E3S Web of Conferences **402**, 12016 (2023) https://doi.org/10.1051/e3sconf/202340212016
TransSiberia 2023

Vibration based damage detection of bridge structures

Yu.Yu. Shatilov[1*], *A.A.* Lyapin[1], *A.V.* Cherpakov[1], and *S.G.* Glushko[1]

[1]Don State Technical University, 344000 Rostov-on-Don, Russia

Abstract. The task of identifying damage to the load-bearing beams of large-span bridge structures using vibration diagnostic methods has been implemented, taking into account experimental uncertainties associated with natural phenomena and technological processes. The methodology for localizing damage is based on the analysis of dynamic characteristics of the structure, such as natural frequencies and modes of vibration. The study presents research on a finite element model of a bridge structure using a method for determining a damage indicator based on normalizing the values of vibration modes with respect to the values of vibration area.

1 Introduction

Vibration based damage detection is a well-known method in structural engineering to identify damage in bridge structures. The method is based on monitoring the vibration modes of the structure and analyzing changes in them to identify any damage. The method is preferred as it is non-destructive and can detect damage before it becomes severe. In this article, we will discuss the concept of vibration based damage detection, the methods used to analyze the modal vibration modes of a structure, and its application in bridge structures.

Vibration based damage detection is a method of identifying damage in structures by analyzing the changes in the natural vibration modes of the structure. These modes are the fundamental modes of vibration of a structure, which are natural and inherent to the structure. They are affected by any changes in the structural properties, including damage. The vibration modes can be obtained by measuring the structural response to an external stimulus, such as an impulse or a harmonic force. The changes in these modes can be analyzed to detect any damage in the structure.

By analyzing the natural frequencies and mode shapes, one can identify any changes in the structure due to damage. There are several methods used to analyze the modal vibration modes of a structure. One of the most common methods is the frequency response function (FRF) method. This method involves exciting the structure with an external force at different frequencies and measuring the response of the structure. The response is then used to calculate the FRF, which is a measure of the transfer function between the input and output signals. The FRF can be used to identify the natural frequencies and mode shapes of the structure.

[*] Corresponding author: art-web@mail.ru

 https://doi.org/10.1051/e3sconf/202340212016

Another method used to analyze the modal vibration modes of a structure is the modal analysis using a finite element model. This method involves creating a finite element model of the structure and solving the eigenvalue problem to obtain the natural frequencies and mode shapes. The model can then be updated with any changes in the structural properties due to damage, and the changes in the natural frequencies and mode shapes can be analyzed to detect the damage. This article discusses and analyzes the results obtained by this method.

Vibration based damage detection is widely used in bridge structures to detect any damage that may occur due to various reasons, such as fatigue, corrosion, or impact. Bridge structures are critical infrastructure that requires regular inspection and maintenance to ensure their safety and longevity [1]. Vibration based damage detection is preferred as it is non-destructive and can detect damage before it becomes severe.

One example of the application of vibration based damage detection in bridge structures is the use of accelerometers to monitor the vibration modes of the structure. The accelerometers are placed at strategic locations on the structure, and the vibration modes are monitored continuously. Any changes in the natural frequencies and mode shapes are analyzed to detect any damage in the structure.

In most cases, the causes of destruction of building structures are defects in construction that were either present initially or formed as a result of the impact of various environmental factors [2]. Monitoring during the construction and operation of buildings and structures allows for the detection of processes that threaten the mechanical safety of buildings and structures. Currently, there are a sufficient number of methods for vibration diagnostics of building structures, most of which are based on measuring the dynamic parameters of the structure. The main tasks of these methods are to determine the natural frequencies of vibration, geometric shapes of structural vibration, calculate the damping decrement, and detect changes in these parameters throughout the life cycle of the structure [3]. Despite the use of these methods in the diagnostics of building structures, there are a number of problems related to the determination of the stress-strain state of large-span structures due to experimental uncertainties.

