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COMPERATIVE STRUCTURAL ANALYSIS OF SUSPENSION BRIDGES WITH DIAGONAL AND VERTICAL HANGERS

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A thesis submitted by Mustafa Mert EYÜPGİLLER in partial fulfillment of the requirements for the degree of **MASTER OF SCIENCE** is approved by the committee on 23.06.2017 in Department of Civil Engineering, Mechanics Program.

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June, 2017

Mustafa Mert EYÜPGİLLER

TABLE OF CONTENTS

Page

LIST OF ABBREVIATIONS

FE	Finite-Element
FEA	Finite-Element Analysis
KGM	Republic of Turkey – General Directorate of Highways
RE	Relative Error

LIST OF FIGURES

Page

LIST OF TABLES

Page

ABSTRACT

COMPERATIVE STRUCTURAL ANALYSIS OF SUSPENSION BRIDGES WITH DIAGONAL AND VERTICAL HANGERS

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MSc. Thesis

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15th July Martyrs Bridge (a.k.a. Bosphorus Bridge) was the longest bridge with diagonal hangers when it was constructed in 1973. Recently a retrofitting project was applied and the diagonal hangers of the aging bridge were changed with vertical hangers.

Literature includes a large volume of studies on the diagonal configuration, both experimental and theoretical. These studies have addressed almost every structural aspects of this suspension bridge with diagonal hangers but there have not been any for the new vertical configuration. In this study one of the most detailed and realistic model of the Bosphorus Bridge is developed by using the finite element method (FEM). While the deck structure and towers are considered as realistic 3D shell structures with intricate details such as inner stiffener plates, the main cable is assumed continuous over the saddles with frictional contact -a unique detail of the model which makes it one of a kind. The model distinguishes itself from others as structural idealizations are kept at minimum unlike others which generally retain on equivalent super-structures. Both diagonal and vertical configurations are modeled in an automated scripted manner within a framework of a commercial FEM package and the effect of this major retrofit on the free vibration characteristics and cable stress distributions are analyzed.

Since the literature includes only results for the old, diagonal configuration and this study is the only one addressing the new configuration, verification is carried out by comparing the natural frequencies with the existing experimental values on diagonal configuration.

Changes in natural frequencies and altered stress distribution for the main cable, hanger cables and deck structure due to new (vertical) configuration are studied in a comparative fashion with respect to the old (diagonal) configuration. Furthermore, the models are subjected to various thermal conditions such that the bridge has been exposed to. Variations on the stress distributions of the deck structure and cable forces are investigated. It is seen that diagonal configuration is more sensitive to the thermal effects and thus the related fatigue. Finally, thermal effects on the natural frequencies are addressed as well.

Keywords: Bosphorus Suspension Bridge, Finite-Element Method, suspension bridges, bridge retrofitting, thermal effects

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ÖZET

EĞİK VE DÜŞEY ASKI KABLOLU ASMA KÖPRÜLERİN KIYASLAMALI YAPISAL ANALİZİ

Mustafa Mert EYÜPGİLLER

İnşaat Mühendisliği Anabilim Dalı

Yüksek Lisans Tezi

Tez Danışmanı:Yrd. Doç. Dr. Çağrı MOLLAMAHMUTOĞLU

15 Temmuz Şehitler Köprüsü (Boğaziçi Köprüsü) inşa edildiği 1973 yılında eğik askı kablolu en uzun köprüydü. Yakın zamanda bir güçlendirme ve iyileştirme projesi geçirdi ve İstanbul'un bu ikonik köprüsünün eğik askı kabloları düşey kablolar ile değiştirildi.

Literatürde köprünün eğik kablolu düzeniyle ilgili, hem deneysel hem teorik çok sayıda araştırma bulunmaktadır. Bu araştırmalar eğik kablolu köprünün neredeyse bütün yapısal özelliklerini ortaya koysalar da düşey kablolu yeni düzeni üzerinde herhangi bir çalışma bulunmamaktadır. Bu çalışmada, sonlu elemanlar yöntemi kullanılarak Boğaziçi Köprüsü'nün en detaylı ve gerçekçi modellerinden biri üretilmiştir. Tabliye ve kuleler rijitleştirici levhalar gibi ince detaylarla gerçekçi üç-boyutlu kabuk (shell) yapılar olarak ele alınırken; ana kablo -modeli türünün tek örneği yapan eşsiz bir özellik- kuleler üzerindeki semerlerde sürtünmeli temas eden sürekli eleman olarak kabul edilmiştir. Bu modelde yapısal idealleştirmeleri minimum tutulması, çoğunlukla eşdeğer elemanlar kullanan diğer modellere göre ayırt edici niteliktedir.

Hem eğik hem de düşey askı kablolu düzenlerin modellenmesinde bir ticari sonlu elemanlar programı çerçevesinde otomatikleştirilmiş kodlar kullanılmış, bu büyük iyileştirme projesinin serbest titreşim karakteristikleri ve kablolardaki gerilme dağılımları analiz edilmiştir.

Literatür köprünün sadece eski, eğik kablolu düzenine ait sonuçları içermesi ve bu çalışma yeni düzene ait tek çalışma olması sebebiyle, analiz sonuçlarının doğrulaması varolan deneysel doğal frekans değerleriyle eğik düzen modelinin sonuçları kıyaslanarak yapılmıştır.

Köprünün iki düzeninin doğal frekanslarının, anakablo, askı kabloları ve tabliyedeki gerilmelerin değişimleri kıyaslamalı olarak incelenmiştir. Bunlara ek olarak, modellere, köprünün gerçekte maruz kaldığı çeşitli sıcaklık değişimleri etkitilmiş, tabliyedeki gerilme değişimleri ve kablo kuvvetleri incelenmiştir. Eğik askı kablolu düzenin sıcaklık etkilerine karşı daha hassas olduğu, dolayısıyla yorulmaya yatkınlığı görülmüştür. Son olarak, sıcaklığın doğal frekanslara etkileri de gösterilmiştir.

Anahtar Kelimeler: Boğaziçi Asma Köprüsü, sonlu elemanlar yöntemi, asma köprü, köprü iyileştirme, sıcaklık etkileri

YILDIZ TEKNİK ÜNİVERSİTESİ

FEN BİLİMLERİ ENSTİTÜSÜ

CHAPTER 1

INTRODUCTION

Bridges are one of few complex solutions for crossing over long gaps. As one of the design options, a suspension bridge is preferred due to create wider and higher openings for the maritime navigation. The larger openings result more complex and costly structures.

The Bosphorus Bridge (a.k.a. 15th July Martyrs' Bridge) in Istanbul, with its 1074 m span length, is a typical example to bridges with long span lengths. It crosses over 1560 m and has been in service since 1973. Its highest clearance over the sea is 64 m. This height was needed in order to maintain the maritime traffic between the Mediterranean Sea and the Black Sea through the strait of Bosphorus.

Even though the bridge has not faced any structural disruptions or incidents, it was decided to improve the bridge due to newer structural technologies. Therefore, a retrofitting project has begun in 2015. This project includes some major changes such as its hanger configuration, restraints of the deck and adding dampers, which would improve the dynamic performance.

The Bosphorus Bridge has always been an interesting subject to be worked on by academic societies. However, the retrofitting project brought out a new opportunity of comparing two bridges with nearly identical properties except their hanger configurations and restraints.

1.1 Literature Review

The latest model by Bas [1], the Bosphorus Bridge, its inclined hangers and approach viaducts are modeled on SAP2000 program, with 263 frame, 387 cable and 3996 shell elements. In this model, 50 frequencies and mode shapes were found and first five of them are compared to experimental findings.

Another article on the Bosphorus Bridge by Apaydin [2] focuses on the seismic performance of the bridge and examines the state of it after a possible earthquake. The model is validated by comparing the outcomes to analytical studies, before applying the ground motion. As a result of Functional Evaluation Earthquake ground motion, which is to refer a high probability earthquake, which has a 50% probability of exceedance in 50 years, the bridge continues its functionality without delay. Furthermore, Safety Evaluation Earthquake ground motion, which has a 2% probability of happening in 50 years, is applied to the inclined configuration of the bridge and it is found to be safe only with repairable light damage in towers, although it had been built by the Earthquake specifications of the year 1967.

Chang et al. [3] studied on the investigation of dynamic response for long-span cable-stayed bridge in Hong Kong. The object of his article is the brigde connecting the islands of Ma Wan and Lantau in Hong Kong. It is a complex bridge with double-layer deck of 750m long and fan type of cables. The finite-element model is built up due to estimations from the initial project of the bridge. All the towers and the deck is modeled with beam elements and, truss elements are assigned for the cables. After applying static loads, attained deformed shape has undergone to modal analysis. The results of the modal analysis, the calculated natural frequencies of the bridge, are quite close to the measured data.

The article of Almutairi et al. [4] proposes a controller system to reduce the nonlinear vibrations of a suspension bridge. The bridge model is based on Lyapunov theory, using the MATLAB program. It shows comperatively that the nonlinear oscillations could be reduced by installing hydraulic actuators, which provides active control on force on the bridge deck. Furthermore, it shows many aspects of the vibrational behavior of suspension bridges.

Brownjohn [5] brings on an evaluation about damping values of suspension bridges. His article separately examines each component of a suspension bridge that contributes to damping and also explains the damping types and models. As a result of that article, it is shown that the deck, deck bearings and hangers are the most contributing structural components; likewise, geometric nonlinearity is found out to be significant only in most severe forms of loading. Thus, it gives an insight into the notion of damping of suspension bridges, and the contribution of each structural element to the total damping occurring.

Warren recommends [6] 4-node linear shell elements, instead of 8-node solid elements, in order to model the deck of a bridge. It is because those shell elements were found to be stably converging to an accurate prediction of natural frequencies, however, the solid elements fail to do so by under and overestimating depending on the model refinement.

1.2 Objective of the Thesis

In this study, the effects of hanger configuration of a suspension bridge were investigated. The Bosphorus Bridge was chosen as a model since it is a significant example of such a bridge type and also it had been retrofitted recently. After more than 30 years of service with diagonal hangers, its hanger configuration was changed to vertical. This retrofitting project provided an opportunity to compare a suspension bridge with diagonal configuration to vertical configuration.

The aim was to create an accurate model of both configurations and compare their mode shapes, modal frequencies and their conditions after various thermal effects.

1.3 Hypothesis

The hangers of a suspension bridge are the parts that connect the deck to the main cables. So, they serve a very important purpose in the vertical modes of the deck. Since the hangers of the Bosphorus Bridge were changed, its vertical modal frequencies were expected to change noticeably. Furthermore, the vertical displacements of the deck, might be caused by some additional mass or thermal effects, are also critically dependent on the strain of the hangers.

Thus, the modal frequencies, displacements of the deck and stress alteration on hangers were investigated in both configurations and compared to each other.

CHAPTER 2

BACKGROUND

Istanbul, the capital of Eastern Roman Empire and Ottoman Empire, is currently locomotive of the economy of Turkey meanwhile being one of the most crowded cities around the world. It is located on flanks of the strait, named the Bosphorus, which allows the passage from Mediterranean to Black sea. This strait is defined as a border between continental Europe and Asia, dividing the city into two over these continents. The Bosphorus has average depth of 65 m and width varying from 700 to 3420 m.

