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ENVIRONMENTAL EFFECT ON THE DYNAMIC CHARACTERISTICS OF RC BRIDGES

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Abstract

Bridges represent key structural elements of transportation systems. They are exposed to different natural and environmental effects that may cause damage representing a potential threat mainly in disturbing the process of transportation of people and goods. The short- and long-term road closures might have a tremendous impact on regional economic and social development. Therefore, the definition of their dynamic characteristics as are natural frequencies by experimental measurements is very important for fast and early assessment of the current conditions. For that purpose, the method of experimental modal analysis is used. This method involves measurement of structural response under ambient conditions. Presented in this paper is investigation of environmental effects upon dynamic characteristics of RC frame bridges. The investigation was carried out on two overpasses with approximately the same geometry. Both structures have two spans each and are in straight direction, but are placed under a skew angle of 58° and 67.8°. The overpasses were constructed in 2016, but have still not been put into operation. They are situated along "Friendship" high-way in N. Macedonia and the distance between them is 3km. Three measurements were performed for each overpass, namely the first measurements were done in October 2017 when dynamic tests were performed, the second were done in March 2020 and the third were done in May 2022. Modal identification of the overpasses was effectively carried out using the enhanced frequency domain decomposition method in frequency domain and stochastic subspace identification method in time domain. The identified dynamic characteristics were compared with each other and with the environmental effects. The results from the analysis show that the identified natural frequencies effectively indicate change of dynamic characteristics of the overpasses due to environmental effects. Greater difference in identified natural frequencies is observed in longitudinal direction, while the least difference occurs in vertical direction.

Keywords: ambient vibration measurements, dynamic characteristics, reinforced concrete bridges, condition assessment

1. Introduction

Bridges, as a vital part of the transportation systems, are inevitably exposed on the daily, seasonal, and annual air temperature variations which affects on the characteristics of the structures. During their service life, local damage can be reflected by the changes in dynamic properties. Therefore, a successful damage assessment relies heavily on the prediction accuracy of the dynamic properties. The variations of modal parameters caused by environmental factors are very significant and often greater than those caused by structural damage [1] or normal loads [2]. The periodic (diurnal, seasonal, and yearly) and transient temperature variations always mask changes in dynamic properties due to actual damage. Recently, more research has focused on the effect of temperature on the dynamic properties of bridges [3].

In practice, the effect of temperature variations on structural dynamic properties have been attributed to the reasons outlined below. First, structural deformations occurred with variations in temperature-varying environments and were called large deformation effects [4]. Second, structural stiffness changed because of thermal stress in the well-known stress stiffening effect [5]. In addition, material

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properties were temperature dependent; for example, the decrease in the elastic modulus of concrete and of steel led to a reduction in modal frequencies. Furthermore, and equally important, the elastic properties of support (especially for bridge structures) were more easily affected by thermal variations, and at low temperature, the boundary conditions also changed suddenly [6]. Accordingly, the factors that affected the dynamic properties of bridge structures were complex and led to some specific damage detection methods, such as technology that does not need estimations of the modal parameters [7]. In addition, a thermal performance study of bridges based on long-term monitoring data still piqued researcher interest [8]; however, the cost of the health monitoring system was high, despite increasingly more advanced structural health monitoring (SHM) technologies [9]. To remove the environmental impacts, regression-based analysis [10] and principal component analysis [11] were adopted, but these analyses were data-driven black box modeling techniques. Although Zhou and Song [12] proposed a physics-based environmental-effects-embedded model updating method to overcome these shortcomings, the selection of the updating parameters was also critical, and a large deflection effect was not taken in account.

In the present study, time-varying thermodynamic properties of 2 span girder bridges were analyzed and compared.

2. Review of the realization of the research and the achieved results

2.1 Applied procedure and description of measuring equipment

The dynamic characteristics have been determined by measurements of ambient vibrations. The equipment with an acquisition system that was used to take the measurements, is sensitive accelerometers that have recorded the acceleration at certain points on the bridge. In this case PCB Piezotronics devices, model 393B12, manufactured by National Instruments with a sensitivity of 10,000 mV and a range of up to 4.9 m/sec^2, with a size of 0.5g (Fig. 1 left) were used. Data acquisition was performed with the acquisition system - module NI cDAQ-9178 and 4 NI 9234 boards (Fig. 1, middle and Fig. 2). The recorded acceleration measurements are expressed in "Earth acceleration - g" (9.81 m/sec^2).

