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Statistic and modal analysis of the Krk bridge utilizing ANSYS

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Abstract. Connecting mainland Croatia and the island of Krk, Krk Bridge lies upon the Krk Channel of the Adriatic Sea. The bridge is one of the longest arch bridges and was the longest when it was built worldwide. However, considering the harsh environment in which the bridge is located, the slender structure of the bridge has raised concerns about the system's stability. However, with the most widely investigated studies focusing on the corrosion impact on the material and finish of the bridge from the harsh environment, there remains largely unexamined structural analysis to be done. Hence, this study seeks to use ANSYS and Workbench to investigate the reliability of Krk Bridge concerning statistical structure and modal analysis to offer insights into the future maintenance and reinforcement of the bridge itself, as well as provide a reference for other infrastructural bridge projects in the future.

Keywords: Bridge structure, ANSYS modeling, Statistic analysis, modal analysis.

1. Introduction

1.1. Background

Along the coastline of the Adriatic border of Croatia in the mid-twentieth century to the late twentieth century, a few beautiful and successful arch bridges were built. One of the most famous ones, which happens to be the longest bridge at the time, was the Krk Bridge. Designed by Ilija Stojadinovic, in cooperation with Vukan Njagulj and Bojan Mozina, the Krk bridge connects mainland Croatia and the island of Krk and passes through the small island Sv. Marko. The construction of the Krk bridge commenced in 1976 and finished four years later.

In the age of mid-late twentieth century, the universal maximum spans of arch bridges were within 350-400 meters. Yet, in the case of the Krk bridge, the longer span of the Bridge, for the first time, has reached 416 meters.

Krk bridge sits on the Adriatic Sea's coastline, bringing the bridge to a rather harsh environment of not only strong wind but also an aggressive marine environment with high salinity water [1]. With the very slender pillars bearing the loads and the wind, the bridge is still relatively good today.

Structurally, the Krk bridge was one of the first patches of bridges that applied the cantilever method during construction [2]. That is, the building is progressively constructed from one end of the bridge, incorporating portions of individual arch ribs and spandrel columns in conjunction, as well as temporary support of upper chords and diagonals composed of steel members and tendons [2].

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1.2. Research Gap

However, proof indicates that maintenance of the Krk bridge has been put on the agenda as defects are detected not just structurally but also in many different aspects. One major problem is the environment in which the bridge is located. The aggressive marine environment with high salinity (approximately 3.5%) and the corrosive marine wind bring severe challenges to the thin concrete finish (2.5cm) of the structure [3]. Consistent maintenance has been arranged, referring to finish protection, reinforcement, and replacement, to protect the geographically and strategically critical infrastructure better.

Also, as mentioned above, Krk Bridge I breached the universal assumption of the span of arch bridges at the time. Furthermore, the bridge has a relatively linear shape, with slender columns and decking. While it is sitting in a harsh environment such as the Adriatic Sea, would the structure be able to suffer such hazards from the beginning to have a stable structure for an extended period of a lifetime?

Another significant factor is that, unfortunately, during the project's operation, there were a few mistakes in design and construction, such as too small concrete cover, poor constructional detailing, crackings on the body, and reinforcement by false strategies of creep and shrinkage and drainage systems [4]. Apart from that, the bridge has been finished for more than 40 years, while the requirements for the infrastructure system are getting stricter. Will the bridge still be at a satisfactory level under the current regulations [5]?

1.3. Aim

This research aims to testify to the credibility of the Krk bridge structurally, check if any potential risk would occur, provide alternatives if needed, and contribute to future infrastructural projects and studies as a case study.

2. Environmental Research

2.1. Background

2.1.1. Wind

In summer, wind speeds in Krk Channel are generally slow—lower than 38km/h. However, in the winter, gusts measuring higher than 61km/h are frequent. There are two types of prevailing winds on Krk.

Island—Southwest (SW) and Northeast (NE). The change of color of the polar coordinates from green to yellow indicates the wind speed distribution in the direction of the wind. The time for the NE wind speed to exceed 38km/h is as high as 48 hours, far exceeding the 7 hours the SW wind takes. The slow SW wind in winter brings warm and moist air to the region, leading to the unique seasonal characteristics of mild and rainy weather. In this case, by the former precedent model by Ana Mandic, a wind velocity of 23m/s is used [5].

