    "HSS114.3X3.2"    "HSS73X5.2"    "HSS127X63.5X3.2"
"HSS63.5X6.4"    "HSS76.2X5.2"    "HSS88.9X50.8X4.8"    "HSS76.2X63.5X4.8"
"HSS76.2X38.1X6.4"    "HSS63.5X50.8X6.4"    "HSS57.2X57.2X6.4"
"HSS152.4X50.8X3.2"    "HSS127X76.2X3.2"    "HSS101.6X101.6X3.2"
"HSS76.2X5.5"    "HSS127X3.2"    "HSS88.9X4.8"    "HSS101.6X50.8X4.8"
"HSS88.9X63.5X4.8"    "HSS76.2X76.2X4.8"    "HSS73X6.4"    "HSS88.9X38.1X6.4"
"HSS76.2X50.8X6.4"    "HSS63.5X63.5X6.4"    "HSS88.9X5.2"    "HSS177.8X50.8X3.2"
"HSS152.4X76.2X3.2"    "HSS127X101.6X3.2"    "HSS114.3X114.3X3.2"
"HSS76.2X6.4"    "HSS101.6X63.5X4.8"    "HSS88.9X5.5"    "HSS101.6X4.8"
"HSS141.3X3.4"    "HSS152.4X3.2"    "HSS88.9X50.8X6.4"    "HSS76.2X63.5X6.4"
"HSS203.2X50.8X3.2"    "HSS177.8X76.2X3.2"    "HSS152.4X101.6X3.2"
"HSS127X127X3.2"    "HSS127X50.8X4.8"    "HSS101.6X76.2X4.8"
"HSS88.9X88.9X4.8"    "HSS76.2X50.8X7.9"    "HSS63.5X63.5X7.9"    "HSS114.3X4.8"
"HSS168.3X3.2"    "HSS88.9X6.4"    "HSS127X63.5X4.8"    "HSS101.6X50.8X6.4"
"HSS88.9X63.5X6.4"    "HSS76.2X76.2X6.4"    "HSS101.6X5.6"    "HSS203.2X76.2X3.2"
"HSS177.8X101.6X3.2"    "HSS152.4X127X3.2"    "HSS139.7X139.7X3.2"
"HSS101.6X5.7"    "HSS177.8X3.2"    "HSS152.4X50.8X4.8"    "HSS127X76.2X4.8"
"HSS101.6X101.6X4.8"    "HSS101.6X6"    "HSS76.2X63.5X7.9"    "HSS127X4.8"
"HSS101.6X63.5X6.4"    "HSS254X50.8X3.2"    "HSS203.2X101.6X3.2"]
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"HSS127X50.8X6.4" "HSS101.6X76.2X6.4" "HSS88.9X88.9X6.4"
"HSS254X76.2X3.2" "HSS177.8X50.8X4.8" "HSS152.4X76.2X4.8"
"HSS127X101.6X4.8" "HSS114.3X114.3X4.8" "HSS88.9X8" "HSS101.6X50.8X7.9"
"HSS88.9X63.5X7.9" "HSS76.2X76.2X7.9" "HSS141.3X4.8" "HSS114.3X6"
"HSS254X88.9X3.2" "HSS127X63.5X6.4" "HSS254X101.6X3.2"
"HSS177.8X177.8X3.2" "HSS152.4X4.8" "HSS101.6X63.5X7.9"
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"HSS127X127X4.8" "HSS152.4X50.8X6.4" "HSS127X76.2X6.4"
"HSS101.6X101.6X6.4" "HSS101.6X50.8X9.5" "HSS88.9X63.5X9.5"
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"HSS254X50.8X4.8" "HSS228.6X76.2X4.8" "HSS203.2X101.6X4.8"
"HSS177.8X127X4.8" "HSS152.4X152.4X4.8" "HSS190.5X4.8" "HSS141.3X6.6"
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"HSS101.6X101.6X7.9" "HSS114.3X8.6" "HSS152.4X6.4" "HSS203.2X50.8X6.4"
"HSS177.8X76.2X6.4" "HSS152.4X101.6X6.4" "HSS127X127X6.4"
"HSS127X7.9" "HSS254X76.2X4.8" "HSS254X88.9X4.8" "HSS114.3X9.5"
"HSS219.1X4.8" "HSS304.8X50.8X4.8" "HSS254X101.6X4.8" "HSS228.6X127X4.8"
"HSS203.2X152.4X4.8" "HSS177.8X177.8X4.8" "HSS152.4X76.2X7.9"
"HSS127X101.6X7.9" "HSS114.3X114.3X7.9" "HSS168.3X6.4" "HSS152.4X7.1"
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"HSS101.6X101.6X9.5" "HSS174.6X6.4" "HSS177.8X6.4" "HSS304.8X76.2X4.8"
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"HSS127X127X7.9" "HSS190.5X6.4" "HSS304.8X101.6X4.8"