Fig. 1. Piesotronics PCB Accelerometer Model 393B12 (left), DAQ-9178 NI Data Acquisition System Module (middle) and NI 9234 Board (right)

Fig. 2. Field monitoring equipment (left), three-way accelerometer (right)

The measurements were carried out using a sampling rate of 2.048 Hz. In total, 15 accelerometers were used with various measurement locations and directions. The measurement system configuration is shown in Fig. 3.

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Fig. 3. Acquisition System (left) and Accelerometer Configuration (right)

During the measurements, the sensors were placed in the different points of the bridge: in the middle of the bays and above the piers. During all measurements, one accelerometer was located in a reference point in order to enable the comparison of the amplitudes of the other sensors with the reference points for defining the tonal forms of vibration. These measurements cover a frequency range from 0 to 40 Hz, where the first resonant frequencies are found. The processing of the record was carried out by applying a fast Fourier transformation so that it was possible to define the frequency composition of the registered vibration from which the natural frequencies of the objects could be identified.

2.2 Bridge measurements

Withing the framework of this research, field measurements of two overpasses (OP2 and OP3) were carried out to determine their dynamic characteristics. The selected bridges are located over the "Friendship" highway, Demir Kapija - Gevgelija section, designed according to modern regulations that consider the seismic action.

The initial measurements of the structures were carried out in October 2017, during which the trial loading of the bridges with static and dynamic loads was performed. The load capacity and deformability of the built construction is compared with the results of the design project. The precision of the performance and the geometry of the elements were checked, and the quality of the incorporated materials and thus the usability of the construction was checked. At the beginning of March 2020, additional measurements were performed on the bridges with a duration of 10 min. The same measurements were repeated in May 2022. The two bridges were not put into use for all years during measurements. Therefore, only the environmental conditions are the external factors that may effect the dynamic properties of the bridges.

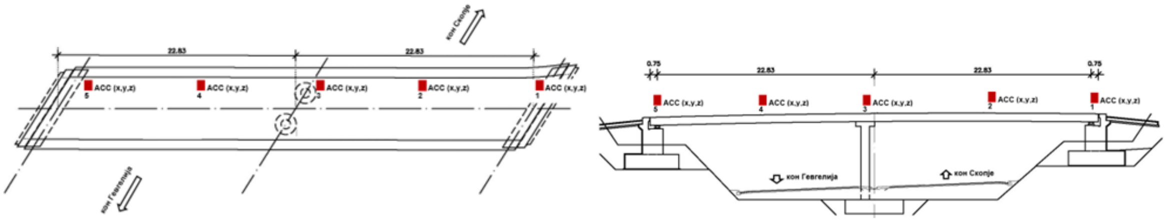


Fig. 4 Position of accelerometers on the measured bridge at base and cross-section for OP2

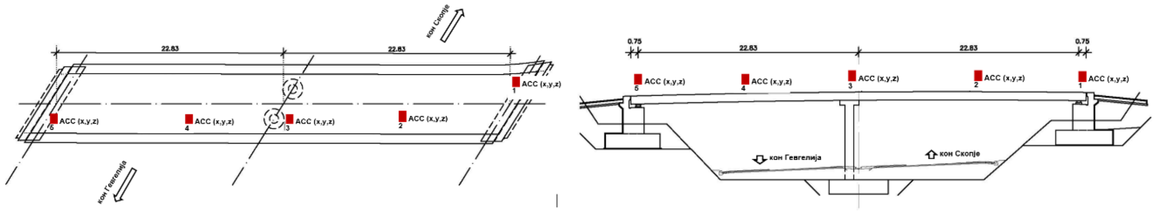


Fig. 5 Position of accelerometers on the measured bridge at base and cross-section for OP3