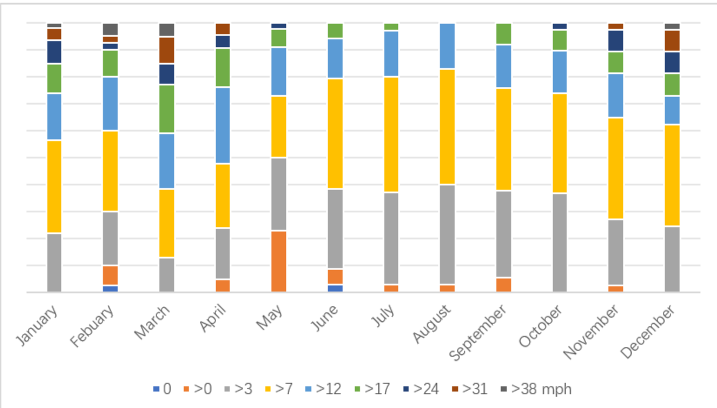

Figure 1. The wind speed around Krk region

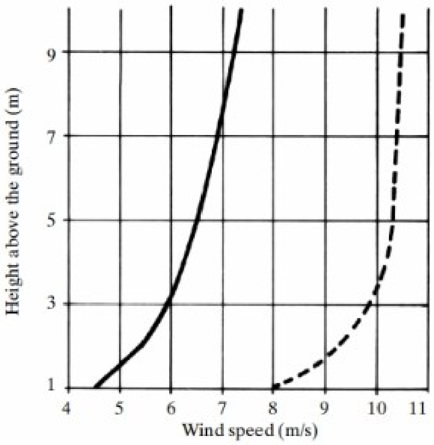

Figure 2. The relationship between wind speed and height

Figure 1 shows the wind speeds observed with different ranges of time periods in Krk region, and Figure 2 indicates the relationship of wind speeds against heights above the ground in the same region. In the Krk bridge region, the gust speeds domain specifically is from 41m/s (v10 min) to 51 m/s (max) [6]. There are 138 days around the area with wind speeds higher than 50 m/s, which has caused a substantial negative impact not only on the quality of the construction but also on the later operation of the bridge. It has to constantly announce stoppages during the construction period, and in the most hazardous weather, it would close for safety precaution [6].

From the wind rose diagram below (Figure 3) of the Krk Bridge, the strongest wind comes from the North and Northeast directions, whereas wind power is relatively unstable from the south. This would also be a concern for the engineers, as the significant variation in the wind can increase the possibility of resonance between the bridge and the natural breeze.

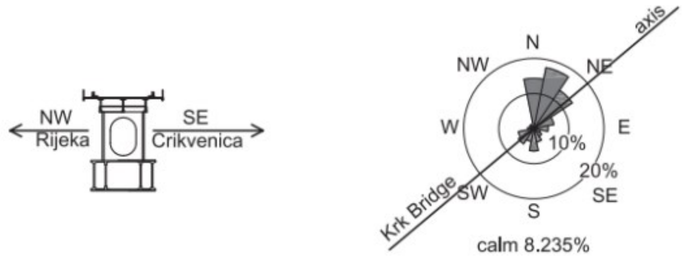

Figure 3. The Section diagram of Krk bridge and the wind rose diagram of local region

2.1.2. Rainfall

Despite being exposed to a harsh marine environment for over forty years with a designed concrete cover thickness of only 2.5 cm, the reinforced concrete structure of Krk Bridge remains in good condition. The local marine environment undergoes frequent changes, with strong winds carrying sea spray in the southern region and during winter months. The Mediterranean climate averages twenty kilometers per hour and occasionally reaches wind speeds characteristic of tropical depressions. The bridge can withstand the volatile weather conditions in the Adriatic Sea due to the quality of concrete used during construction in its frame.