2.1 A Brief History of Suspension Bridges

The concept of suspension bridges roots back to discovery of Americas. Chronicles of Spanish conquistadors wrote about the fearful view of the braided-fiber rope bridges crossing over the hills of Andes and rivers of South America [11]. Nevertheless, the first design of a modern suspension bridge with a roadway that allows vehicle traffic, was made and patented by James Finley in 1808 [12]. From that day forwards, the iron chains and then steel wire strands have become the one of the ingrained parts of a modern suspension bridges.

Figure 2.1 An Inca suspension bridge (1877) and George Washington Bridge over the Hudson River [11]

2.2 History of the First Bridge on the Bosphorus

The idea of a bridge crossing the Bosphorus does not belong only to recent era. As written in the fourth book of Herodotus' history books, a pontoon bridge (floating bridge) was built by the engineer named Mandrocles in order to allow passage of the armies of King Darius I (Darius the Great) of on a mission to Thrace around 514-512 BC [7]. However this bridge only belonged to that time. The Bosphorus had remained without a structure across. Even though templates of a tunnel below the strait were designed by French engineer S. Preault commissioned by the Sultan Abdulmecid I, this project was dropped due to financial difficulties. Transportation between European and Asian sides of Istanbul was provided only by boats and ferries until the construction of the Bosphorus Bridge in the second half of 20th century. The bridge is designed by a team of civil engineers, who also designed the alike diagonal configuration in the Humber Bridge after. In 1968, Freeman Fox & Partners is assigned for engineering works. It was constructed by multinational co-contractors from the year 1970 to 1973.

2.3 General Properties of the Bosphorus Bridge

The Bosphorus Bridge is a single-span, two-hinged stiffening girder, with vertical hangers (diagonal hangers before retrofitting) and externally-anchored bridge. It has portal type of main tower skeleton and parallel wire strands.[8] Though there are other types of constraints, in the Bosphorus Bridge, hangers are built inclined in order to restrict longitudinal displacement of the deck. Even though it has not had a complication arising from its inclined hangers for the last 40 years, this design is rarely preferred. This special constraint type in a long bridge can also be observed in the Humber Bridge in England. Thus, the Bosphorus Bridge is a typical example to analyze free vibrations of a suspension bridge with diagonal hangers. Since the hangers are inclined, they, as a statically consequence, has more axial stress under vertical loads comparing to vertical hangers. There are hangers (strands), which are basically groups of wires with 5 mm approximate diameter, as a linking element between the main cables and the deck,. The reason of choosing strands instead of a truss is not only to improve strength but also to decrease ductility. A wire is typically four times as strong as a mild steel, while, being much less ductile [13].

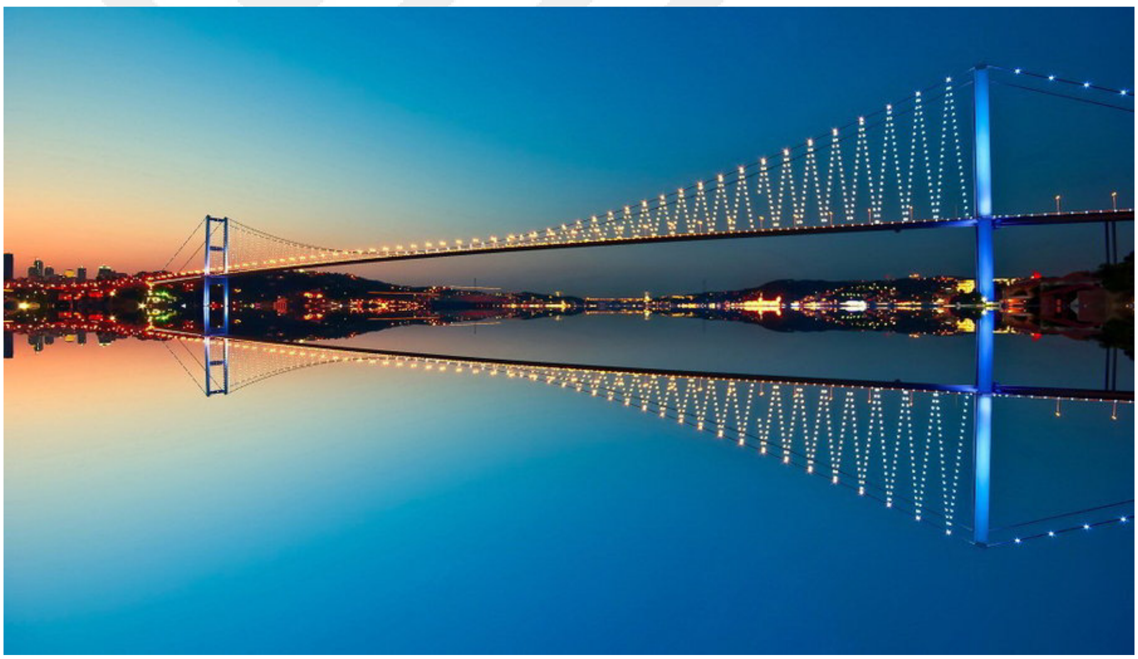


Figure 2.2 The view of the Bosphorus Bridge with diagonal hangers [15]

Figure 2.3 The view of the Bosphorus Bridge from above[16]

Table 2.1 List of suspension bridges with diagonal hangers, ranked by longest main span [16]

#	Name	Country	main span
1	Humber Bridge	United Kingdom	1410 m
2	Bosphorus Bridge	Turkey	1074 m
3	Severn Bridge	United Kingdom	988 m
4	Osijek Footbridge	Croatia	210 m
5	Samora Machel Bridge	Mozambique	180 m

2.4 Principal Dimensions and Quantities

Table 2.2 Material properties and some element dimensions

Young's modulus	200 GPa	Plate thicknesses	Towers	17-22 mm
Poisson's ratio	0.25		Deck	6-12 mm
Yielding stress of the cables	1500 MPa	Sectional area of cables	Main cables (backstay)	0.219 m2
Yielding stress of the structural steel	320 MPa		Main cables (span)	0.205 m2
			Hangers (both Diagonal and Vertical)	0.00196 m2

Table 2.3 Dimensions of the structure and project details [17][18]

<u>Dimensions of the structure</u>	
Span Length:	1074 m
Length of Approach Viaducts- (Ortaköy):	231 m
(Beylerbeyi):	255 m
Main Span Length:	400 m
Clearance of the Main Span:	64 m
Height of the Towers:	165 m
Main Cable Sagging:	93 m
Height of the Standard Deck Unit:	3 m
Width of the Standard Deck Unit (w/o side plates):	28 m
<u>Design Loads</u>	
Live Load:	1.33 tons/m
Wind Load:	45m/s
Ground Acceleration:	0.1 g
<u>Some Manufacturing quantities</u>	
Excavation:	63 000 m3
Concrete:	71 000 m3
Concrete reinforcement:	4 000 tons
Steel:	17 000 tons
Cables:	6 000 tons
Cost of the bridge:	191 785 265 TL (Turkish Lira)
	23 213 666 USD

CHAPTER 3

FINITE ELEMENT MODELLING

3.1 Dimensions

Whole bridge parts were redrawn in electronic environment based on hardcopy drawings because of lacking the softcopy of the design drawings.

3.1.1 Deck Structure

Deck, the superstructure, is the biggest continuous structure of the bridge. The deck structure of the bridge consists of 60 modules. Each module is 17.9 m long and 33.4 m wide. The height of the modules are highest in the mid-section with the dimension of 3m. On the inner surfaces of the decks, there are two types of stiffeners, one of which is V shaped and the other is single sided bulb flat. 40 V shaped stiffeners are only used on the upper plate (the ones that carry the vehicle load) and 56 single sided bulb flats are welded to rest of the inner surfaces. In order to prevent local buckling, 240 diaphragms are places equally spaces along the total length of the deck.

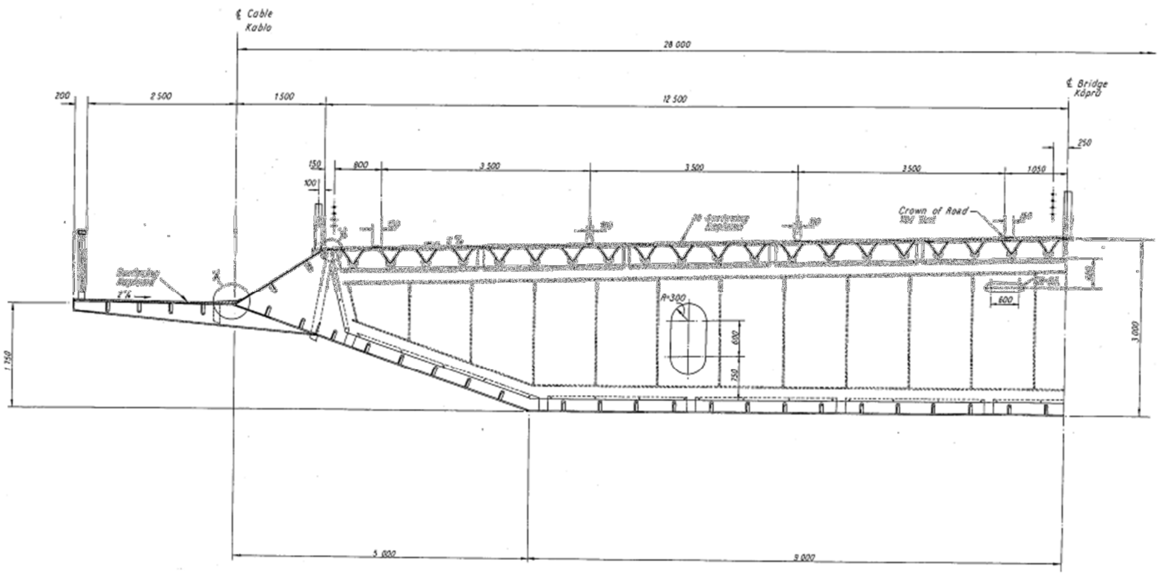


Figure 3.1 Original cross-section of the deck

3.1.1.1 Longitudinal Parts

Longitudinal parts are the components welded along the deck structure. These parts form the box girder of the deck and longitudinal stiffeners.