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"HSS168.3X7.9" "HSS203.2X76.2X7.9" "HSS177.8X101.6X7.9"
"HSS152.4X127X7.9" "HSS139.7X139.7X7.9" "HSS254X88.9X6.4"
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"HSS152.4X101.6X9.5" "HSS127X127X9.5" "HSS152.4X9.5"
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"HSS177.8X127X7.9" "HSS152.4X152.4X7.9" "HSS190.5X7.9" "HSS127X12.7"
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"HSS355.6X152.4X4.8" "HSS304.8X203.2X4.8" "HSS254X254X4.8"
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"HSS254X6.4" "HSS174.6X9.5" "HSS177.8X9.5" "HSS254X88.9X7.9"
"HSS139.7X12.7" "HSS141.3X12.7" "HSS254X50.8X9.5" "HSS228.6X76.2X9.5"
"HSS203.2X101.6X9.5" "HSS177.8X127X9.5" "HSS152.4X152.4X9.5"
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"HSS203.2X152.4X7.9" "HSS177.8X177.8X7.9" "HSS273.1X6.4"
"HSS219.1X8.2" "HSS190.5X9.5" "HSS168.3X11" "HSS177.8X76.2X12.7"
"HSS152.4X101.6X12.7" "HSS127X127X12.7" "HSS193.7X9.5"
"HSS355.6X101.6X6.4" "HSS304.8X152.4X6.4" "HSS254X203.2X6.4"
"HSS228.6X228.6X6.4" "HSS152.4X12.7" "HSS304.8X304.8X4.8"
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"HSS152.4X127X12.7" "HSS254X7.9" "HSS406.4X101.6X6.4"
"HSS355.6X152.4X6.4" "HSS304.8X203.2X6.4" "HSS254X254X6.4"
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"HSS355.6X6.4" "HSS244.5X9.5" "HSS190.5X12.7" "HSS304.8X101.6X9.5"
"HSS254X152.4X9.5" "HSS228.6X177.8X9.5" "HSS203.2X203.2X9.5"
"HSS254X9.5" "HSS508X101.6X6.4" "HSS457.2X152.4X6.4"
"HSS406.4X203.2X6.4" "HSS355.6X254X6.4" "HSS304.8X304.8X6.4"
"HSS406.4X101.6X7.9" "HSS355.6X152.4X7.9" "HSS304.8X203.2X7.9"
"HSS254X254X7.9" "HSS254X88.9X12.7" "HSS273.1X9.5" "HSS406.4X6.4"
"HSS254X101.6X12.7" "HSS228.6X127X12.7" "HSS203.2X152.4X12.7"

```

"HSS177.8X177.8X12.7"    "HSS203.2X101.6X15.9"    "HSS152.4X152.4X15.9"
"HSS355.6X101.6X9.5"     "HSS304.8X152.4X9.5"     "HSS254X203.2X9.5"
"HSS228.6X228.6X9.5"     "HSS219.1X12.7" "HSS304.8X254X7.9"    "HSS355.6X7.9"
"HSS406.4X101.6X9.5"     "HSS355.6X152.4X9.5"     "HSS304.8X203.2X9.5"
"HSS254X254X9.5"        "HSS508X101.6X7.9"    "HSS457.2X152.4X7.9"
"HSS406.4X203.2X7.9"     "HSS355.6X254X7.9"     "HSS304.8X304.8X7.9"
"HSS244.5X12.7" "HSS304.8X101.6X12.7"    "HSS254X152.4X12.7"
"HSS228.6X177.8X12.7"    "HSS203.2X203.2X12.7"    "HSS323.9X9.5"
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"HSS304.8X254X9.5"    "HSS219.1X15.9" "HSS355.6X9.5"    "HSS273.1X12.7"
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"HSS406.4X203.2X9.5"     "HSS355.6X254X9.5"     "HSS304.8X304.8X9.5"
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"HSS457.2X457.2X22.2"    "HSS558.8X558.8X19" "HSS508X508X22.2"
"HSS558.8X558.8X22.2"];
```

```

a=harea(i);
```

```

        d=hdepth(i);
        b=hwidth(i);
        t=hthick(i);
        n=hname(i);
end