Figure 4 records the local precipitation amount observed in different ranges of time periods. Under the influence of the marine west wind and subtropical climate, the rainfall in the Krk region is relatively low in summer. Still, it increases in considerable amounts in winter. The average rainfall day in summer time is 12.5 days, which is less than the intermediate days of 14.9 days in other months, and the rainfall days with precipitation less than 10mm are only 2.2 days, but with the influence of the west wind belt,

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the rainfall days are more frequent in the winter and spring, where the rainfall days with precipitation more than 10mm are four days.

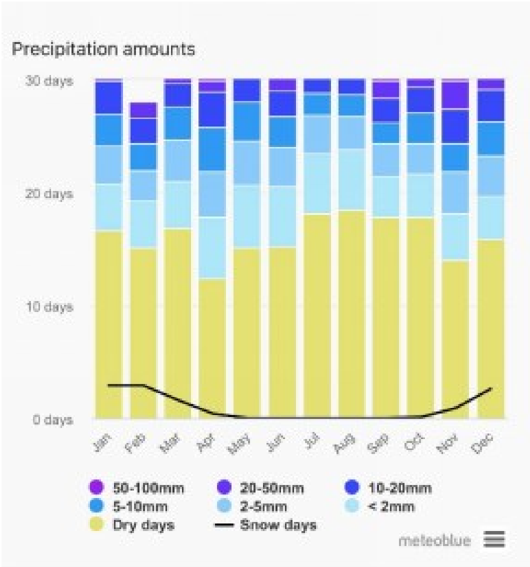

Figure 4. The local precipitation amount

2.1.3. Temperature
The temperature in this region is relatively suitable throughout the year. Although there are differences in summer and winter temperatures, extreme temperatures are rare. The daily maximum temperature from July to September averages higher than 15°C, with sporadic days with temperatures higher than 30°C. The temperature in winter is relatively mild. Though frost can be prevalent in winter, the maximum temperature was almost always above -5°C.

2.2. Data Collected
Even though the total span of Krk Bridge is 1430m, it is composed of two individual arch bridges with a joint of 235 m on the island of St Marco. The spans of the two bridges are 416 m and 244m, respectively. Since the two arch bridges share the same design, in this study, the one with the longer span will be used as the model to proceed with the investigation.

The material would be an essential element in this study, as the deformation of the entire bridge varies greatly. The materials used in the construction of the Krk Bridge are mainly concrete, and, despite the lack of awareness of the concrete structure's durability, the concrete that Krk Bridge utilized was the stablest at that time [1,4].

Table 1 below indicates the number of different components in the concrete mixture. According to this table, a density of 2520 kg/m3 is adopted.

Table 1. The concrete properties used for Krk Bridge

Property	Standard	Unit	Result
Fresh Concrete			
Slump	EN 12350-2	cm	2.5
Bleeding	EN 480-4	ml	73.5
Density	EN 12350-6	Kg/m^3	2520
Air Content	EN 12350-7	%	2.6
Hardened Concrete			
Compressive strength	EN 12390-3	N/mm^2	48.8-55.6

Table 1. (continued).

Flexural strength	EN 12390-5	N/mm^2	9.3
Static Modulus of elasticity (stress until 1/3 of compressive strength)	HRN U.M 1.025	N/mm^2	41.300
Water permeability	EN 12390-8	mm	<10
Capillary absorption	EN 13057	$Kg/(mm^2h^{0.5})$	0.63
Gas permeability	EN 993	$(*10^{-16})m^2$	1.66
Freeze-thaw resistance of concrete--internal structural damage	CEN/TR 15177	%	4

The desired building mass of 41977000kg was divided by the 1.0801*10^(5)m^3 volume to get a density of 388.64kg/m^3. The input density ensures that the result of the subsequent operation is correct.