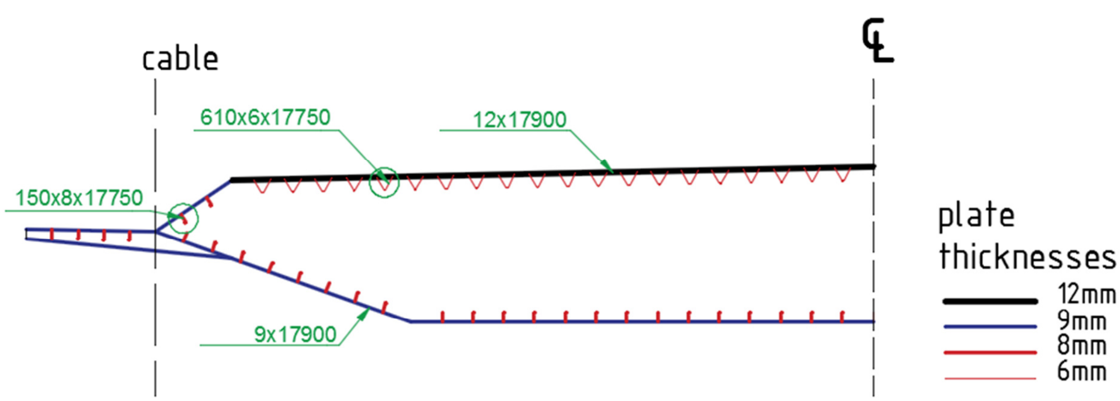


Figure 3.2 Cross-section of the deck showing longitudinal parts

The box girder of the deck was build up by plates with various thicknesses. The upper deck plate was formed by 10 plates of 12mm thickness, 2470mm width and 17900mm length. The rest of the outer parts of the deck - namely the bottom deck section, the footway and the connector side plates – were made of plates of 9mm thickness.

The longitudinal stiffeners on the upper plates are of type Vee, with the thickness of 6 mm. This type of stiffeners has several advantages such as supporting flange plate on multiple lines, providing resistance against shear forces and increasing the torsional rigidity [19]. The rest of the deck is supported by 8 mm thick single sided bulb flats.

3.1.1.2 Deck Diaphragms

In steel box girders, transverse diaphragms are the elements which are placed vertically, act as stiffeners in order to maintain cross-sectional proportion and they provide torsional rigidity [20].

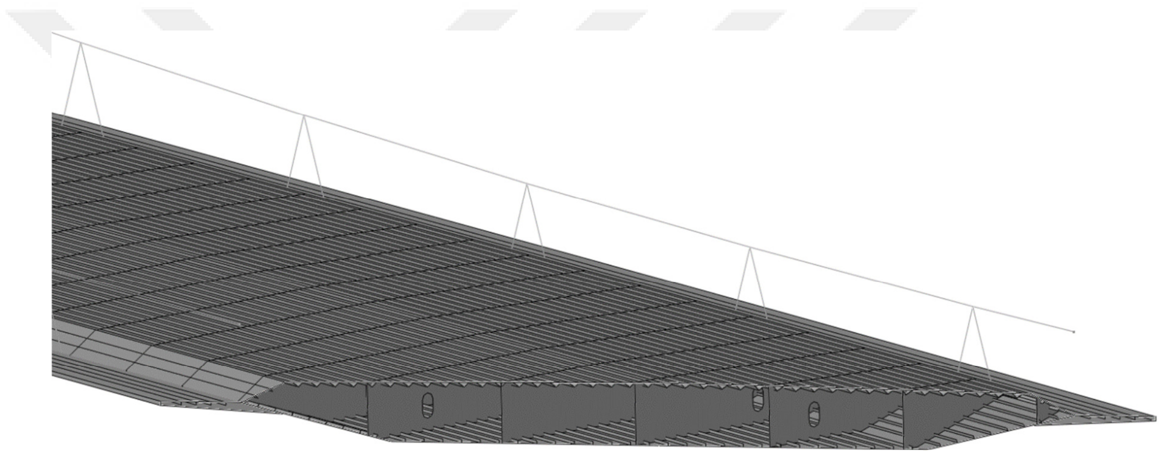


Figure 3.3 Transverse diaphragms and longitudinal stiffeners are shown in a section of the deck model

Main diaphragms of the deck were built up with plates of 6mm thickness on every 4475mm. They have two openings large enough only for a man to pass through.

3.1.2 Main Cables

In initial project, the main cables had been designed to have 82 strands (each containing 127 wires) over main-span and 88 strands (each containing 127 wires) in back-stays.

However, this design had been abandoned to have 19 strands (each containing 192448 wires) in main-span and additional 4 strands (each containing 192 wires) in back-stays.

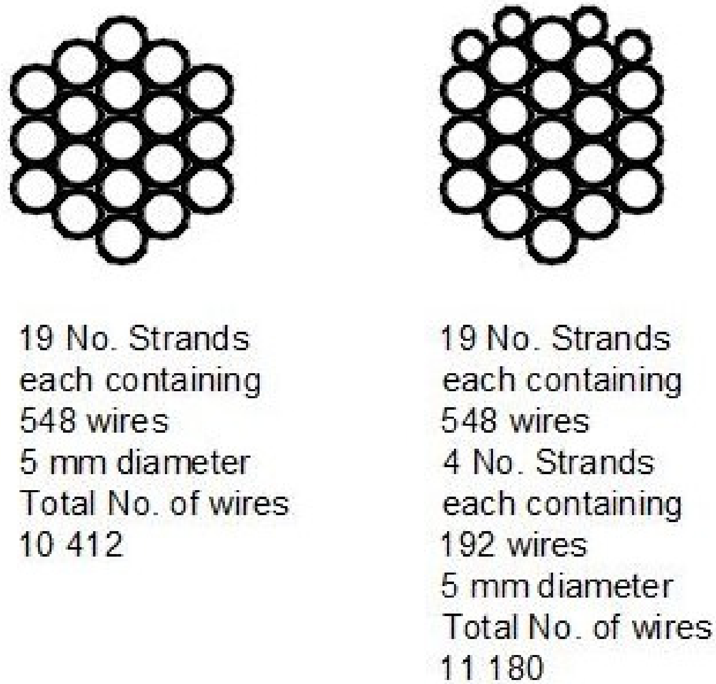


Figure 3.4 Arrangement of uncompacted main cables [21]

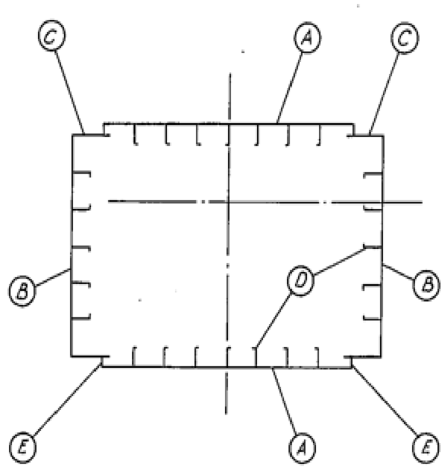
3.1.3 Hangers

The hangers are the elements transferring the weight of the deck and loads on it to the main cables. Each hanger in both configurations is single spiral galvanized wire strands with approximate diameter of 52 mm. In diagonal configuration, the hangers were pinned in longitudinal direction at their ends. However, in vertical configuration the hangers are pinned in three directions and they were built in pairs.

3.1.4 Towers

The towers do not have a constant section. The section of a tower is height dependent.

The cross-section of a tower is height dependent, it is widest on the bottom while it is narrowest on the top, decreasing linearly.



Section	Plate A	Plate B	Plate C	S.S.B.F D	Corner Angles E
1	5570x22	4677/ 4423,5x 22	800x22	343 x17,5	200x100x15
2	"	4423,5/ 4156 x 22	"	"	"
3	"	4156/ 3888,5x22	"	"	"
4	"	3888,5/ 3621,5x20	"	"	"
5	"	3621,5/ 3354 x 20	"	"	"
6	"	3354/ 3087 x 20	"	"	"
7	"	3087/ 2819,5x20	"	"	"
8	"	2819,5/ 2566 x 20	"	"	"

Figure 3.5 Tower cross-section and its components

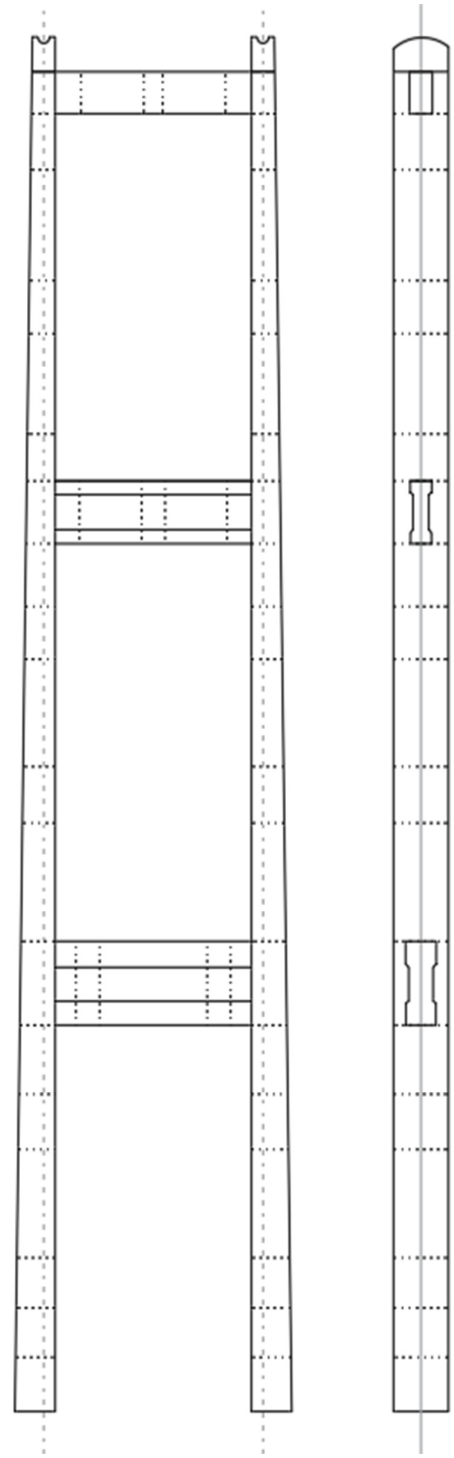


Figure 3.6 View and section of the towers drawn in AutoCAD

3.1.5 Bridge Profile

Bridge profile was modeled due to project drawings. Deck shape was obtained by revolving the deck cross-section along the axis of the deck. This axis was defined by a polynomial (3.a), in which the height over the sea was represented by y.

$$y_{deck\_axis} = -2.794x10^{-5}x^2 + 68.25 \qquad (3.a)$$

Main cables were restrained in their anchorage locations and hangers were pin connected to the main cables and the deck surface. These connection points on the surface of the deck also corresponds to the deck diaphragms, thus, stress was distributed over the deck. Main cables were modeled continuous over the saddles, where there is a contact assigned with the coefficient of friction of 0.3. However, the main cables did not slip over the saddles during the gravitational and traffic loading.