```

Weight Function

Weight function is sphere function, should be minimized to obtain optimum design of the bridge. The function is divided into five sections.

Section One “The function parameters”:

```

%Specific weight of the steel
gamma=7.697*10^-8;

%Total Length for each member group
HL=307874.85;
BL=348871.97;
BDLL=191048.94;
BDLCL=95524.47;
BDTL=112000;
BDTCL=86209.77;
ArchL=131381.75;
CableL=836164.26;

% Names of each group
fname=["BDL" "BDLCenter" "BDT" "BDTCenter" "Bracing" "Hexagons" "Arch"
"Cable"];

% Names of each load case
LCase=["Pedstrian" "W0" "W45" "W90" "W135" "W180" "W225" "W270" "W315"];

% Constraint's variables
c=0;      % Constraints Summation
sc=0;     % Strength Constraints
dc=0;     % Deflection Constraints
gc=0;     % Geometry Constraints

```

Section Two “Defining The frame Sections”:

```
%% Defining the frame sections

%Allowable Deflection
Dallow=100000/360;

% Reset all pervious results and analysis
ret = SM.SetPresentUnits(SM.eUnits.kN_mm_C);
ret = SM.DesignSteel.DeleteResults;
ret = SM.SetModelIsLocked(false);

% Defining Sections
for j=1:6
    ret = SM.SetPresentUnits(SM.eUnits.kN_mm_C);
    if j<5 %Defining section of Bridge deck frames (long and Trans)
        [a(j),d,b,f,w] = Wsection(x(:,j));
        ret=SM.PropFrame.SetISection(frname(j), 'S355',d,b,f,w,b,f);
        if j>1
            gc=gc+max(0,d/dper-1);
        end
        dper=d;

    elseif j<6 %Defining sections of Bracing
        [a(j),od,wt] = Pipe(x(:,j));
        ret=SM.PropFrame.SetPipe(frname(j), 'S355',od,wt);
    else %Defining sections of hexagons
        [a(j),d,b,t] = Hsection(x(:,j));
        ret=SM.PropFrame.SetTube(frname(j), 'S355',d,b,t,t);
        gc=gc+max(0,od/d-1);
    end
end

%Defining section of Arch
dpool=1000:25:3500;
bpool=1000:25:3500;
tfpool=50:1:150;
twpool=50:1:150;

d=dpool(x(:,7));
b=bpool(x(:,8));
tf=tfpool(x(:,9));
tw=twpool(x(:,10));

% Arch constraints
B =b-2*tw;
D =d-2*tf;

sc=sc+max(0, ((B/tf)/(1.12*sqrt(2*10^5/355)))-1);
sc=sc+max(0, ((D/tw)/(2.42*sqrt(2*10^5/355)))-1);

a(7)=d.*b-D.*B;
ret=SM.PropFrame.SetTube(frname(7), 'S355',d,b,tf,tw);

%Defining section of Cable

diapool=10:1:110;
```

```

dia=diapool(x(:,11));

a(8)=pi()/4.*dia.^2;
ret=SM.PropFrame.SetCircle(frname(8),'Cable',dia);

[ret,Fy,Fu,SSType,SSHysType]=SM.PropMaterial.GetOTendon(frname(8));
Pty=0.9.*Fy.*a(8);
Ptr=0.75.*Fu.*a(8);

```

Section Three “Deflection Constraints”:

```

%% Deflection Results

```

```

ret = SM.Analyze.RunAnalysis;

for z=1:9
    ret = SM.SetPresentUnits(SM.eUnits.kN_mm_C);
    ret=SM.Results.Setup.DeselectAllCasesAndCombosForOutput();
    ret = SM.Results.Setup.SetCaseSelectedForOutput(LCase(z));

    [ret,NumberResults,Obj,Elm,LoadCase,StepType,StepNum,U1,U2,U3,R1,R2,R3]=SM.
    Results.JointDisplAbs('ALL',SM.eItemTypeElm.GroupElm);
    if z==1
        Dmaxv=max(abs(U3));
    else
        Dmaxh(z-1)=max([abs(U1) abs(U2)]);
    end
end
dc=dc+max(0,Dmaxv/Dallow-1);
dc=dc+max(0,max(Dmaxh)/Dallow-1);