2 Theoretical base and algorithm

The article discusses the determination of a criterion for analyzing the results of vibration-based diagnostics, which would allow identifying the presence of structural damage without using additional types of structural analysis, such as determining the strength of concrete and reinforcement using destructive control methods. The considered criterion is developed based on a widely used method of changing the vibration modes of the structure, with normalization of the values taking into account the area function obtained by interpolating the coordinates of the vibration mode shape [4]. This method of normalization, with the calculation of the area of the vibration mode shape, will be less sensitive to the number and location of sensors used in conducting the experimental study.

$$\varphi_i = \frac{\varphi_{0i}}{Area(\varphi_0)} \qquad (1)$$

where is the φ_i – i-th element of the normalized vector of vibration shape φ with n coordinates, φ_{0i} – is the i-th element of the original vector φ_0 before normalization, $Area(\varphi_0)$ is the area of the figure bounded by the function $\varphi_0(x)$, calculated as follows:

$$Area(\varphi_0) = \int_0^1 |\varphi_0(x)|dx \qquad (2)$$

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where $\varphi_0\ (x)$ – is a function obtained by cubic spline interpolation of the original vibration shape of the structure.

$$\Delta\varphi_{mn} = \varphi_m - \varphi_n \qquad (3)$$

$$\Delta A = \int_0^1 |\Delta\varphi_{mn}(x)\ |dx \qquad (4)$$

while the areas of two vibration forms of the structure, the reference structure and the damaged one, φ_m and φ_n respectively, are identical due to the procedure of normalizing to a unit area (3), the distribution of the area over the entire length of the structure will differ. Thus, the area of change in vibration form - ΔA - can be used as an indicator of the presence of damage. The larger the value of the parameter ΔA, the more likely it is that there is a defect in the examined structure.

3 Integration and results

To determine the capabilities of the criterion for identifying structural damage, a finite element model of a bridge structure with defects of various types and sizes was developed. As a result of modal analysis, vibration forms of the structure were obtained to determine the degree of damage to the structure based on the method described above.

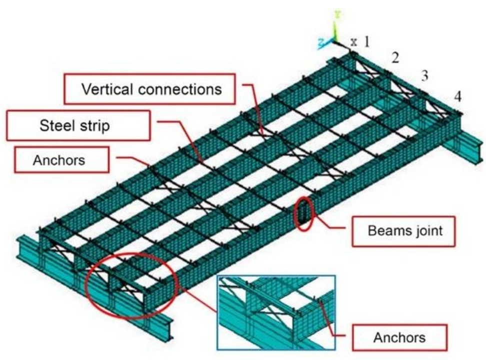

Fig. 1. Finite element model of a bridge structure.

Figure 1 shows the finite element model of the bridge used in this study, created using ANSYS finite element analysis software based on experimental data of a reinforced concrete bridge. The supporting elements of the reinforced concrete deck are steel I-beams. Material properties used in the finite element model are listed in Table 1. All materials are assumed to be linearly elastic, which implies a linear relationship between the stress tensor components and the strain tensor components. The I-beam, hinged at both ends with a span of 8 meters, consists of two equal-length segments. The construction model was calibrated for the first two natural modes of vibration by adjusting the concrete density and anchor bolt stiffness.

Table 1. Physical properties of materials in the finite element model

No.	Material	Density, kg/m3	Elastic modulus, GPa	Poisson's ratio
1	Concrete	2450	28.6	0.0053
2	Steel	7800	200	0.0055

After the model was calibrated and the dynamic characteristics of the structure were obtained, damaged states of steel beams were simulated. In total, 3 different cases of

https://doi.org/10.1051/e3sconf/202340212016

structural damage were investigated, with the types of defects depicted in Figure 2. Table 2 provides the values of the areas of the vibration modes of the I-beam depending on the type of defect relative to the defect-free structure model, calculated according to formula 4.