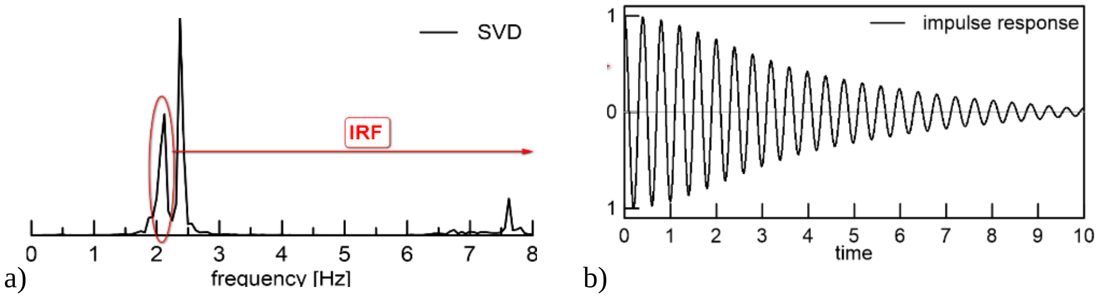
For performing the measurements, 15 accelerometers were used, in 5 places, 3 each in the longitudinal x direction, the transverse y direction and the vertical z direction, and they were placed on the edge of the upper structure, in the field and above the middle support (Fig. 4 and Fig. 5). During the first measurement, the accelerometers were placed on the part of the upper construction, in the direction of Skopje (Fig. 4), while during the second measurement, they were placed in the direction of Gevgelija, with the first accelerometer as a benchmark during both measurements being placed in the same place (Fig. 5).

2.2.1 Description of modal damping estimation methods

The methods available to perform identification of modal parameters (in this case modal damping, but it is the same for all modal parameters) of dynamic systems based on their response to ambient excitation are classified as frequency domain or time domain methods. The frequency domain methods start from the output spectrum of half- spectrum matrices estimated from the measured outputs. After obtaining the frequency response curves of the analysed system, modal damping can be measured using half-power bandwidth method and Enhanced Frequency Domain Decompositon (EFDD) method. The half-power bandwidth method consists of locating the resonant frequency and two nearby frequencies f1 and f2 located in the frequency spectrum by application of equation 1:

$$\xi = \frac{f_2 - f_1}{2 f_r} \times 100\% \tag{1}$$

Enhanced Frequency Domain Decompositon was performed in order to calculate the damping (IRF) by using the impulse response of a single degree of freedom. Once a set of points with similar singular vectors is selected for a particular mode (Figure 6a), this segment of an auto-spectrum may be converted to a time domain (Figure 6b). An auto-correlation function with the contribution of a single mode is obtained. As the output correlation of a dynamic system excited by white noise is proportional to its impulse response, it is possible to estimate the modal damping coefficient. This can simply be performed by fitting an exponential function to the relative maxima of the correlation function and extracting the modal damping ratios from the parameters of the fitted expression taking into account the classical expression for the impulse response of a single degree of freedom.



a) b)

Fig. 6. FDD method, estimation of the modal damping ratio

2.2.2 Overpass OP2

Using the previously described procedure, most of the records were obtained at individual points of the investigated bridge. Based on these registrations and their singular value of spectral densities, a certain amount of data on the dynamic characteristics of the investigated structures were obtained. Below, on Fig.7 the curves of singular value of spectral densities for OP2 are presented.

Table 1 shows the frequencies obtained from all measurements, when the accelerometers were placed on the part of the upper construction in the direction of Skopje (measurement 1). From the obtained results, it can be concluded that almost all accelerometers that measured the acceleration in a certain direction show similar results, that is, for longitudinal direction, the frequency is 2.58Hz for 2017year, 3.58 for 2020year and 2.65Hz for 2022.