2.3. *ANSYS Modelling*

ANSYS Workbench was used to analyze and model the natural frequencies of the Krk Bridge. Throughout the modeling process, multiple models were constructed, and the most suitable model for testing was chosen. The models were separated into different categories: raw model, refined model, and test model. Additionally, while the Krk Bridge has two spans (Krk I and Krk II), they do not influence each other much; therefore, only the longer span (Krk I) was modeled (Figure 5)

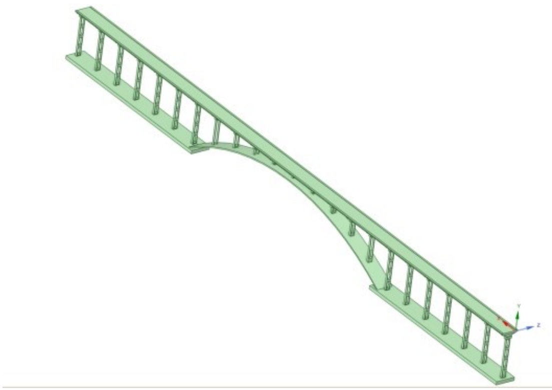

Figure 5. Grid model of KRK bridge.

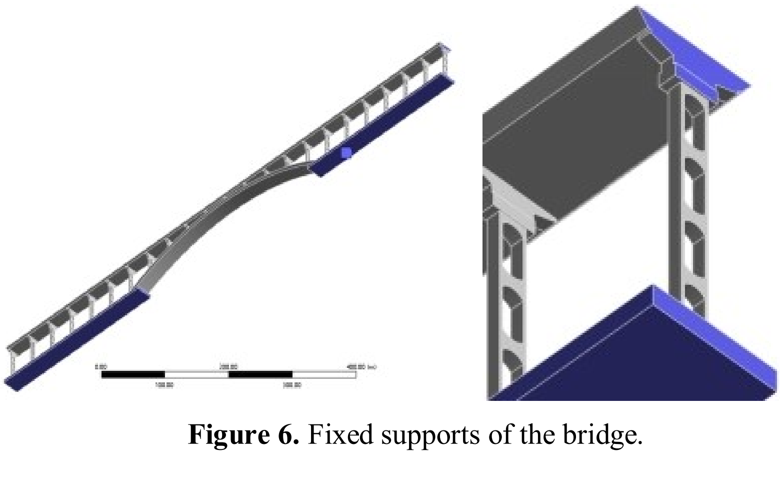

Figure 6. Fixed supports of the bridge.

As Figure 6 shows, the degree of freedom of the model is restricted by setting the boundary conditions. Fixed supports (blue part in figure 6) were set up on the underside of the bridge columns to determine the direction of the force on the bridge and to ensure that it does not move randomly. The fixed supports in this model are set on surfaces that have direct contact with the solid environment, such as the earth and other infrastructure systems around the Krk Bridge.

3. Analysis

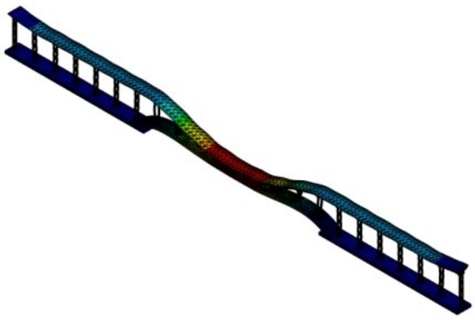

Figure 7. Statistic analysis result

According to the simulation result (Figure 7), the primary deformation will occur in the bridge's center. The average deformation is 0.14 meters, while the maximum and minimum deformations are 0.50 meters and 0.06 meters. There is slight deformation on both sides of the bridge decking. However, the primary deformation occurs in the middle of the bridge, supported by the arch.

Table 2. Modes and frequencies used for the analysis

mode	**1**	**2**	**3**	**4**	**5**	**6**
Frequency	0.20476	0.26653	0.30652	0.36685	0.47424	0.6562

The modal analysis tells us the natural frequency of the entity of the structure and the tendency of deformation at specific frequencies, recorded as Table 2. In this Workbench simulation process, the deformation under six frequencies is simulated, and the results are shown below:

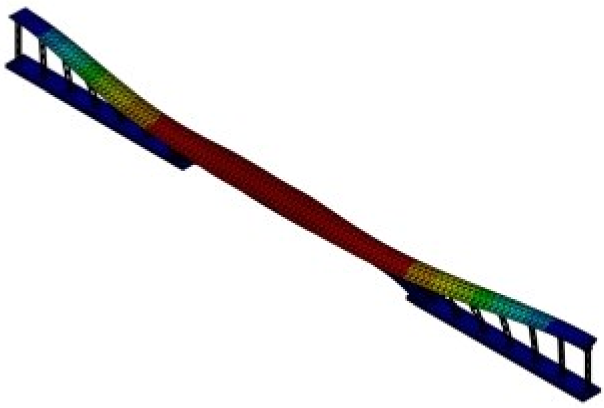

Figure 8. mode one result

Figure 8 shows the deformation of the mode 1 that under the frequency of 0.20476hz the bridge mainly suffers from the shearing forces in the horizontal direction, which leads to slight deformation from one flank to the other.

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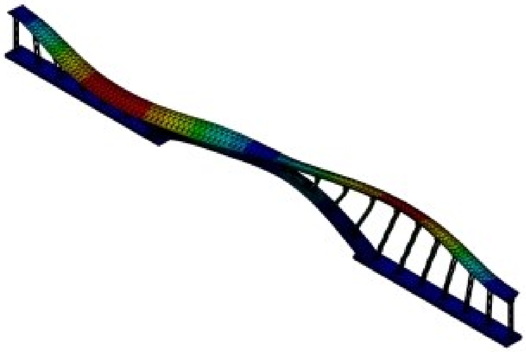

Figure 9. mode two result

Figure 9 shows the deformation of mode 2 at a frequency of 0.26653hz; more deformation can be detected from the decking and the individual piers. The significant deformation happens in the middle where the arch structure applies, gradually decreasing along the span to both endings of the bridge.

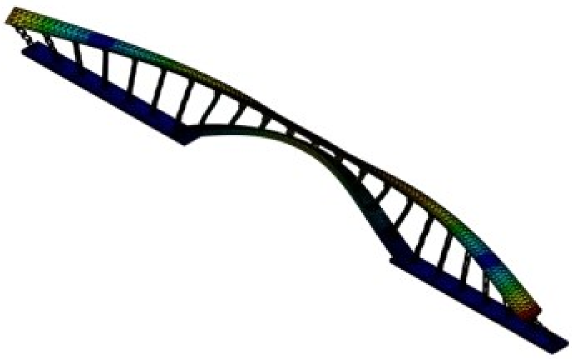

Figure 10. mode three result

Figure 10 shows the deformation of mode 3 at a frequency of 0.30652hz; the deformation mainly occurred in the bridge's center by the shear force and only swung in one direction.

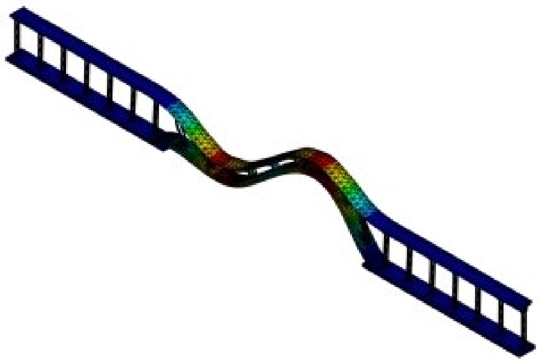

Figure 11. mode four result

Figure 11 shows the deformation of mode 4 at a frequency of 0.36685hz; the bridge's decking shows minor deformation, while the arch in the middle starts to deform vertically. Under this frequency, the shear force brings little influence to the structure itself. Instead, the main deformation factor comes from the structure's pressure.