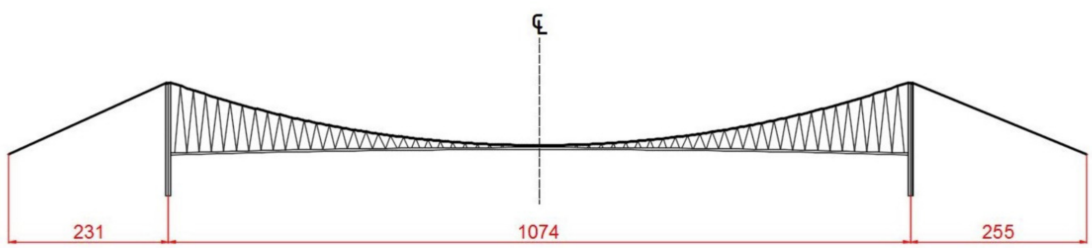


Figure 3.7: Bridge profile as in AutoCAD interface

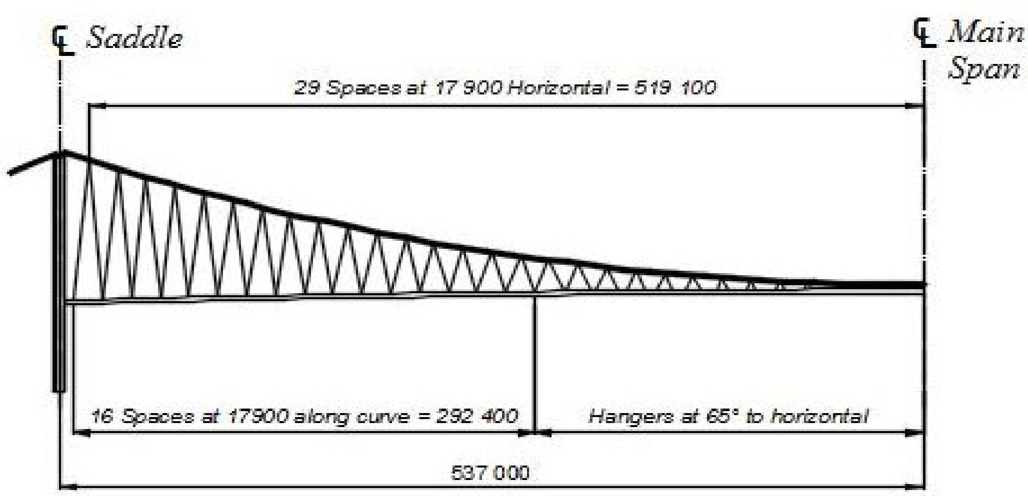


Figure 3.8 Aspects of the Diagonal Configuration

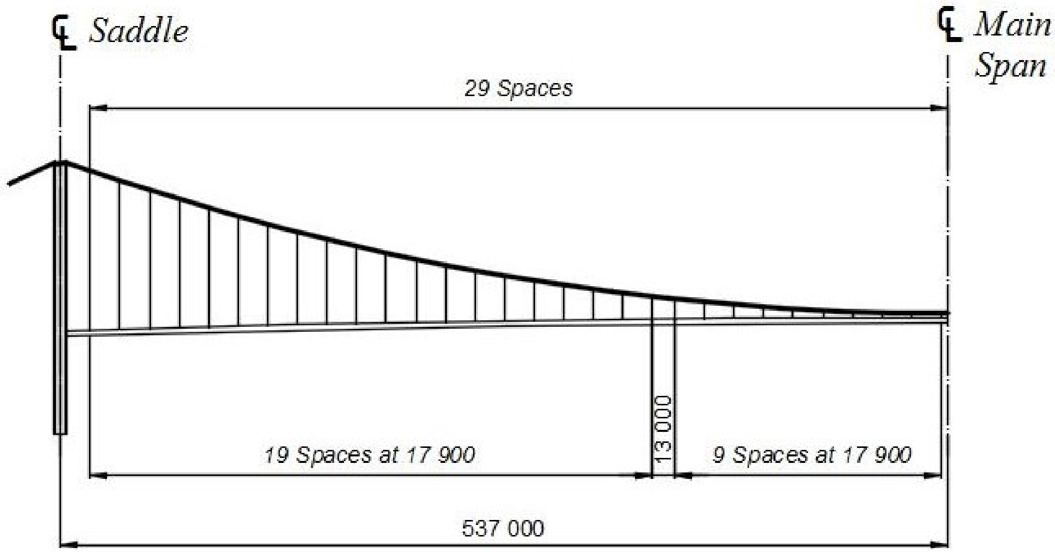


Figure 3.9 Aspects of the Vertical Configuration

3.2 3-D FE Model of Diagonal Configuration of the Bridge

In order to create an accurate and distinctive model, element types in the 3-D model were chosen to be as close to original structure as possible.

Basically, the coordinates of corners, beginning and endings of shell and line elements were exported from AutoCAD drawings and brought into Excel spreadsheets to have them usable. Using these coordinates, element types were chosen and assigned with the real-like boundary conditions.

After all of the parts were modeled in the ABAQUS FEA environment, calculated stresses were given only to hangers and the main cables, since the design drawings of the bridge and the model were defining the eventual position of the bridge. Then, an optimization process was performed for these stresses by a script in order to decrease the displacements which happened after the step of gravity exposure.

3.2.1 Deck Modelling

The coordinates that were extracted from AutoCAD drawings, were the key points of cross-section of the deck. Each component of the deck were created connecting these points and revolving along the curved axis of the deck by python scripts. The thicknesses were considered and implemented while creating the components. There are primarily three different thicknesses of the plates used in the deck construction, 6 mm, 9 mm and 12 mm. S4R shell element was assigned with original thicknesses for the plates. S4R is a basically quadrilateral, robust and general-purpose element that fits to our model [22].

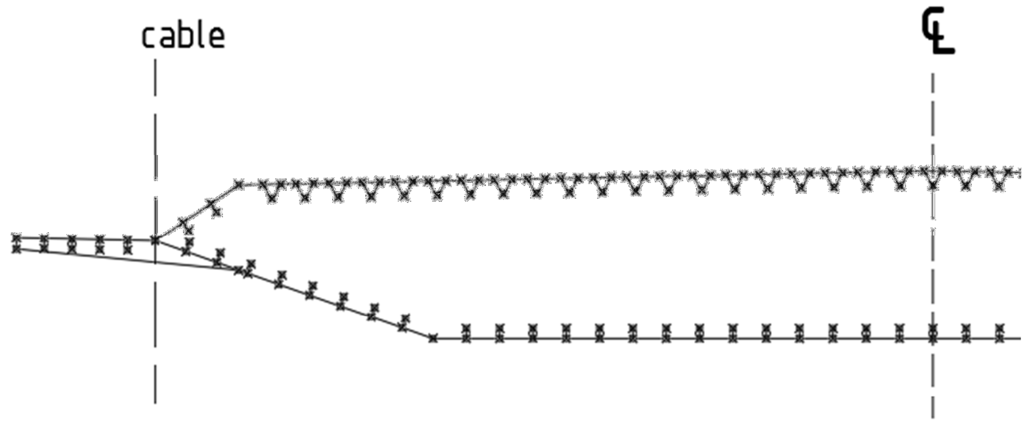


Figure 3.10 Key points that were extracted from AutoCAD drawing

3.2.2 Cable Modelling

Main cables were modeled as straight lines through numerous coordinates extracted from AutoCAD drawings. Along the span, those coordinates were chosen to be the connections of cable and hangers. Over the towers, the coordinates are in accordance with the geometry of saddles and were taken in every 1 cm horizontal distance. The backstays are straight lines from towers to anchorages bearings. T3D2 elements were assigned to the main cables. T3D2 element type of ABAQUS stands for trusses, rods that can carry only axial loads, have no resistance to bending, and are suitable for modeling pin-jointed frames [23].

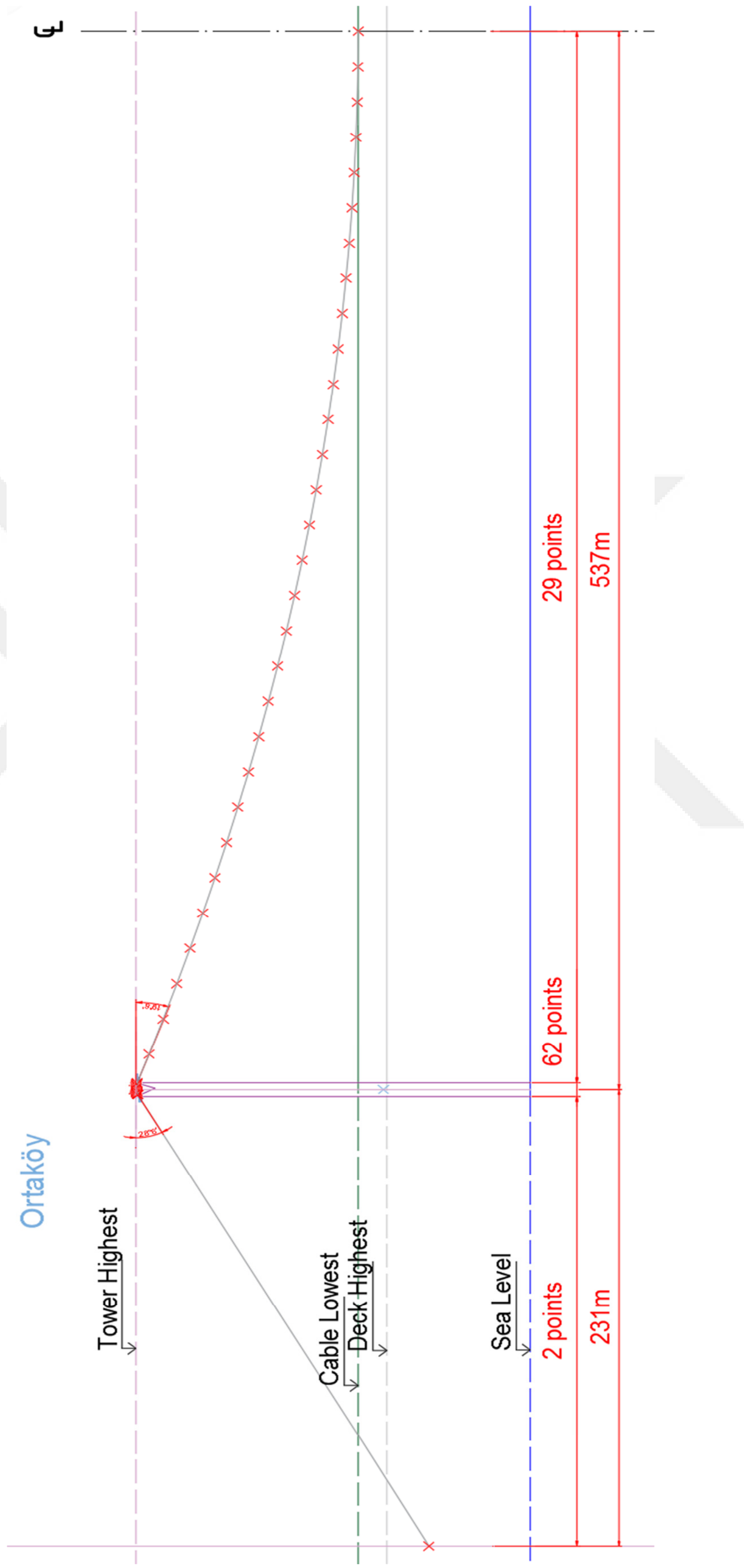


Figure 3.11 Points extracted from AutoCAD drawings to create main cables

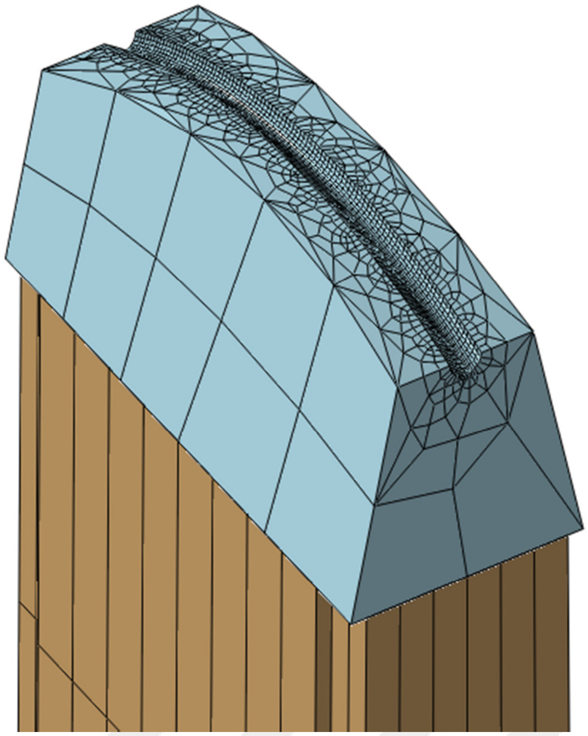


Figure 3.12 Mesh structure of a saddle

3.2.3 Saddle Modelling

The saddles are the components of the tower and transfers the loads from the main cables to the body of the towers. To acquire this function correctly and to distribute the loads of cable evenly to the towers, the saddles were made up of 3D rigid elements (R3D3). Contacts was defined between each cable and saddle. The meshes are finer on the surface of saddle, where the contact happens, than the rest of the saddle.