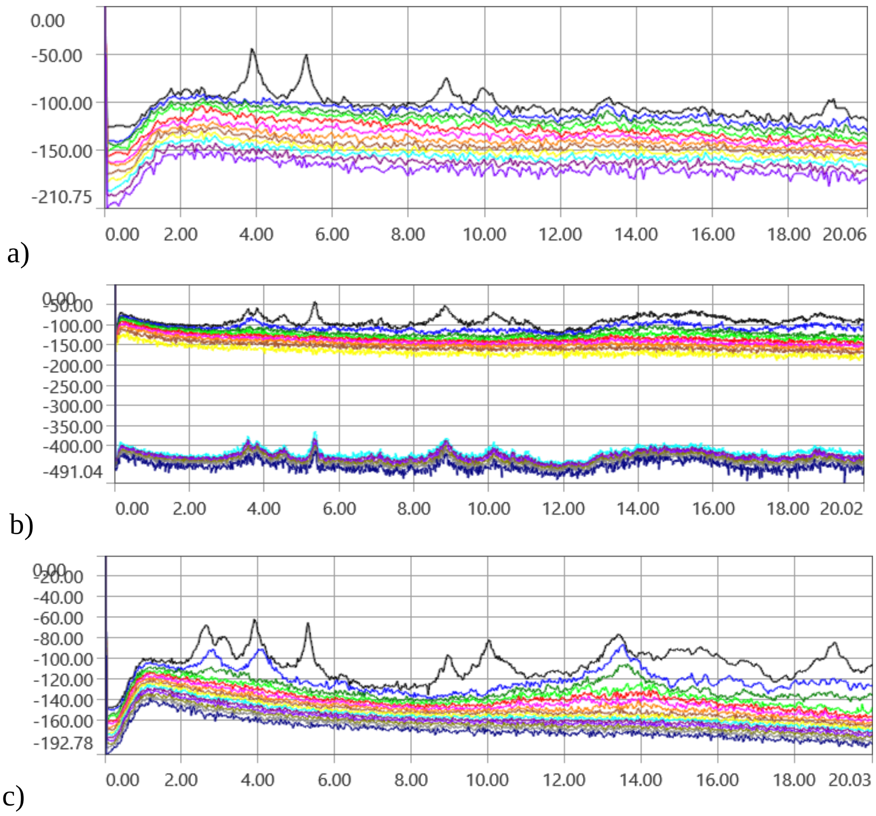


Fig.7 Singular value of spectral densities for OP2
a) 2017, b) 2020, c) 2022

It can be seen that the frequency has increased in 2020 and in 2022 came back. In the Transversal direction, the frequency of the structure is 2.97Hz for 2017year, 3.80 for 2020year and 3.12Hz for 2022. In the vertical direction, the frequency of the structure is 3.88Hz for 2017year, 3.81 for 2020year and 3.91Hz for 2022. In this direction, the frequency decreased in 2020 and then in 2022 increased to 3.91Hz.

Table 1 Natural frequencies of the structure for OP2

Mode	Direction	Frequency [Hz]		
		2017	2020	2022
1	Longitudinal	2.58	3.58	2.65
2	Transversal	2.97	3.80	3.12
3	Vertical	3.88	3.81	3.91
4	Vertical	5.31	5.36	5.32
5	Vertical	8.99	8.83	8.97
6	/	10.0	10.1	10.03

Table 2 shows the damping for each frequency by two methods: half power and IRF. In general, the damping calculated by the two methods corelates with each other. For the first frequency in the vertical direction, the damping is within the range of 0.88% for 2017, 0.73% for 2020 and 1.25% for 2022. For the first frequency in the Longitudinal direction, the damping is within the range of 0.71% for 2020 and 3.3% for 2022.

Table 2. Modal damping [%] for OP2

No.	2017			2020			2022		
	Freq.	Half Power	IRF	Freq.	Half Power	IRF	Freq.	Half Power	IRF
1 (Vertical)	3.88	0.80	0.88	3.81	0.37	0.73	3.91	0.73	1.25
2 (Vertical)	5.31	0.58	0.64	5.40	0.39	0.46	5.32	0.40	0.45
3 (Longitudinal)	2.58	n/a	n/a	3.58	0.54	0.71	2.65	2.43	3.3

2.2.3 Overpass OP3

Using the same procedure za OP2, all records were obtained at individual points of the investigated bridge. Based on these registrations and their singular value of spectral densities, a certain amount of data on the dynamic characteristics of the investigated structures were obtained. Below, on Fig.8 the curves of singular value of spectral densities for OP3 are presented.