```

Section Four “Strength Constraints”:

```

ret = SM.SetModelIsLocked(false);
ret = SM.Analyze.RunAnalysis;

[ret,NumberResults,Obj,ObjSta,Elm,ElmSta,LoadCase,StepType,StepNum,P,V2,V3,
T,M2,M3]=SM.Results.FrameForce('Cable',SM.eItemTypeElm.GroupElm);
Pmax=abs(max(P));
sc=sc+max(0,Pmax/min(Pty,Ptr)-1);

ret = SM.DesignSteel.StartDesign;
for j=1:7
    ret = SM.SetPresentUnits(SM.eUnits.kN_mm_C);

    [ret,NumberItems,FrameName,Value]=SM.DesignSteel.GetDetailResultsValue(frna
me(j),SM.eItemType.Group,2,'TotalRatio');
    sc=sc+max(0,max(Value)-1);

    [ret,NumberItems,FrameName,Value]=SM.DesignSteel.GetDetailResultsValue(frna
me(j),SM.eItemType.Group,3,'VMinorRatio');
    sc=sc+max(0,max(Value)-1);

    [ret,NumberItems,FrameName,Value]=SM.DesignSteel.GetDetailResultsValue(frna
me(j),SM.eItemType.Group,3,'VMajorRatio');

```

```
        sc=sc+max(0,max(Value)-1);  
end
```

Section Five “Output”:

```
%% Output
```

```
W=gamma.*(BDLL.*a(1)+BDLCL.*a(2)+BDTL.*a(3)+BDTCL.*a(4)+BL.*a(5)+HL.*a(6)+A  
rchL.*a(7)+CableL.*a(8));  
c=gc+sc+dc;  
Weight=W.*(1+c).^2;  
end  
%end of whole function
```

APPENDIX-C

Optimized Design Analysis

Results

APPENDIX-C Optimized Design Analysis Results

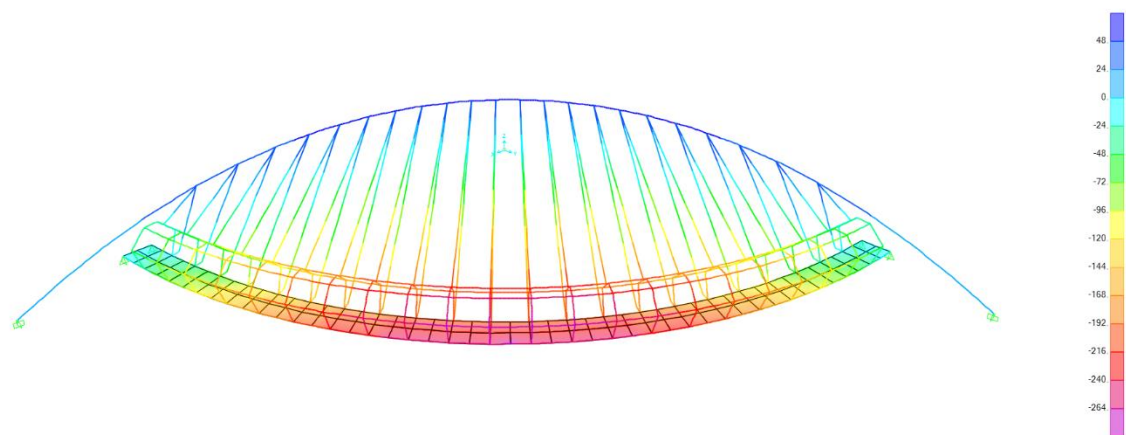


Figure C- 1 Vertical Deflection Contour of Un-factored Live Load (mm)