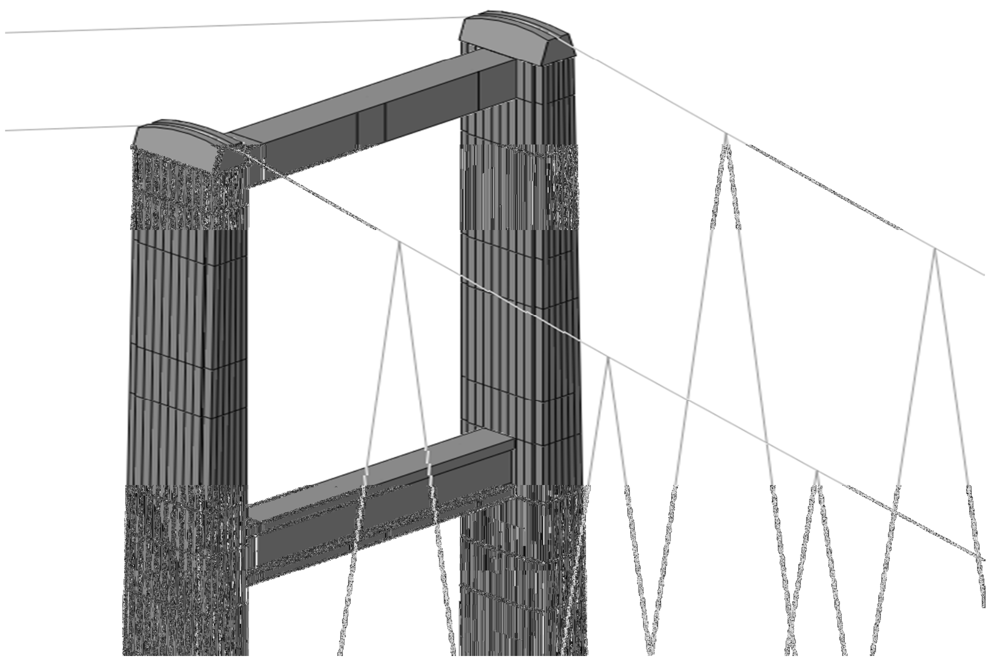


Figure 3.13 Assembly of the saddles in ABAQUS FEA environment

3.2.4 Tower Modelling

Towers were modeled with the same principles at the deck modeling. The key points were extracted from the AutoCAD drawings and created the tower model using the python scripts. The changing cross-section and shifting stiffeners were modeled using their start and end coordinates. Therefore, some S3R elements were used in addition to S4R elements. S3R element have the same properties with S4R elements except S3R is a 3- node triangular shell element, while S4R is a 4-node triangular element.

The area of diaphragms of the towers were adjusted due to the sections at the locations of the diaphragms. As a consequence, each diaphragm has different area. The limits of the diaphragms were found by calculating the sections of towers on each elevation where a diaphragm is placed. For this operation, all AutoCAD, Excel and Python scripts were used. Three beams between the towers and their diaphragms were also modeled 3D using S4R elements.

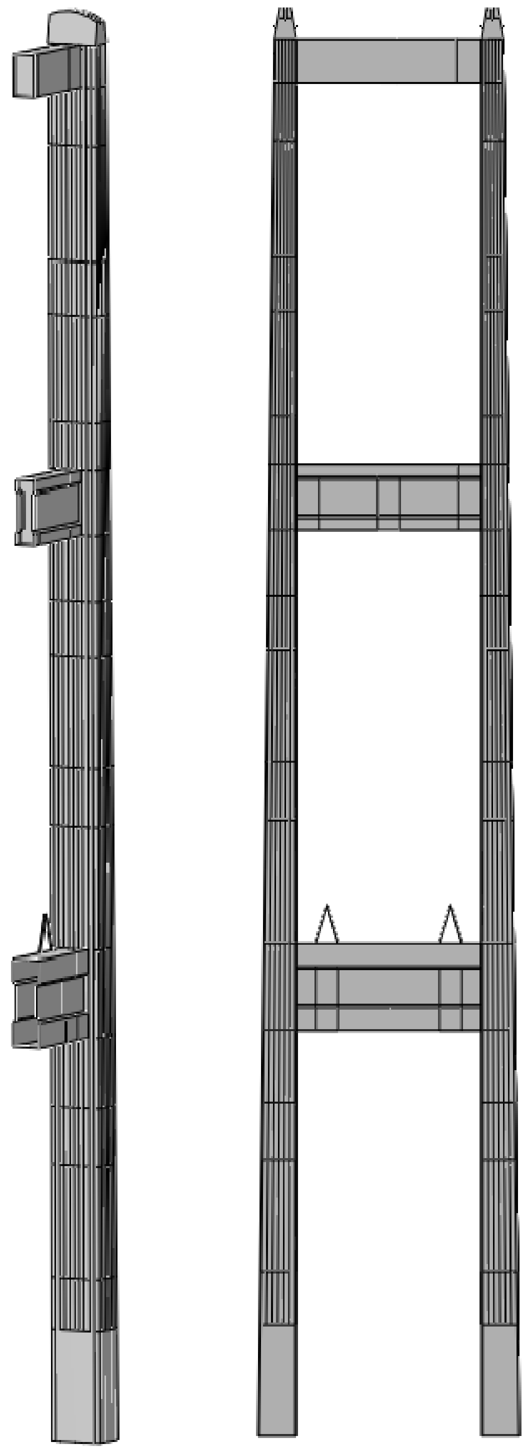


Figure 3.14 The view and a section of towers

3.2.5 Hanger Modelling

The hangers were modeled using T3D2 elements, the same element type with the main cables. On both ends of each hanger were connected to the deck and the main cable with pinned joints. They were attached to the exact same points on the deck.

3.2.6 Complete 3-D FE Model of Diagonal Configuration of the Bridge

The complete three-dimensional finite element model of the diagonal configuration of the Bosphorus Bridge was generated running the scripts for each part in ABAQUS FEA.

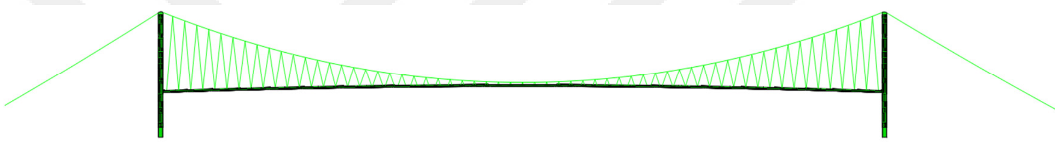


Figure 3.15 3D FE model of the diagonal configuration

3.2.7 FE Model Analysis of Diagonal Configuration

After all instances were built in, the model was ready for static and dynamic analysis. This procedure requires a powerful computer to analyze such problem since the whole model of diagonal configuration consists of 152495 nodes and 114653 elements.

The first step of the model (equilibrium under its own weight and pretension) was run in dynamic (implicit) analysis, since the static analysis fails converging because of the complex model structure, geometric nonlinearity and frictional contact. The dynamic analysis in this step was run in quasi-static state, in which the loading is applied too slowly to create inertial forces. The pre-stresses and gravitational acceleration were increased linearly over 500 seconds. Then, the modal analysis was run.

In order to analyze the models with thermal effects and additional mass, another step was added. In the model with thermal effects, all components of the bridge were heated in that step. In the model with additional mass, the mass of the upper plates of the deck was increased to obtain the total mass of the deck with full traffic load.

Besides the static and unloaded state of the bridge, there are several possible cases to develop understanding of bridge behavior. In section 5.4 and 5.5 of this dissertation, two more cases are also presented, one of which is with the additional mass and the other is under various thermal conditions.

3.3 3-D FE Model of Vertical Configuration of the Bridge

As explained before, the structural components, which were affected the most by the retrofitting project, were the constraints of the deck and the hangers. Two dampers were added to each of both ends of the deck with the properties retrieved from the manufacturer [34] and the hanger configuration was changed to vertical as in the design drawings.

Vertical hangers are actually pair of strands with the same diameter of the strands used in diagonal configuration. Thus, they were modeled as a single truss element with the twice as large area.

Figure 3.16 3D FE model of the bridge with vertical hangers

CHAPTER 4

MODEL VALIDATIONS

Before beginning to model the vertical hanger configuration of the bridge, a model validation should be checked. This validation shows the compatibility and appropriateness of the work done so far. For this purpose, the vertical, lateral and torsional modes were compared to the experimental results in the literature.

As mentioned before, the Bosphorus Bridge has always been a focal point of many bridge engineering studies and surveys. Two of the most important experimental works was came out by Brownjohn et al. (1989) [24] and by Erdogan (2005) [25] to estimate the dynamic characteristics of the bridge. Erdogan (2005) [25] showed the vertical and lateral modes identified between 0 and 1.035 Hz, while, Brownjohn et al. (1989) [24] identified the vertical, lateral and torsional modes between 0-1.1 Hz. In the sections below, the results of diagonal configuration model were compared to the data from those surveys.

For the purpose of checking the validity, the analysis results obtained from the model were compared to the outcomes of past experimental studies. The first five lateral, vertical and torsional modes of the FE model are listed below, in comparison to the results of Brownjohn et al. [24]. "Relative error" (R.E.) stands for:

R.E. = ABS(FE Model Result – Experimental Result) / (Experimental Result) (3.1)

4.1 Comparison of Experimental and Analytical Results ofr Vertical Modes

The model with the diagonal configuration showed quite accurate results in vertical modes comparing to experimental findings. The highest relative error was found to be 8.89% in the 10^{th} mode, and in the first mode it was as accurate as 1.59%.

