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Investigations of Thermal Effects on Retrofitted Bosphorus Bridge: Comparison between Diagonal and Vertical Hanger Configurations

M. Mert Eyupgiller[1], Cagri Mollamahmutoglu[2]
[1] *Civil Eng. Dept., F.M.V. Isik University, Istanbul, 34980, Turkey*
[2] *Civil Eng. Dept., Yildiz Technical University, Istanbul, 34220, Turkey*

Summary

Bosphorus Bridge which was constructed in 1973 recently has undergone a retrofitting process. In the process, original diagonal hanger configuration has changed into the vertical configuration. Literature includes numerous studies which address almost every aspect of the structural analysis of the diagonal case but lacks any study concerning the recent vertical configuration. In this study, an advanced 3D finite element model (FEM) of the complete bridge has been developed with intricate details. The model includes detailed structural components such as stiffeners with realistic 3D towers and also incorporates a frictional contact model for the cable saddle interaction – a unique feature among the model realm. Both diagonal and vertical configurations are taken into consideration with an automated script in the framework of a commercial FEM package. In order to demonstrate the effectiveness and usefulness of the model, we have opted to work on thermal effects on the bridge among various other possible research directions which can be tractable by the model such as vehicle interactions, forced vibrations, fatigue etc. We have studied the effects of homogeneous heating of the deck structure and various parts of the towers for both configurations. 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.

KEYWORDS: Bosphorus Suspension Bridge, 15th July Martyrs' Bridge, Finite-Element Method, Thermal Effects

1. INTRODUCTION

Istanbul, the capital of Eastern Roman Empire and Ottoman Empire, is currently locomotive of the economy of Turkey, and meanwhile is 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

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continents. The Bosphorus has an average depth of about 50 m and its width varies from 0.7 to 3.5 km [1].

The first suspension bridge, namely the Bosphorus Bridge (a.k.a. 15th July Martyrs' Bridge), over this strait was opened in 1973. A recent retrofitting project on the bridge has changed some major components, such as its hangers. Although there are numerous studies on the former configuration of the Bosphorus Bridge, its new design has not been studied yet.

In this study, an advanced 3D finite element model (FEM) of the complete bridge has been developed with intricate details. The model includes detailed structural components such as stiffeners with realistic 3D towers and also incorporates a frictional contact model for the cable saddle interaction – a unique feature among the model realm. Both diagonal and vertical configurations are taken into consideration with an automated script in the framework of a commercial FEM package. In order to demonstrate the effectiveness and usefulness of the model, we have opted to work on thermal effects on the bridge among various other possible research directions which can be tractable by the model such as vehicle interactions, forced vibrations, fatigue etc. We have studied the effects of homogeneous heating of the deck structure and various parts of the towers for both configurations. Variations on the stress distributions of the deck structure and cable forces are investigated.

2. DESCRIPTION OF THE BOSPHORUS BRIDGE

The Bosphorus Bridge, located between Ortaköy and Beylerbeyi villages in Istanbul, is a single-span, two-hinged stiffening girder, with vertical hangers (diagonal hangers before retrofitting) and externally-anchored (gravity anchored) bridge. It has a portal type of main tower skeleton and main cables made of parallel wire strands [2]. As a linking element between the main cables and the deck, there are hangers (spiral rope), which are basically groups of wires of 5 mm approximate diameter. The reason for 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 [3]. In the Bosphorus Bridge (figure 1), the hangers are built inclined in order to restrict longitudinal displacement of the deck. This special constraint type in such a long bridge can also be observed in the Humber Bridge in England. Although it has not had a complication arising from its inclined hangers for over 40 years, this rarely preferred design went through a retrofitting.