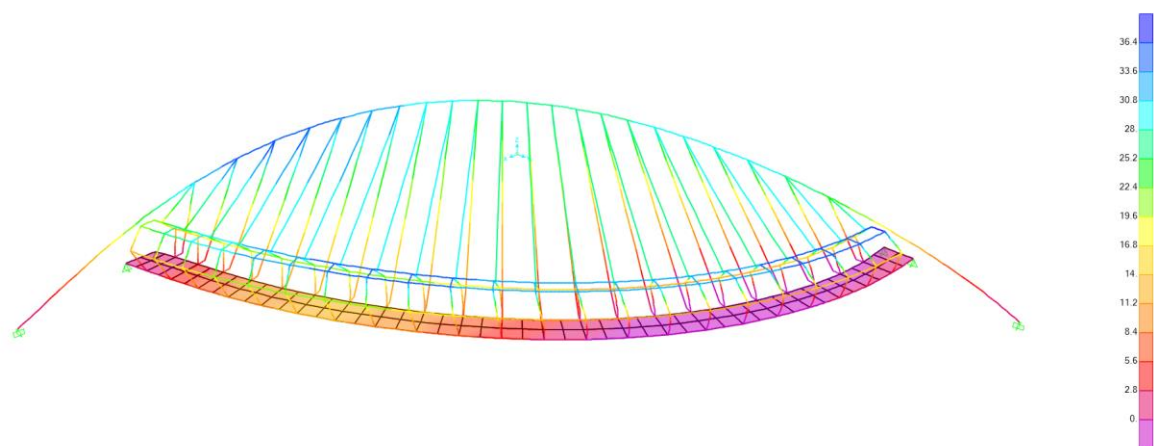


Figure C- 2 Horizontal (Ux) Deflection Contour of Un-factored Wind Load (W315) (mm)

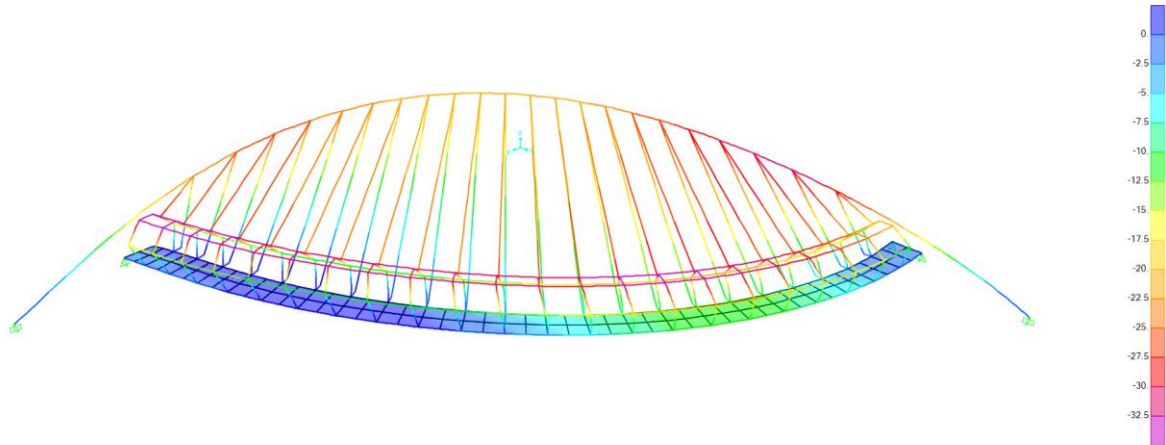


Figure C- 3 Horizontal (Uy) Deflection Contour of Un-factored Wind Load (W315) (mm)