In the article of Brownjohn et al., it is explained that the Bophorus Bridge was found to be having its first mode in two different frequencies. The authors pointed out the reason which caused this situation as the "split personality" of the bridge. The first mode shape with higher frequency was caused by the heavy traffic load, therefore, that value was not included to the table 4.1.

Table 4.1 Comparison of vertical modes between theoretical and experimental results

Vertical Modes					
Theoretical frequency (Hz)	**Symmetry**	**Nodes**	**Antinodes**	**Experimental frequency (Hz)-Brownjohn et al. [24]**	**Relative Error (%)**
0.12695	a	1	2	0.129	1.59%
0.16784	s	2	3	0.16	4.90%
0.23161	s	2	3	0.217	6.73%
0.28880	a	3	4	0.277	4.26%
0.38163	s	4	5	0.362	5.42%
0.46667	a	5	6	0.446	4.63%
0.57292	s	6	7	0.544	5.32%
0.67882	a	7	8	0.637	6.57%
0.78469	s	8	9	0.739	6.18%
0.90376	a	9	10	0.83	8.89%

4.2 Comparison of Experimental and Analytical Results for Lateral Modes

The lateral modes of the model were consistent with the experimental results. Table 4.2 shows that in the first seven modes, the highest relative error between the lateral modes is %3.47 and the average of relative errors of the first nine modes is %2.45.

Table 4.2 Comparison of lateral modes between theoretical and experimental results

Lateral Modes					
Theoretical frequency (Hz)	**Symmetry**	**Nodes**	**Antinodes**	**Experimental frequency (Hz)- Brownjohn et al. [24]**	**Relative Error (%)**
0.07243	s	0	1	0.07	3.47%
0.21433	a	1	2	0.209	2.55%
0.27855	s	0	1	0.284	1.92%
0.29164	a	1	2	0.294	0.80%
0.36499	s	2	3	0.365	0.00%
0.38512	s	2	3	0.382	0.82%
0.44125	s	2	3	0.44	0.28%
0.57019	s	2	3	0.525	8.61%
0.73304	a	3	4	0.762	3.80%

4.3 Comparison of Experimental and Analytical Results for Torsional Modes

There are five torsional modes found in the frequency range of the experiments (0-1.1 Hz) in 1989. Our model also showed the same amount of modal shapes between 0-1.1 Hz. Frequencies of these modes of the model with diagonal hangers had a good agreement with the experimental results in academic literature. %5.13 is the highest relative error among the five torsional modes. Table 4.3 shows the torsional mode frequencies obtained from the FE model and comparison with the experimental results.

Table 4.3 Comparison of torsional modes between theoretical and experimental results

Torsional Modes					
Theoretical frequency (Hz)	symmetry	nodes	antinodes	Experimental frequency (Hz)-Brownjohn et al. [24]	Relative Error (%)
0.33356	s	0	1	0.324	2.95%
0.49833	a	1	2	0.474	5.13%
0.50976	a	1	2	0.492	3.61%
0.67050	s	2	3	0.649	3.31%
0.89433	a	3	4	0.877	1.98%

CHAPTER 5

COMPARISON OF DIAGONAL AND VERTICAL CONFIGURATIONS

In this chapter, models of the two configurations of the bridge were compared to each other in various features such as their mode frequencies, mode shapes and responses to thermal effects.

The works until here were FE modeling the bridge with diagonal hanger configuration and comparing modal frequencies of the model to experimental data in order to approve the convergence of the model.

To further the study, the model of the bridge was modified to fit into the vertical configuration. The same operations held also on the latter model to get the model shapes and frequencies. The results of these operations were compared to the previous results obtained from the diagonal configuration.

Moreover, both models were subjected to thermal effects to investigate their responses and the alterations occurring in the structures. These effects were limited to the realistic temperatures, to which the bridge has been exposed for years. Alterations of the superstructure and stresses on the hangers in various thermal conditions were investigated.

5.1 Comparison of Vertical Modes and Mode Shapes

Vertical modes are the modes that were expected to have the highest difference in frequencies after retrofitting, since the main difference between two models is their vertical hangers. The mode shapes and their frequencies are given in the Fig. 5.1.