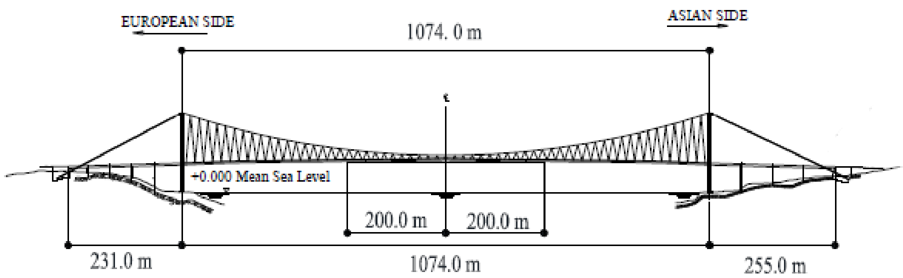

Figure 1. General arrangement of the Bosphorus Bridge [4]

The retrofitting project might have redesigned many characteristics of the bridge but its main components are still in use as they were. The hangers and the rocker bearings at the ends of the deck were changed, in new configuration, hangers are vertically aligned and paired, while dampers were added to the ends of the deck. However, the deck superstructure and main cables had only been under maintenance renovations and the principal dimensions of the bridge remained the same.

Table 1: 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

Principal Dimensions [5]

Span Length	: 1074 m
Length of Approach Viaducts- (Ortaköy)	: 231 m
(Beylerbeyi)	: 255 m
Length of the Main Span	: 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
Some Quantities About the Construction	
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

3. FINITE ELEMENT MODELING OF THE BOSPHORUS BRIDGE

In order to compare the thermal effects on former and the current configurations of the Bosphorus Bridge, two different three-dimensional (3D) finite element (FE) models were created in finite element analysis program ABAQUS. It is the first work that includes 3D FE model of both configurations of the Bosphorus Bridge. It is also unique because of the elements used. Instead of using equivalent beam elements for towers and the deck, these components were also modelled in 3D space and no additional restraints were assigned.

3.1 Finite Element Modelling of the Diagonal Configuration

The construction project of the bridge had been drawn regarding the conclusive state of the bridge (Figure 2). In other words, the cables had been loaded with the stress that they were going to resist, and then they were cut in their design lengths. Therefore, in modelling phase, the bridge model was designed as in the projects and the calculated stresses were assigned in the first step. If the bridge was to be loaded with these stresses in the initial state, it would go out of balance in dynamic step. However, it was totally balanced and had deflections around ±10 cm, when it was loaded gradually with the calculated stresses and the gravitational acceleration.

The deck and the towers are composed of thin plates made of steel. Thickness of the plates differs as their positions. The deck structure was built by plates with the thickness of 6 mm to 12 mm, and in the towers that range is 15 to 22 mm. These plates forming the components of the bridge were modelled with S3R and mostly S4R, which are, respectably, triangular and quadrilateral shell elements. The main cables and hangers were modelled with T3D2 elements. This element type is ideal for modelling cables or rods under the axial loads. In this model, 152495 nodes and 114653 elements were used.