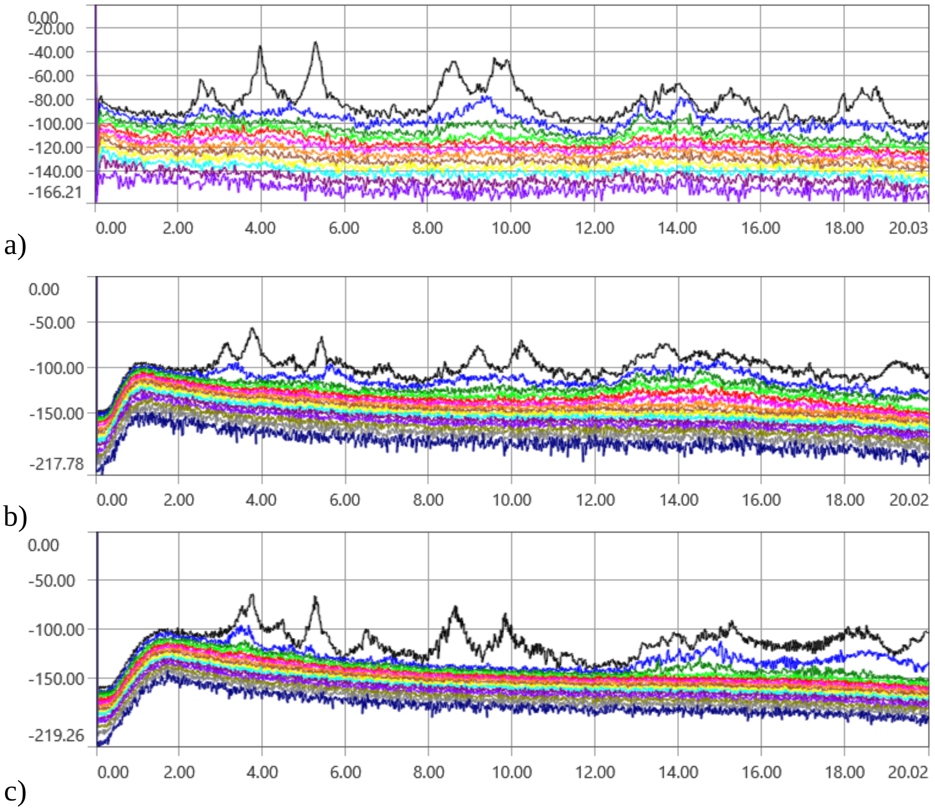


Fig. 8 Singular value of spectral densities for OP3
a) 2017 b) 2020 c) 2022

Table 3 shows the frequencies obtained from all measurements, when the accelerometers were placed on the part of the upper construction in the direction of Skopje (measurement 1) for bridge OP3. From the obtained results, it can be concluded that almost all accelerometers that measured the acceleration in a certain direction show small differences in natural frequencies. For longitudinal direction, the frequency is 2.53Hz for 2017year, 3.14 for 2020year and 3.50Hz for 2022. It can be seen that the frequency has continuously increased in 2020 and in 2022. In the Transversal direction, the frequency of the structure is 2.84Hz for 2017year, 3.49 for 2020year and 3.77Hz for 2022. In the vertical direction, the frequency of the structure is 3.98Hz for 2017year, 3.78 for 2020year and 3.78Hz for 2022. In this direction, the frequency decreased in 2020 and continued with same value till 2022.

Table 3. Natural frequencies of the structure for OP3

Mode	Direction	Frequency [Hz]		
		2017	2020	2022
1	Longitudinal	2.53	3.14	3.50
2	Transversal	2.84	3.49	3.77
3	Vertical	3.98	3.78	3.78
4	Vertical	5.28	5.35	5.27
5	Vertical	9.62	9.16	8.64

Table 4 shows the damping for each frequency by two methods: half power and IRF. In general, the damping calculated by the two methods corelates with each other. For the first frequency in the vertical direction, the damping is within the range of 0.78% for 2017, 1.44% for 2020 and 1.06% for 2022. For the first frequency in the Longitudinal direction, the damping is within the range of 0.82% for 2017 and 2.18% for 2020.

Table 4. Modal damping [%] for OP3

No.	2017			2020			2022		
	Freq.	Half Power	IRF	Freq.	Half Power	IRF	Freq.	Half Power	IRF
1 (Vertical)	3.98	0.59	0.78	3.78	1.15	1.44	3.78	1.06	1.06
2 (Vertical)	5.28	0.61	0.84	5.35	0.49	0.65	5.27	0.25	0.62
3 (Longitudinal)	2.58	0.69	0.82	3.14	2.02	2.18	3.50	n/a	n/a

3. Monitor the climate conditions

Engineering materials change their properties and are vulnerable to damage from the surrounding environment, whether they are concrete, steel, or wood. Some environmental factors are considered during structural design, primarily in terms of stress conditions. However, the changes in fundamental environmental conditions such as temperature and humidity can be challenging because they may influence structural dynamic properties. Environmental monitoring is therefore an essential component of this bridge measurement program. The monitoring program involves gathering information on temperature, humidity, and environmental data analysis. Because the object region has a limited number of monitoring sensors, a relatively good profile of the environmental conditions was constructed by collecting monitored data for at least 6 months before the bridge measurements. The weather monitoring was conducted for the years 2017, 2020 and 2022. The most essential information to consider in these records will be the extremes in averages of temperature and humidity.