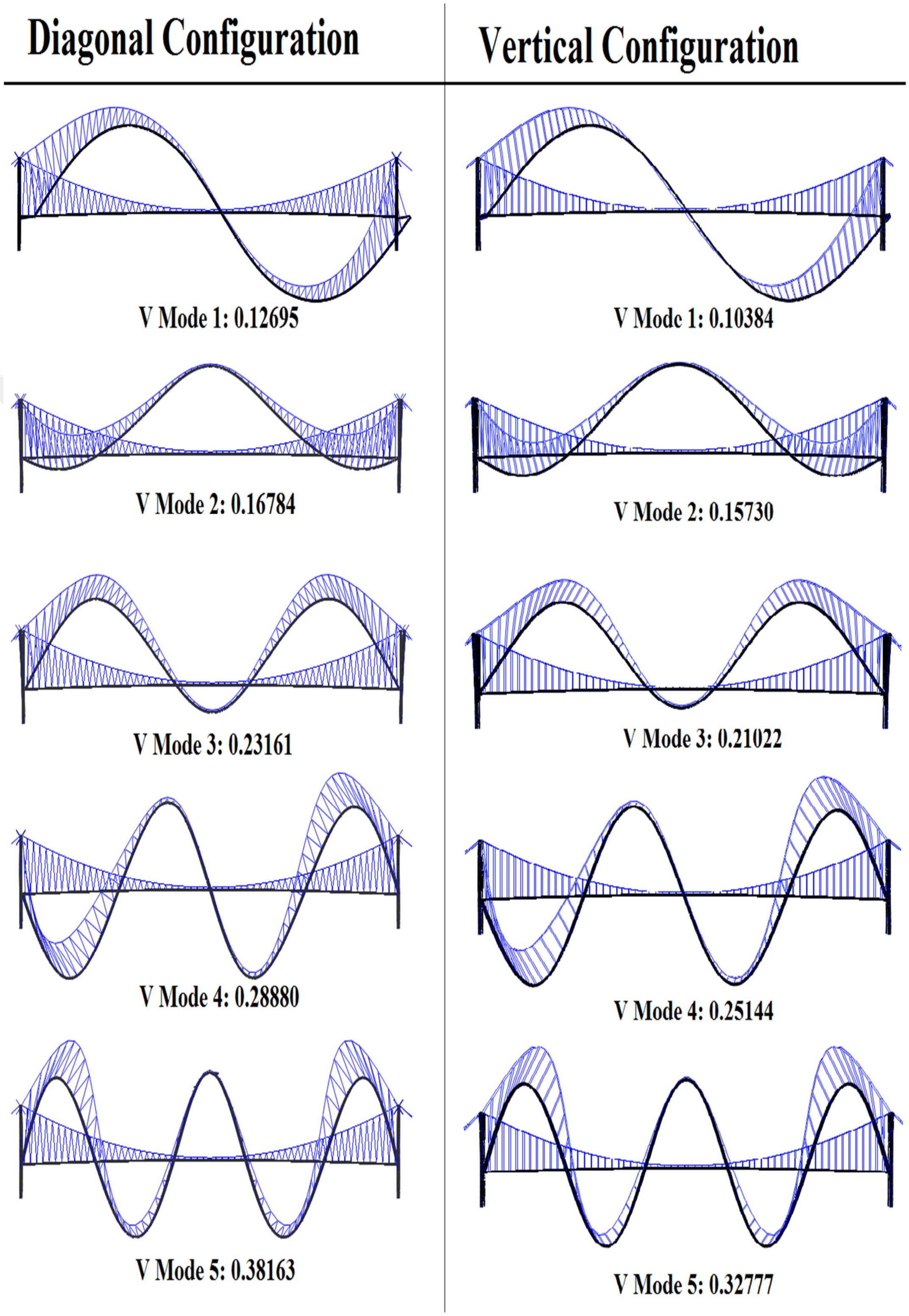


Figure 5.1 Comparison of diagonal and vertical configurations for vertical modes

5.2 Comparison of Lateral Modes and Mode Shapes

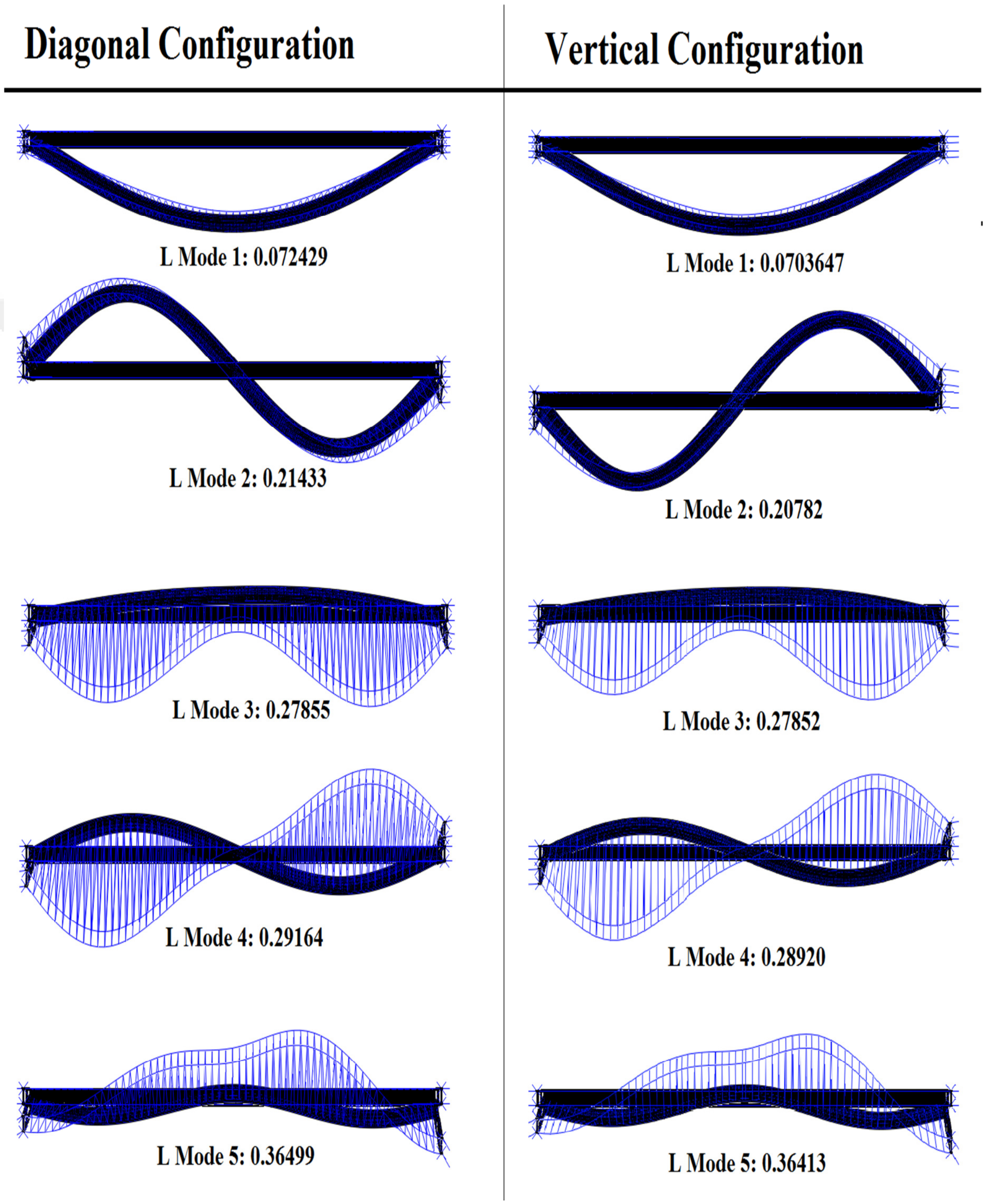


Figure 5.2 Comparison of diagonal and vertical configurations for lateral modes

5.3 Comparison of Torsional Modes and Mode Shapes

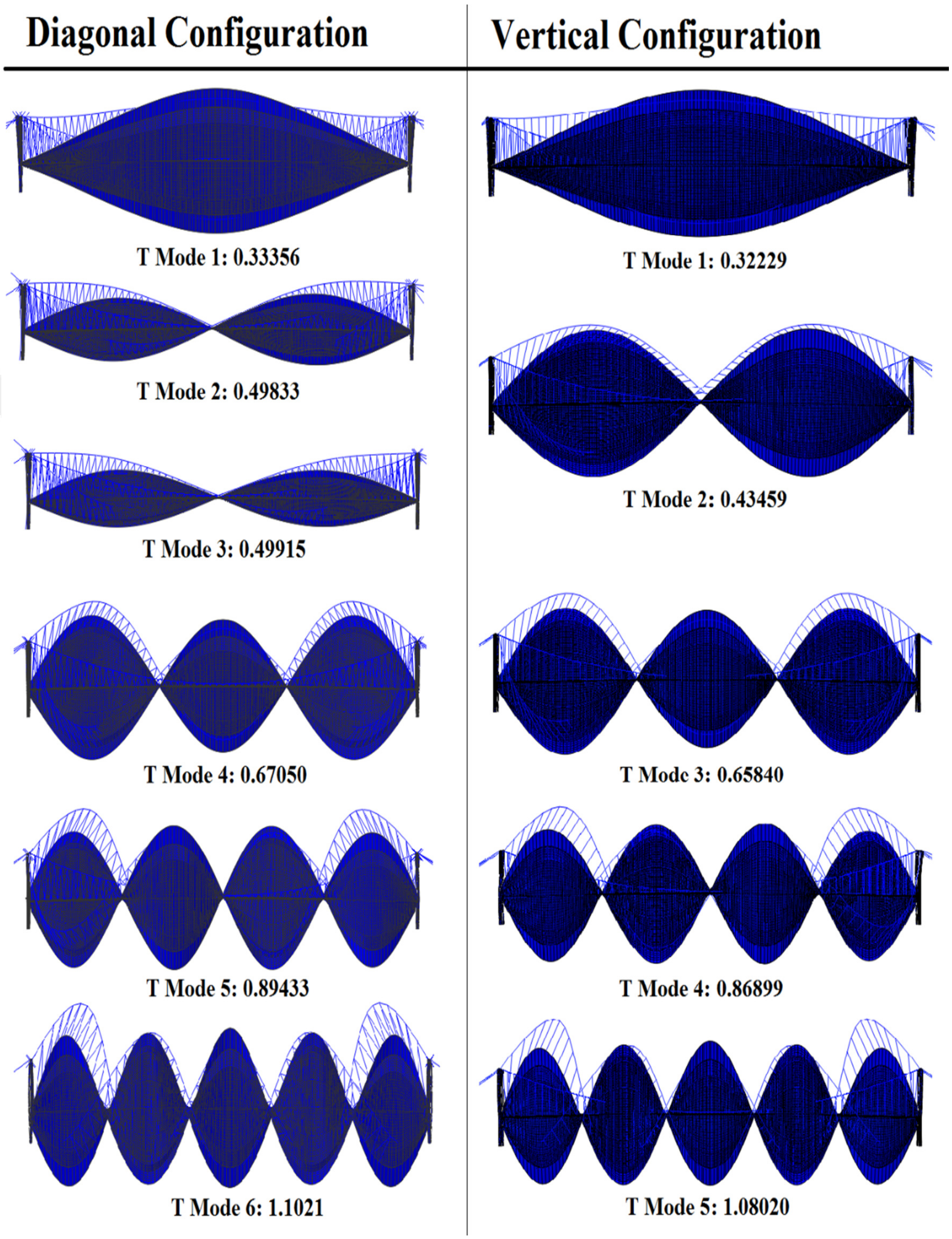


Figure 5.3 Comparison of diagonal and vertical configurations for torsional modes

5.4 Thermal Effects on the Bridge Models

Effects of environmental conditions on bridges have been the subject of many researchers. Many of the researches finds temperature as the most affecting environmental condition on modal frequencies [26],[27],[28],[29],[30],[31],[32],[33]. Peeters and De Roeck (2011) observed Z24-Bridge for a year to find relations between the eigenfrequencies and several environmental conditions such as temperature, wind characteristics, humidity and rainfall. The authors suggest that the only condition that had such a relation was temperature.

Different temperatures were imposed to both models and their responses were recorded. In Istanbul, the extremum temperatures of weather are -16.1°C and 41.1°C [10]. Therefore, the models were exposed to ±30 °C temperature changes. The responses of the models were compared in various aspects such as displacements of their decks, alteration of loads on their hangers and natural frequencies.

5.4.1 Comparison of Loads on the Hangers of Under Various Thermal Conditions

In this section, loads on each hanger in different thermal conditions were investigated for both configurations and compared.

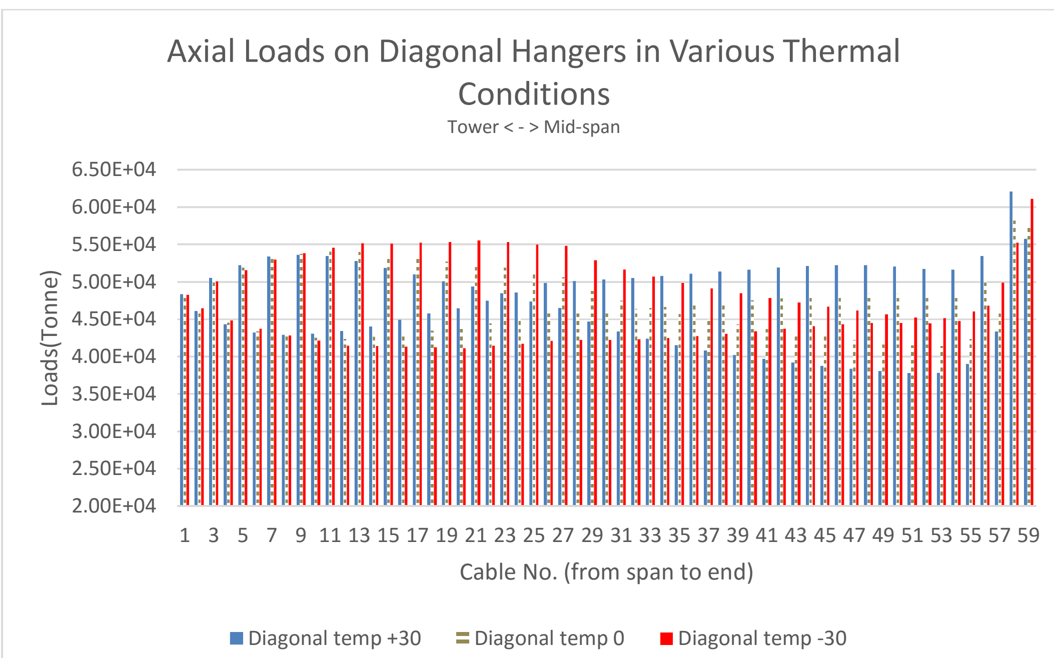


Figure 5.4 Axial loads on diagonal hangers in +30°C and -30°C temperatures

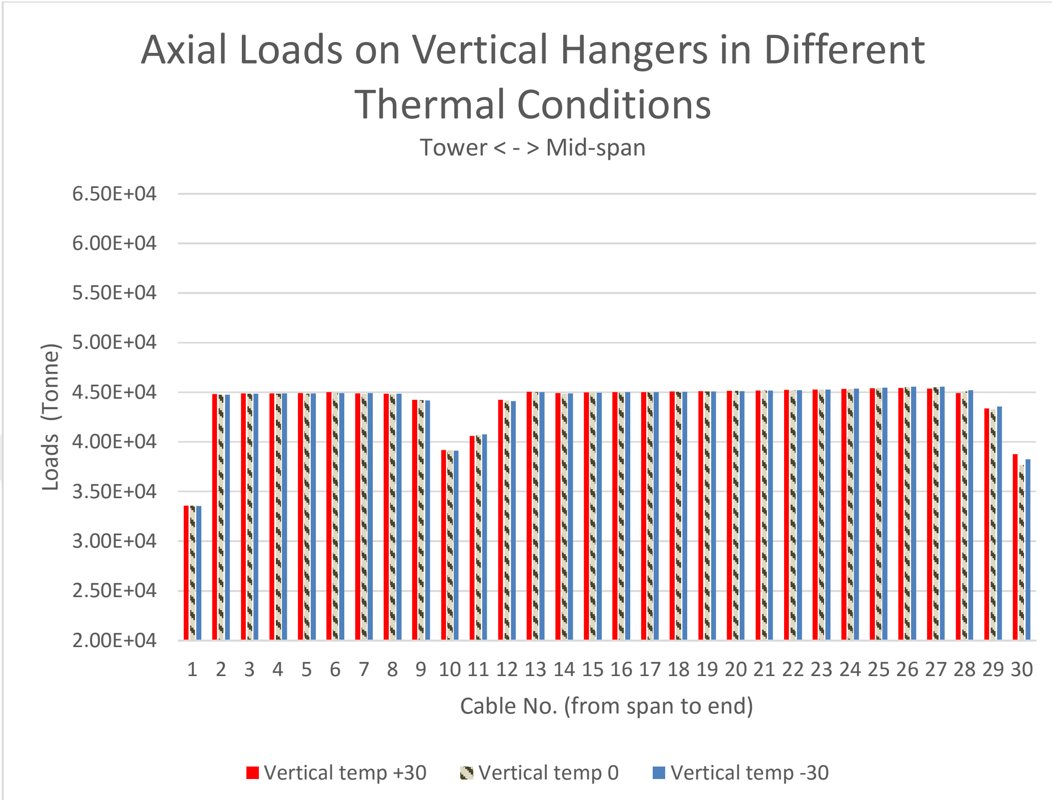


Figure 5.5 Axial loads on vertical hangers in +30°C and -30°C temperatures

Figure 5.4 and 5.5 show how the loads on the hangers are effected due to variance of structural proportion under different thermal conditions. Diagonal hangers have obvious shift of loads in such conditions while the vertical hangers have slight differences.

These results give clues to how the hangers face fatigue during thermal load cycles. The range of loads in diagonal configuration allows it to be more prone to damages caused by fatigue.