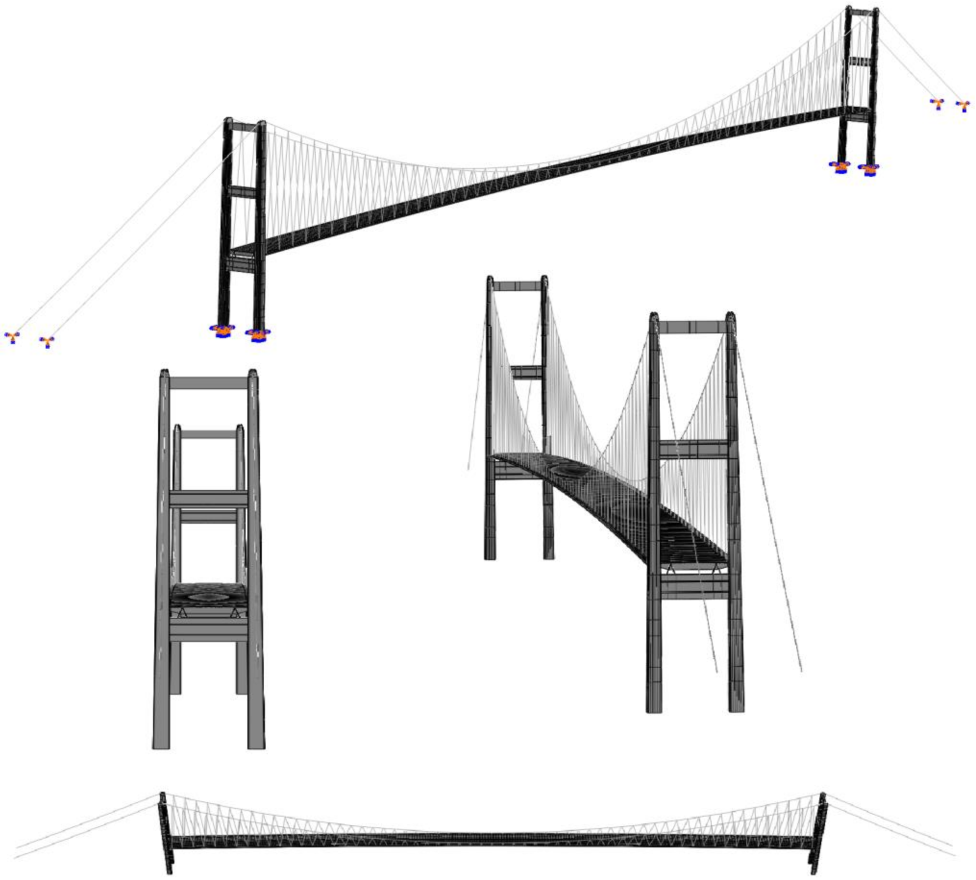

Fig.2: The 3D FE model of diagonal configuration of the Bosphorus Bridge

3.1.1 Validation of the Model

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. [6]. “Relative error” (R.E.) stands for:

R.E. = ABS (FE Model Result- Experimental Result) / (Experimental Result) (1.1)

Table 2: Comparison of frequencies between the model and the results from the experimental studies [6]

Lateral modes		Experimental frequency-Brownjohn et al.	Relative Error
mode 1	0.072429	0.07	3.47%
mode 2	0.21433	0.209	2.55%
mode 3	0.27855	0.284	1.92%
mode 4	0.29164	0.294	0.80%
mode 5	0.36499	0.365	0.00%
Vertical modes		Experimental frequency-Brownjohn et al.	Relative Error
mode 1	0.12695	0.129	1.59%
mode 2	0.16784	0.16	4.90%
mode 3	0.23161	0.217	6.73%
mode 4	0.2888	0.277	4.26%
mode 5	0.38163	0.362	5.42%
Torsional modes		Experimental frequency-Brownjohn et al.	Relative Error
mode 1	0.33356	0.324	2.95%
mode 2	0.49833	0.474	5.13%
mode 3	0.49915	0.492	1.45%
mode 4	0.6705	0.649	3.31%
mode 5	0.89433	0.877	1.98%

3.2 Finite Element Modelling of the Vertical Configuration

Most of the structural components remained from the diagonal configuration. However, the hanger configuration was changed in this model, dampers were placed and, the towers were strengthened as in the retrofitting project. In this model, 152445 nodes and 114539 elements were used. It can be seen that the difference of element numbers between two models was relatively small (Figure 3).

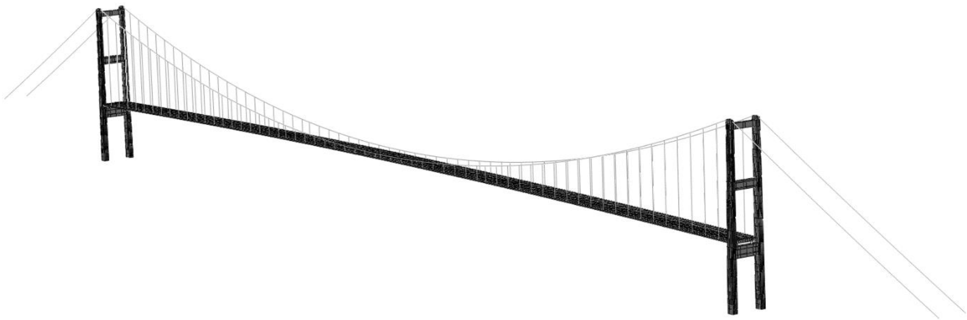

Figure 3. The 3D FE model of vertical configuration of the Bosphorus Bridge

4. COMPARISON BETWEEN THE TWO MODELS

Different temperatures were affected to both models and their responses were recorded. The extremum temperatures of weather are -16.1^{o}C and 41.1^{o}C [7]. Therefore, the models were exposed to ±30 ^{o}C temperature changes. The responses of the models were compared in various aspects.