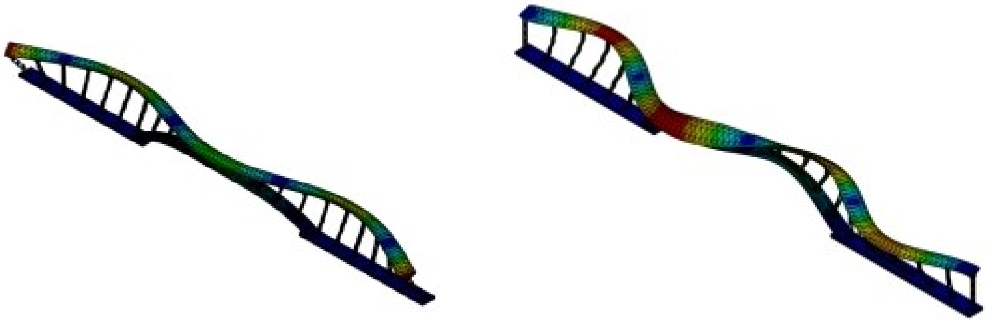

Figure 12. mode 5 and 6 result

Figure 12 shows the deformations of the modes 5 and 6 that under the frequency of 0.47424hz and 0.6562hz, the shear force dominates the structure again. The deformation happens to the bridge structure, and torts tortured the bridge into a sinusoidal shape.

Having mentioned the tendency of the deformation on the bridges under different frequencies, even though the slender structure of the bridge looks worrying in the deformation, the outcome of the deformation amount is above satisfactory. Table 3 below shows the detailed amount of the bridge deformation under different frequencies.

Table 3. the amount of deformation from note 1 to note 6

Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode6
0.00011856Max	0.00012125Max	6.7919e-5Max	6.9e-5Max	0.00010094Max	9.4794e5max
0.00010538	0.00010777	6.0373e-5	6.1333e-5	8.9723e-5	8.4261e-5
9.221e-5	9.4302e-5	5.2826e-5	5,3666e-5	7.8508e-5	7.3728e-5
7.9037e-5	8.0831e-5	4.528e-5	4.6e-5	6.7292e-5	6.3196e-5
6.5865e-5	6.7359e-5	3.7733e-5	3.8333e-5	5.6077e-5	5.2663e-5
5.2682e-5	5.3887e-5	3.0186e-5	3.0667e-5	4.4862e-5	4.213e-5
3.9519e-5	4.0415e-5	2.264e-5	2.3e-5	3.3646e-5	3.1598e-5
2.6346e-5	2.6944e-5	1.5093e-5	1.5333e-5	2.2431e-5	2.1065e-5
1.3173e-5	1.3472e-5	7.5466e-6	7.6666e-6	1.1215e-5	1.0533e-5
0Min	0Min	0Min	0Min	0Min	0Min

Table 3 records all the frequencies received from different modes in the simulation process. As the digits indicate, taking mode 1 as an example, the maximum deformation under the frequency of 0.20476hz is 0.00011856 m only. As for note 6, which has the highest frequency in this case, the maximum deformation is only 9.4794e-5 m.

4. Conclusion

From the statistical model, the average deformation of the bridge is only 0.14m, while the maximum deformation reaches only 0.50m. For a long-span bridge such as the Krk bridge, the allowed deflection can be 1/600 of the entire bridge. Therefore, in the case of the Krk bridge, the allowed deflection would be 416/600=0.69m, which is far beyond the maximum deformation of the statistic model of the Krk bridge in this report. This provides strong proof to support the credibility of the statistical structure of the bridge.

The modal analysis also provides the positive outcome of guaranteeing the quality of the bridge. The model tested how the bridge would deform under various frequencies, and it does tell the bridge would be affected by the horizontal shearing force. However, with the small amount of tortuosity that would happen to the bridge (9.47947e-5m maximum), the impact on the bridge by its natural frequency can be neglected.

The harsh environment of the local region of Krk Bridge will still need to be put with close attention. As mentioned above, the seawater and precipitation with high salinity would have a significant impact on the fragile finish of concrete on the structure, which is currently taking place on the bridge. What is to be aware of is that this report would not be adaptive for such cases if the corrosion level on the structure reaches a certain point and defects the bridge structurally.

Furthermore, even though little tortuosity was detected under specific frequencies in the modal analysis, a significant factor that needs to be noticed is the wide range of wind speeds in the local region [7]. Unfortunately, the direction with the most potent wind power is in the Northwest, which happens to be in the same order as the way the bridge tortures. This can be a slight potential threat if resonance occurs, considering the local wind frequencies are various and hard to detect.

Krk bridge has been a remarkable infrastructure construction throughout its history, and the relative studies and reports would not only help the local committee to maintain better and reinforce the bridge itself but also be beneficial for future research on the structure.

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