5.4.2 Comparison of Displacements of Under Various Thermal Conditions

Previously, the variance of structural proportion under various thermal conditions were mentioned as a reason of the changes of loads on hangers. Thus, the displacements of the deck were investigated in this section to point out this feature.

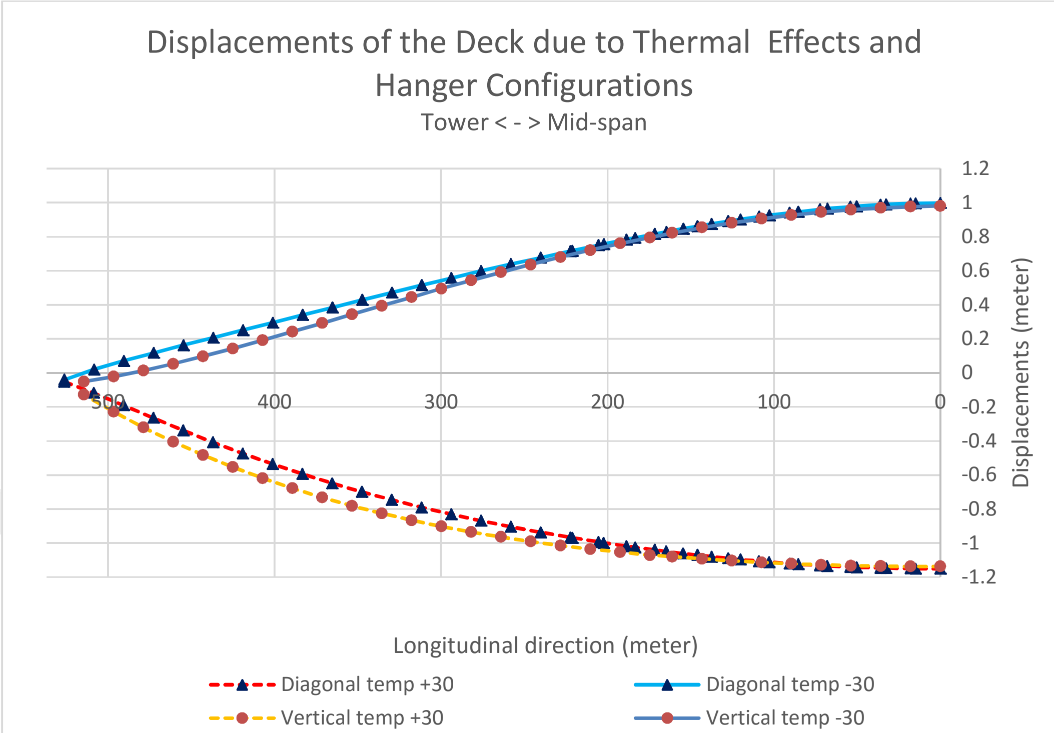


Figure 5.6 Displacements of the deck due to Thermal Effects and Hanger Configurations

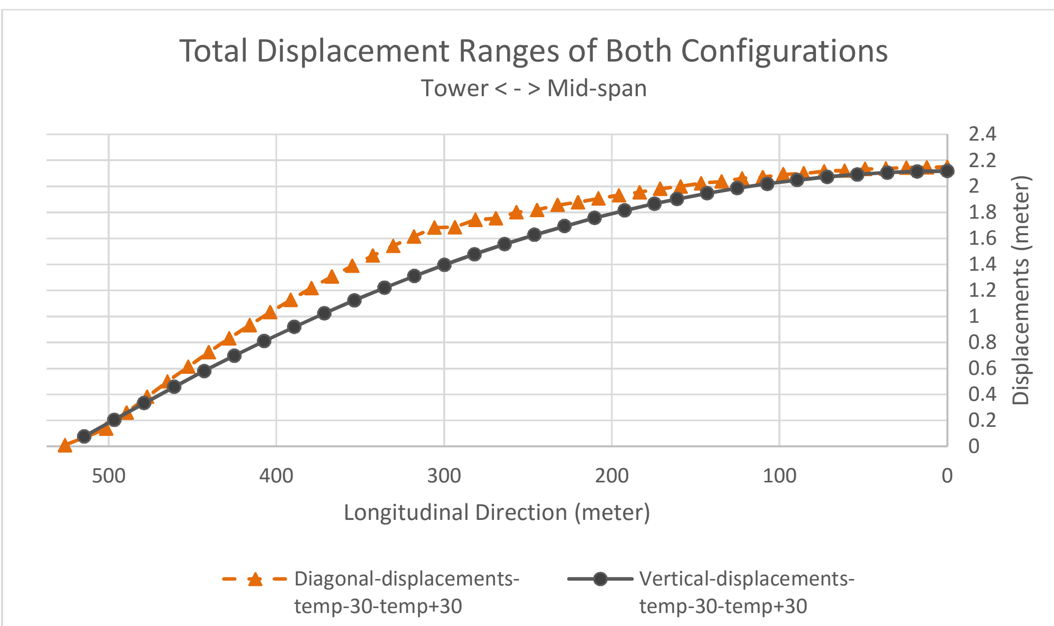


Figure 5.7 Total displacement ranges of both configurations under thermal effects

5.4.3 Comparison of Mode Frequencies

In order to find out mode frequencies, modal analysis was runned in all models. These models are the Normal Conditions, 30° heated up and 30° cooled down models of both configurations. Thus, this section shows the mode frequencies comparatively.

Table 5.1 Mode frequencies of the diagonal configuration

Lateral modes			
	TEMP -30	Normal Cond.	TEMP +30
mode 1	0.0725605	0.0724289	0.0723059
mode 2	0.21460	0.21433	0.21405
mode 3	0.27934	0.27855	0.27777
mode 4	0.29234	0.29164	0.29095
mode 5	0.36596	0.36499	0.36403
mode 6	0.38655	0.38512	0.38373
mode 7	0.44307	0.44125	0.43945
mode 8	0.57300	0.57019	0.56746
mode 9	0.73648	0.73304	0.72954

Vertical modes			
	TEMP -30	Normal Cond.	TEMP +30
mode 1	0.12791	0.12695	0.12609
mode 2	0.16719	0.16784	0.16842
mode 3	0.23151	0.23161	0.23178
mode 4	0.28998	0.2888	0.28765
mode 5	0.38301	0.38163	0.38029
mode 6	0.46857	0.46667	0.4648
mode 7	0.57474	0.57292	0.57116
mode 8	0.68043	0.67882	0.67729
mode 9	0.78672	0.78469	0.78268
mode 10	0.90552	0.90376	0.90174

Table 5.1 Mode frequencies of the diagonal configuration (Continues)

Torsional modes			
	TEMP -30	Normal Cond.	TEMP +30
mode 1	0.33261	0.33356	0.33453
mode 2	0.50026	0.49833	0.49697
mode 3	0.50178	0.50976	0.5089
mode 4	0.6716	0.6705	0.66922
mode 5	0.89583	0.89433	0.89274

Table 5.2 Mode frequencies of the vertical configuration

Lateral modes			
	TEMP -30	Normal Cond.	TEMP +30
mode 1	0.0704052	0.0703647	0.0702016
mode 2	0.20778	0.20782	0.20765
mode 3	0.27153	0.27852	0.27789
mode 4	0.28563	0.2892	0.28865
mode 5	0.36424	0.36413	0.36338
mode 6	0.38485	0.38467	0.38343
mode 7	0.44614	0.43715	0.43566
mode 8	0.5705	0.57	0.56754
mode 9	0.74199	0.73062	0.72778

Vertical modes			
	TEMP -30	Normal Cond.	TEMP +30
mode 1	0.1039	0.10384	0.10347
mode 2	0.15728	0.1573	0.15741
mode 3	0.21007	0.21022	0.21079
mode 4	0.25189	0.25144	0.25016
mode 5	0.32814	0.32777	0.32634
mode 6	0.4068	0.4063	0.40458
mode 7	0.49566	0.49492	0.49302
mode 8	0.58931	0.58879	0.58674
mode 9	0.693	0.69246	0.6903
mode 10	0.80282	0.80265	0.80042

Table 5.2 Mode frequencies of the vertical configuration (Continues)

Torsional modes			
	TEMP -30	Normal Cond.	TEMP +30
mode 1	0.32209	0.32229	0.32355
mode 2	0.43454	0.43459	0.43397
mode 3	-	-	-
mode 4	0.65866	0.6584	0.65774
mode 5	0.86899	0.86899	0.86784

Table 5.3 Comparison of vertical mode frequencies of both configuration under normal thermal conditions

	DIAGONAL CONFIGURATION	VERTICAL CONFIGURATION
	Vertical modes	
mode 1	0.12695	0.10384
mode 2	0.16784	0.1573
mode 3	0.23161	0.21022
mode 4	0.2888	0.25144
mode 5	0.38163	0.32777
mode 6	0.46667	0.4063
mode 7	0.57292	0.49492
mode 8	0.67882	0.58879
mode 9	0.78469	0.69246
mode 10	0.90376	0.80265

Table 5.4 Comparison of lateral and torsional mode frequencies of both configuration under normal thermal conditions

	DIAGONAL CONFIGURATION	VERTICAL CONFIGURATION
	Lateral modes	
mode 1	0.0724289	0.0703647
mode 2	0.21433	0.20782
mode 3	0.27855	0.27852
mode 4	0.29164	0.2892
mode 5	0.36499	0.36413
mode 6	0.38512	0.38467
mode 7	0.44125	0.43715
mode 8	0.57019	0.57
mode 9	0.73304	0.73062

	Torsional modes	
mode 1	0.33356	0.32229
mode 2	0.49833	0.43459
mode 3	0.50976	-
mode 4	0.6705	0.6584
mode 5	0.89433	0.86899

CHAPTER 6

CONCLUSION

Diagonal configuration of the hangers are more prone to fatigue, since the loading-unloading range is larger than the vertical configuration. Vertical hangers have less load in both unloaded and loaded state of the bridge, while, having the same diameter as diagonal hangers.Vertical configuration of the bridge sags more than the diagonal configuration. It is because the loads and the cable axis are alligned in this configuration.Both configurations are stiffer (higher natural frequencies) at lower temperatures.Range of loads on hangers due to thermal effects are wider in diagonal configuration, which may result as fatigue failure.

This study allows us to further the investigations about the bridge. These models will be analyzed for other various thermal conditions, live vertical and horizontal loads and, also earthquakes.

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Undergraduate	Civil Eng.	Istanbul Tehcnical University	2013
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WORK EXPERIENCE

Year	**Corporation/Institute**	**Enrollment**
2016-17	F.M.V. IŞIK UNIVERSITY	Res. Asst.
2015-16	Yalçın Proje	Statics Engineer
2011	NU Mühendislik	Intern Engineer

PUBLISHMENTS

Conference Papers

1. INTRICATE FINITE ELEMENT MODELING of THE RETROFITTED 15th JULY MARTYRS BRIDGE, International Conference on Civil and Environmental Engineering ICOCEE2017, TURKEY

2. INVESTIGATION of THERMAL EFFECTS ON RETROFITTED BOSPHORUS BRIDGE, Conference on Computational Engineering CCE2017, ROMANIA