4.1 Comparison of Displacements of the Deck

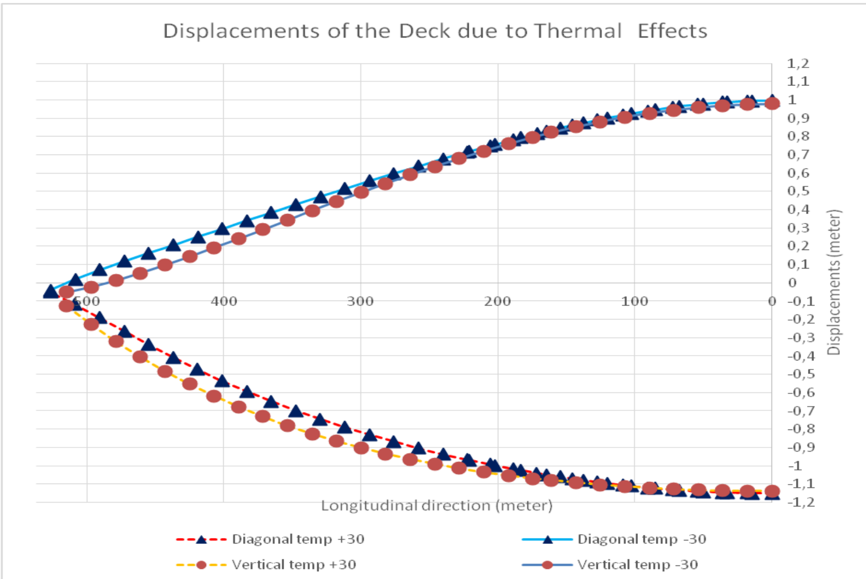

Figure 4. Displacements of the deck due to Thermal Effects

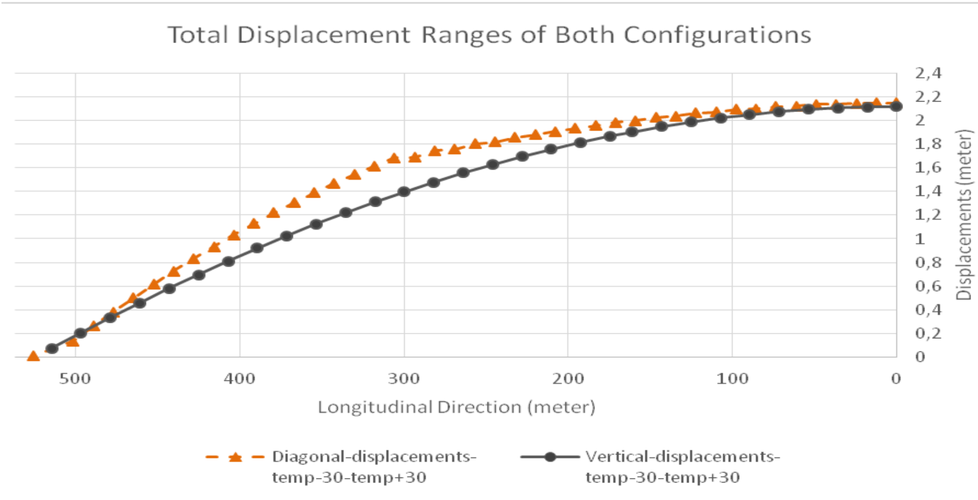

Figure 5. Total displacement ranges of both configurations under thermal effects

4.1 Comparison of Stresses on Hangers

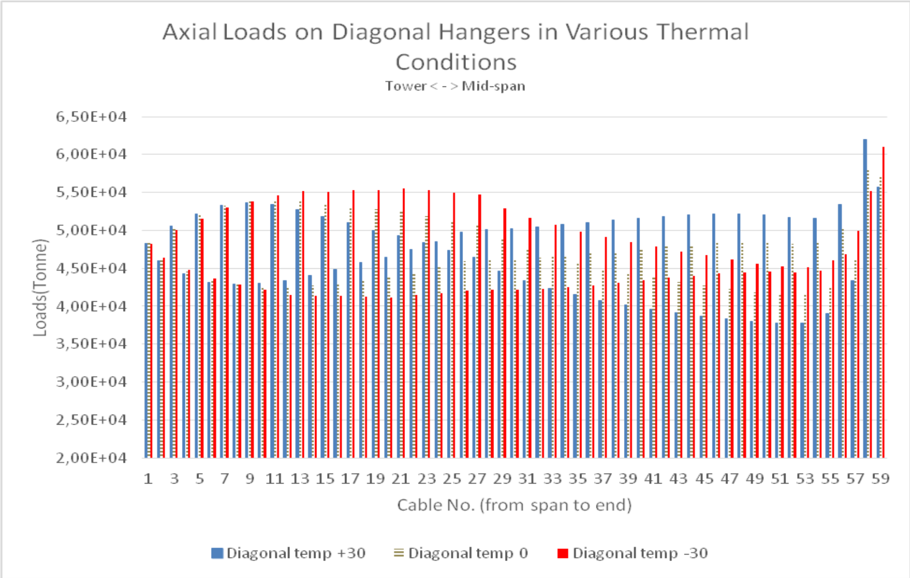

Figure 6. Axial stresses on diagonal hangers in various thermal conditions

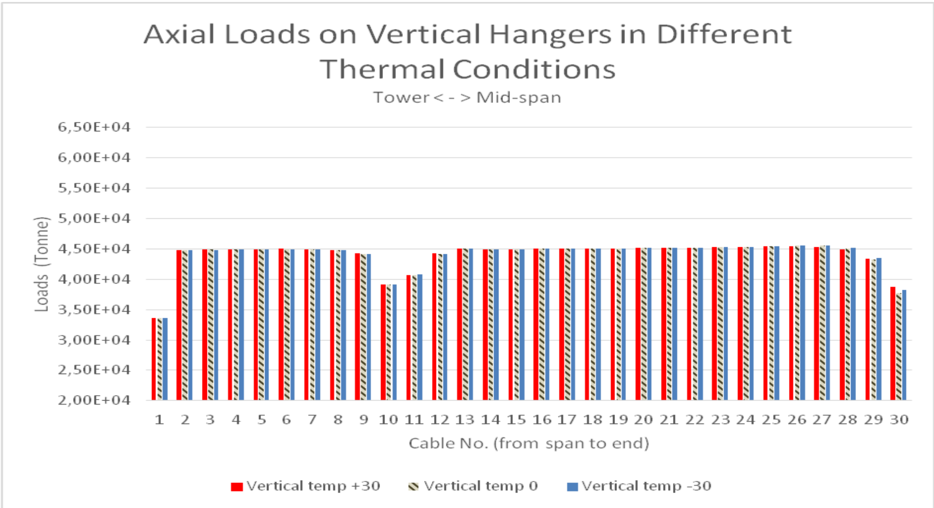

Figure 7. Axial stresses on vertical hangers in various thermal conditions

3. CONCLUSIONS

The comparison of the experimental results and the FE model of diagonal configuration indicated the accuracy of the model. Then, the study proceeded to comparing thermal responses of two different hanger configurations of the Bosphorus Bridge. These comparisons showed that, under thermal effects, the displacements of the Bosphorus Bridge does not change drastically after the retrofitting on cable configurations. However, the model with diagonal hangers was found to be affected more than the model of vertical hangers did. The axial stresses on the diagonal hangers closer to the mid-span were changed noticeably due to thermal effects. In the high temperature environment, the cables that are inclined toward the centerline of the bridge, tended to get higher loads. In contrast, the load on them decreased as the model cooled down. The percentage of change, the hangers faced during heating and cooling, showed that the diagonal configuration was more prone to fatigue failure than the vertical configuration of the hangers.

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