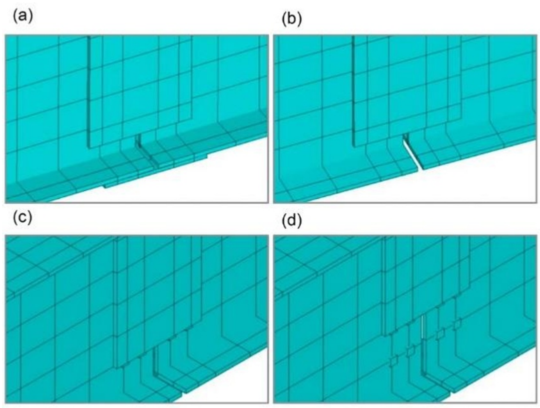

Fig. 2. Simulated damage to the supporting steel beam #4 (a) - undamaged state of the structure, (b) - absence of the lower chord splice plate, (c, d) - violation of the size of the splice plate on the flanges of the I-beam.

Table 2. Change in the area of natural vibrations of an I-beam depending on the type of defect

No.	Type of defect	ΔA, % 1st mode	ΔA, % 2nd mode	ΔA, % 3d mode
1	Absence of the lower flange cover plate (b)	12.89%	17.74%	2.89%
2	Non-compliance with the dimensions of the cover plate on the flange walls (c)	15.87%	21.88%	2.53%
3	Non-compliance with the dimensions of the cover plate on the flange walls (d)	43.32%	60.95%	3.08%

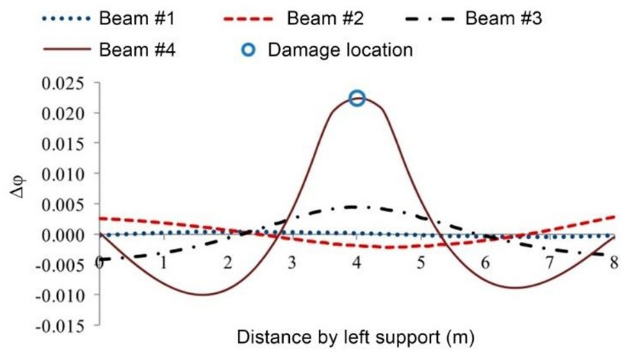

Fig. 3. Defect localization based on comparison of vibration shapes for defect #1

Figure 3 shows the result of defect localization, in the form of the absence of the lower chord splice plate, using the discussed method of normalization of vibration shape values at measurement points, taking into account cubic spline interpolation to obtain intermediate values. The application of this method in practice will minimize the number of locations for accelerometer sensors during vibration analysis of the structure, by introducing an additional parameter for normalization of vibration shapes. This method of damage identification in structures will allow for highly accurate identification of damages, taking into account experimental uncertainties such as natural and man-made influences.

4 Conclusion

The developed approach was tested on a real bridge structure, and the results demonstrated the effectiveness of the method for identifying the location and severity of damage. The approach can be used as a tool for early detection of damage to bridge structures, which is important for ensuring their safety and longevity.

One of the advantages of the proposed approach is its ability to take into account experimental uncertainties, such as those related to environmental and operational conditions. This makes it possible to obtain more accurate results and reduce the risk of false alarms.

In addition, the method can be used to evaluate the effectiveness of repair and maintenance measures. By comparing the dynamic characteristics of the structure before and after repair, it is possible to assess the degree of improvement and ensure that the repairs were successful.

Overall, the developed approach for identifying damage to bridge structures using vibration diagnostic methods has the potential to improve the safety and longevity of critical infrastructure. Further research is needed to optimize the methodology and evaluate its effectiveness under different operational and environmental conditions.

In conclusion, vibration based damage detection is an effective method for identifying damage in bridge structures. The method is based on monitoring the natural vibration modes of the structure and analyzing any changes in them due to damage. Several methods are used to analyze the modal vibration modes of a structure, including the FRF method and modal analysis using a finite element model. Vibration based damage detection is widely used in bridge structures to ensure their safety and longevity, and examples of its application include the use of accelerometers and ambient vibration testing. The method is preferred as it is non-destructive and can detect damage before it becomes severe, allowing for timely repairs and maintenance to be carried out. Overall, vibration based damage detection is a valuable tool in the field of structural engineering for ensuring the safety and longevity of critical infrastructure such as bridge structures.

5 Acknowledgments

The study was supported by the Russian Science Foundation grant No. 22-29-01259, https://rscf.ru/project/22-29-01259/ .

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