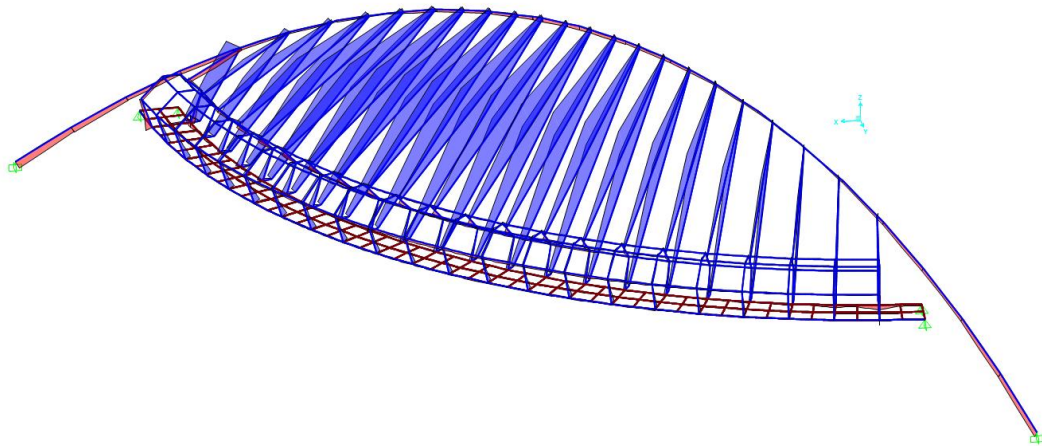


Figure C- 4 Axial Stress due to Strength I

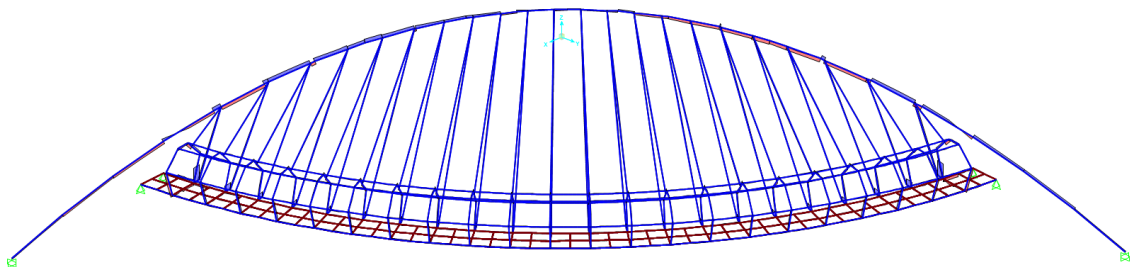


Figure C- 5 Stress on Cross-Sections due to Strength I

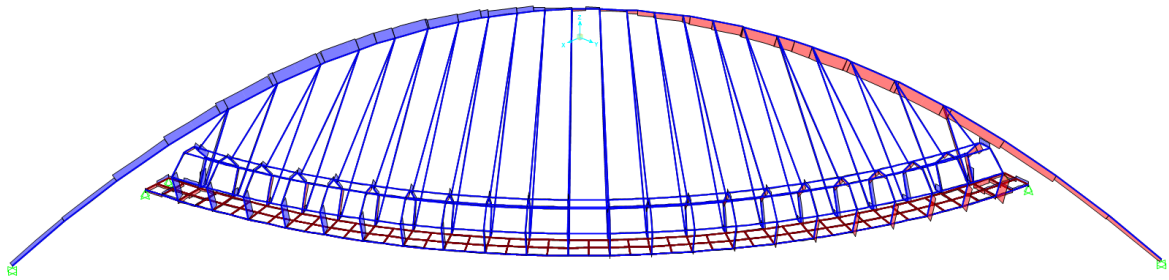


Figure C- 6 Torque Stress due to Strength I

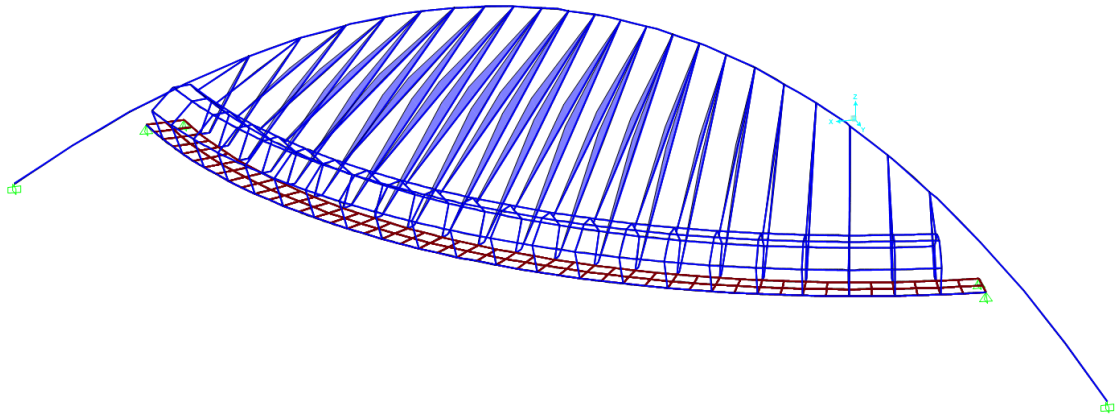


Figure C- 7 Axial Stress due to Strength III