3.1 Temperature

According to the monitored program, the regularly collected set of data was grouped into three monitoring periods. The first monitoring period was a period of one month before the bridge measurements, while the second monitoring period was a period of three months prior to the measurements. The last analyzed period was a period of six months before the structure's measurements. The determination of real temperature inside each structural part was not conducted because the measurements were only for ambient temperature. As a result, it was decided to evaluate how these conditions might affect the structural dynamic characteristics.

Tables 5 to 7 show the ambient temperatures for 2017, 2020 and 2022. The temperature was studied for three periods of 1, 3 and 6 months before the measurements. For a period of 6 months, the average mean temperature for 2017 is 19.2°, while for 2020 and 2022 it has dropped to around 7.5-9.2°. For a period of 3 months, the average mean temperature is different for each year, where for 2017 it is 20.5°, for

2020 it is 4.5° and for 2022 it is 10.1°. For a period of 1 month, the average mean temperature for 2017 and 2022 is around 15.5°, while for 2020 it has dropped to 6.5°.

Table 5 Temperature observation for period of 1 month before bridge measurements

Year	Avg Max [^{O}]	Avg Mean [^{O}]	Avg Min [^{O}]	Max [^{O}]	Min [^{O}]
2017	23.7	15.7	8.3	37	-3
2020	13.3	6.5	0.3	25	-6
2022	23.1	15.2	7.5	34	-2

Table 6 Temperature observation for period of 3 months before bridge measurements

Year	Avg Max [^{O}]	Avg Mean [^{O}]	Avg Min [^{O}]	Max [^{O}]	Min [^{O}]
2017	28.6	20.5	12.3	40	-3
2020	10	4.5	-0.4	25	-9
2022	17.2	10.1	3.3	34	-9

Table 7 Temperature observation for period of 6 month before bridge measurements

Year	Avg Max [^{O}]	Avg Mean [^{O}]	Avg Min [^{O}]	Max [^{O}]	Min [^{O}]
2017	26.9	19.2	11.4	40	-3
2020	15.6	9.2	3.5	34	-9
2022	13.6	7.5	1.66	34	-10

Fig. 9 show the temperature observation over past six months before bridge measurements: maximum daily values, minimal daily values, and average daily data.