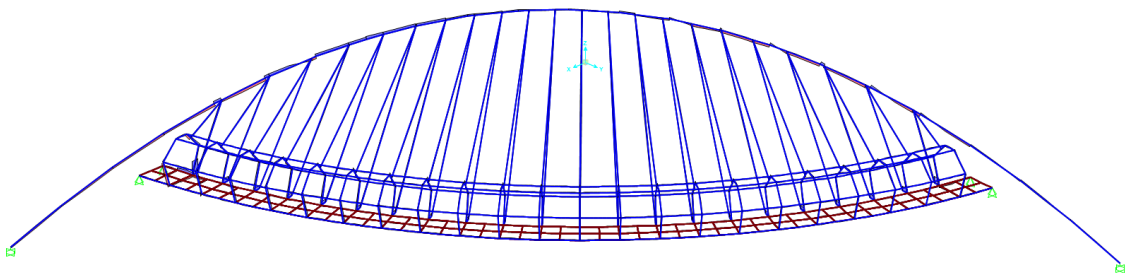


Figure C- 8 Stress on Cross-Section due to Strength III

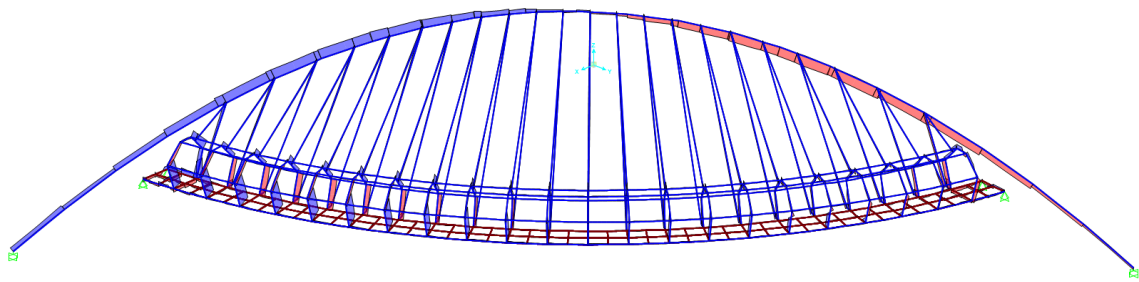


Figure C- 9 Torque Stress due to Strength III

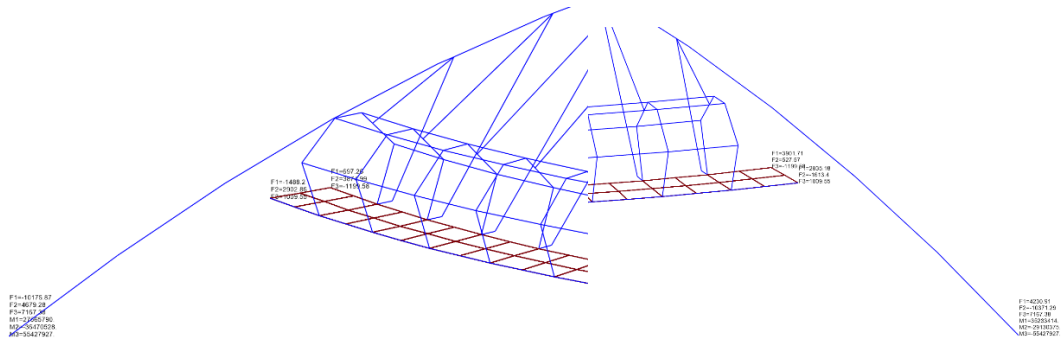


Figure C- 10 Supports Reactions due to Strength I (KN)

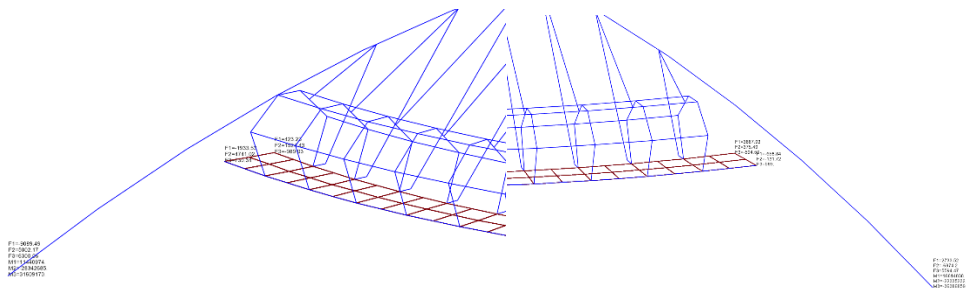


Figure C- 11 Supports Reactions due to Strength III (KN)