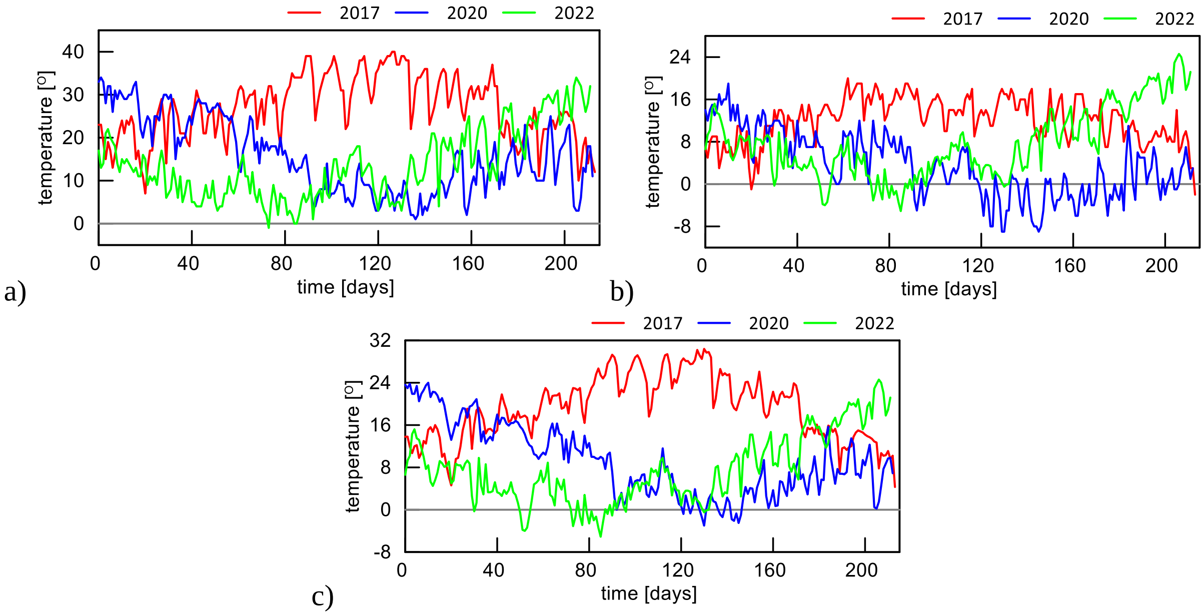


Fig. 9 Temperature observation over past six months before bridge measurements
a) Maximal daily values b) Minimal daily values c) Average daily data

Fig. 10 (left) shows the maximum, minimum and average temperatures (in ◦C) of the location in the period of the construction of the bridges to the end of the May, 2022, when the last measurements of the bridges were performed. Right figure (Fig. 10) presents the temperature the air needs to be cooled

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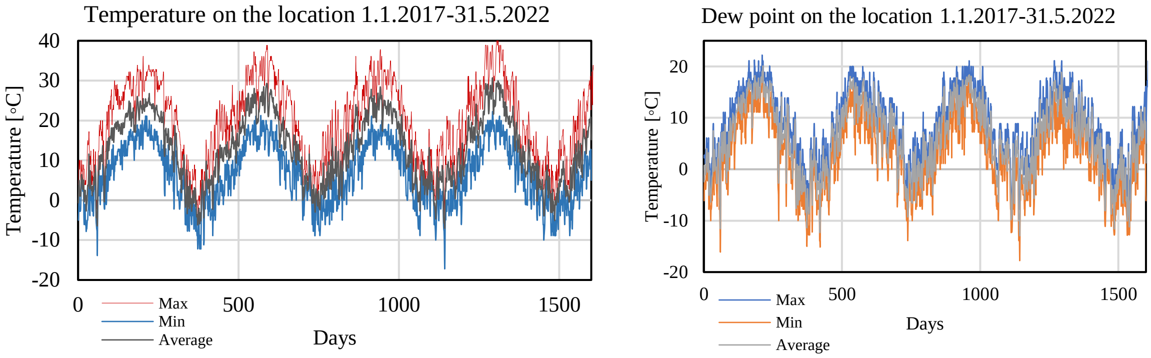
to (at constant pressure) to achieve a relative humidity (RH) of 100% (source: www.wunderground.com).



a) b)

Fig. 10 a) Maximum, minimum and average temperatures on the location, b) dew point values for the period of existing the structures. *Source: www.wunderground.com*

3.2 Humidity

In addition to the analysis of the ambient temperature, an observation of humidity was also performed for a period of 1, 3 and 6 months before the measurement of the bridges. The results of this observation are shown in Table 8 through the average of daily maximum values. The average of daily maximum humidity for a period of 6 months is in range of 87.7%, 92.4% and 91.9%. In the case of a period of 1 month the average of daily maximum humidity is almost constant between 91.8% and 92.1%.

Table 8 Mean humidity of maximum daily values

Observation Period [months]	Average of daily maximum values [%]		
	2017	2020	2022
1	92.1	91.8	91.95
3	85.3	92.9	90.0
6	87.7	92.4	91.9

The maximum, minimum and average humidity on the location in the period of existing the structures, almost 5 years, (1.1.2017-31.5.2022) is presented on Fig. 11. This figure shows that the average humidity during the whole period is almost 70%.