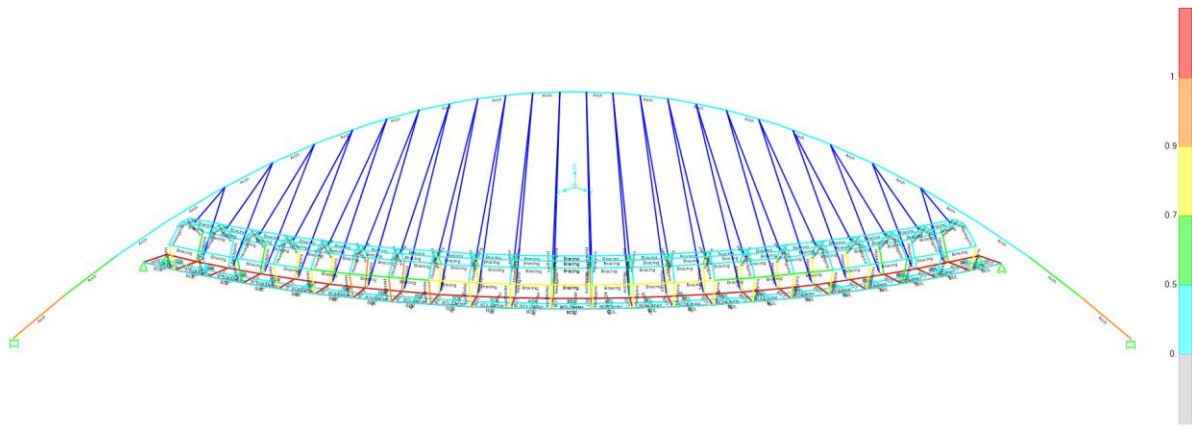


Figure C- 12 Design Check Contour Line According to Strength I & Strength III

الملخص

تهدف هذه الدراسة إلى تحقيق التصميم الأمثل لجسر مشاه غير خطي هندسياً. لهذا الغرض ، تم النظر في تصميم جسر المشاة التابع للطريق ماتلاند الذي يقع في ولاية فلوريدا بالولايات المتحدة الأمريكية، وتم بناء النموذج الهيكلي للجسر باستخدام SAP2000. بمجرد تصميمها، تم تصنيف أعضاء الهيكل إلى سبع مجموعات وفقاً لوظائفهم وطريقة حمل أحمال التصميم؛ ولذلك تم تصنيف هذه المجموعات على أساس أشكال مقاطعهم العرضية وهي: أقسام الهيكلية الحرف (I)، أقسام هيكلية مجوفة (HSS)، أقسام أنابيب وأقسام الكابلات، بينما أقسام أعضاء القوس تم تصنيفها على أقسام هيكلية مجوفة ولكن مبنية نظراً لحجمها الهائل.

تعمل عملية التحسين على استخدام مساحة المقطع العرضي لهذه الأقسام المصنفة كمتغيرات وذلك يرجع إلى تأثيرهم في الوزن الإجمالي الخاص بالهيكل العام للجسر ويتم تقييم هذه المتغيرات طبقاً لمعايير AISC / AASHTO. أُستخدم في عملية تحسين ثلاث خوارزميات فوقية الكشف (metaheuristic) إلا وهم: خوارزمية تدريس التحسين القائم على التعلم (TLBO) ، خوارزمية مستعمرة النحل الاصطناعية (ABC) ، و خوارزمية التطور التفاضلي (DE). لقد تم استخدام برنامج MATLAB لعملية التحسين، إلى جانب استخدام API SM toolbox كمتبرمج بين SAP2000 و MATLAB. أظهرت النتائج أن خوارزمية DE هي الأفضل للحصول على التصميم الأمثل لجسر المشاه مستغرقاً وقتاً أقل ومحققاً أعلى نسبة التخفيض، حيث تم تخفيض وزن التصميم إلى 27.79% من وزن التصميم الأولي له ممضياً 11.59 يوماً فقط، بينما خوارزمية ABC وصلت إلى 33.86% مستهلكاً 21 يوماً و خوارزمية TLBO وصلت إلى 27.79% مستغرقاً 30.5 يوماً.

جامعة البحرين



قسم الهندسة المدنية

كلية الهندسة

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أطروحة مقدمة كجزء من متطلبات الحصول على درجة الماجستير في العلوم الهندسة

المدنية

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