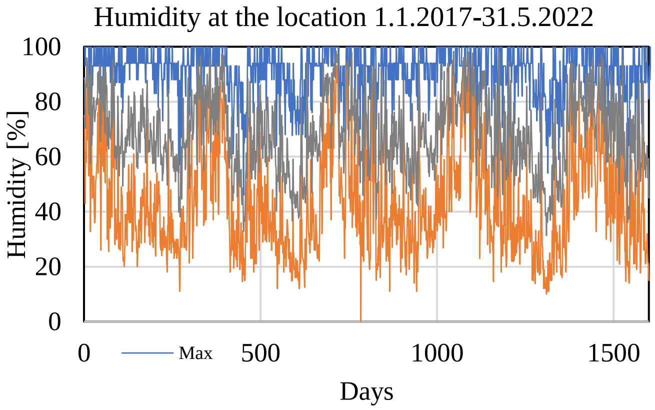


Fig. 11 a) Maximum, minimum and average humidity [%] on the location
Source: www.wunderground.com

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3.3 Wind speed

Wind speed is a characteristic of air movement that can influence of the dynamic characteristics of bridge structures, especially of long span bridges. Minh et al. [13] concluded that the interaction of the structure with surrounding air currents can produce changes in structural dynamics as wind speeds change. In their investigation, they concluded that due to very low vibration frequencies, the gust response of a long-span bridge is very sensitive to turbulence properties, especially spatial coherence. Some of their effects on the gust response of long-span bridges have been pointed out.

Cheli et al. [14] showed that with increasing wind speed, the frequencies of the first vertical and torsional modes respectively rise and fall, and hence tend to converge. In addition, damping ratios generally increase significantly with wind speeds. These aero-elastic effects were confirmed in sectional model wind tunnel testing [15], but the range of wind speeds during the test have been not sufficient to confirm this behavior (being below 15m/sec and usually less than 10m/sec).

Since the measured bridges in this investigation do not have longe spans, the influence of the wind conditions of their dynamic characteristics have to be additionaly investigated. Herein, only maximum and average wind speed at the location is presented in the period of bridges existence (Fig. 12).

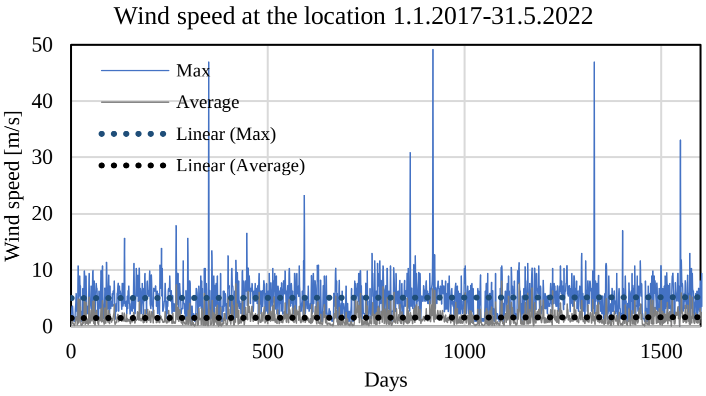

Fig. 12 Wind speed at the location of bridges
Source: www.wunderground.com

From the Fig. 12 it can be concluded that on the location of the bridges, the maximum wind speed is almost 50 m/s, but the average speed is 1.5m/s.

4. Conclusion

The objective of this study is to investigate the environmental effects on the dynamic characteristics of two base-isolated highway monolithically constructed frame overpasses. The dynamic characteristics of the structures are defined using large scale ambient vibration testing. To consider the difference in the dynamic characteristics of the structures, three measurements were performed to both bridges. The first measurements were realized after the construction of the structures, in 2017; second one 3 years later, in 2020; and the last one 2 years after the second measurements, in 2022. The ambient vibration tests were conducted under the environmental excitations in the bridges and the dynamic characteristics of structures were accurately extracted. Both overpasses were exposed on only environmental atmospheric conditions. They are still not in use, so they were no exposed-on service loads. From the obtained results and the environmental investigation, it can be stated that:

- There are differences in the results from the performed ambient vibration testing in three periods of the existing the structures. Since they are not in use and are no exposed to service loads, it can be concluded that the environmental conditions have influence of the dynamic characteristics of the structures.
- The natural frequencies of both structures are higher with the time. Especially in longitudinal and transversal directions. The difference in vertical direction is almost the same.

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- The difference between the measured frequencies from first two measurements is bigger than the second and the third measurement, that means that the structure is getting stabilized.
- Temperature and humidity have influence of the dynamic characteristics of the structures.
- Wind speed do not have influence of the dynamic characteristics of the structures.

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