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Research Article

Structural Damage Identification Method Based on Parametric Boundary Condition Optimization

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According to the heterogeneous background interference, the subjective consciousness, inaccurate quantification, and high cost in practical engineering, a method of applying the Bouc–Wen hysteresis nonlinear model to hysteresis characteristics of rubber isolation bearings is proposed, and this method analyzes the sensitivity of nonlinear parameters of the Bouc–Wen hysteresis model and obtains the order of nonlinear parameters of hysteresis model under different sizes of excitation. The results show that the prediction error of fatigue life is 16% less under various stress ranges, a rectangular identification frame with a certain probability guarantee rate is used to realize multitype seismic damage classification and location, the average accuracy of the identification of concrete cracking and spalling, steel bar exposure, and buckling is more than 80%, and the average coverage rate is more than 88%. During the use of civil engineering structures, the working environment is constantly changing; combined with the current damage identification and detection methods, the structure health monitoring system is established, and it is of great significance to promote the practical development of structural damage identification methods to accurately monitor the structure state in real time and to make a rapid and accurate diagnosis when the structure damage occurs.

1. Introduction

With the rapid development of the national economy, important civil engineering structures are developing to large scale and complex gradually. In the process of long-term service, the structure will be damaged due to the aging of materials, corrosion, long-term action of load, fire, earthquake, and other natural disasters. The damage not only shortens the service life of the engineering structure but also threatens the safety of people's life and property, and if these damages cannot be found and dealt with in time, it will lead to structural damage and serious consequences [1]. The timely detection of structural damage location and assessment of the degree of damage can not only ensure the safe operation of the structure but also reduce the loss of personnel and property. Therefore, the research on structural damage identification method has become a hot topic in the civil engineering field [2]. As early as the 1940s, structural damage identification techniques and methods have attracted the attention of the civil engineering field, and a variety of research methods have been developed, mainly some local civil engineering defect detection technologies, such as static loading, ultrasonic, magnetic method, radar imaging, and X-ray. Methods for monitoring, locating, and quantifying structural damage based on changes in structural vibration response or dynamic characteristics are reviewed in detail. Then, damage identification is divided into five progressive levels: (1) determine whether there is damage in the structure; (2) determine the location of damage; (3) determine the type of damage; (4) quantify the degree of damage; and (5) estimate the remaining service life of the structure. Structural damage identification methods can be divided into local damage identification methods and global damage identification methods [3–5]. Local damage identification method refers to the use of nondestructive testing technology to detect the local damage of the structure to judge the damage condition. Local damage identification methods are divided into two types: the first is the use of ultrasonic method, X-ray method, and γ ray method, and other electromagnetic detection technology of the structure of the local periodic inspection; the other one is to fix the sensor on the important component for remote detection. Local damage identification can directly determine the damage location, which has a wide range of applications in aerospace and ship fields. The disadvantages are as follows: (1) this method can only be used to detect the damage of local components, and it is almost impossible to detect the damage of each part of a large complex engineering structure; (2) the detection time is long, which is not suitable for real-time online monitoring. In order to solve the damage identification and diagnosis of large complex structures, scholars have gradually developed global damage identification methods [6]. When structural damage occurs, structural physical parameters such as structural stiffness and damping will change, leading to the change of frequency response function and modal parameters, and finally, the dynamic response of the whole structure will change. The global damage identification method uses the dynamic response of the structure to identify the structure's physical parameters and their changes, so as to judge the damage state of the structure. Compared with local damage identification methods, this method has greater advantages, especially in the identification of large complex structure damage, so domestic and foreign scholars are keen on the research of global damage identification methods [7].

Ahmad, H. A. et al. identified the damage of a double-span continuous beam based on the model updating method of the static response surface. The results show that this method has high accuracy, reduces the number of structural finite element calculation, and improves the update efficiency of the optimized calculation model [8]. Tayfur, S. et al. proposed a structural damage identification method based on the response surface model correction technique and the damage index of element modal strain energy. By identifying the test model of the simply supported beam and Baishi Bridge, it was verified that the proposed method has good sensitivity to cracking damage and support damage [9]. Marini, J. J. et al. proposed an interval uncertainty parameter identification method based on response surface and sensitivity analysis. The interval uncertainty parameter identification was conducted for a numerical example of a mass-spring system and a group of engineering examples, and the feasibility and reliability of the proposed method are verified. The results also show that the proposed method has high computational efficiency and can effectively avoid the convergence problem caused by interval optimization [10].

Rubber vibration isolation bearings are generally divided into four types: natural rubber bearings, lead rubber bearings, high damping rubber bearings, and tin core rubber bearings. The vibration isolation layer can use lead rubber bearing + natural rubber bearing, high damping rubber bearing, natural rubber bearing + viscous damper (or lead damper), or a combination of the above vibration isolation devices. The experimental model of rubber isolation structure was established according to the seismic isolation bearing used in engineering structure, and the experimental research of GZN110 rubber isolation bearing was carried out, the experimental model of the rubber isolation structure was established by using the isolation bearing, and a set of stiffness elements was adopted in the experiment to realize the sudden change of the stiffness of the model, and in the experimental process, the occurrence of structural damage was simulated online, and an adaptive tracking technique based on optimization method was proposed to identify the system parameters of rubber isolation bearing and rubber isolation structure almost online; in addition, the changes of seismic isolation structure parameters are tracked to determine the occurrence of structural damage, including the time, location, and degree of damage [11].

2. Deterministic Method for Structural Damage Identification

The deterministic method of structural damage identification refers to the mapping relationship between the damage characteristic parameters and the real damage, and the purpose of structural damage identification is realized by reasoning, analysis, and calculation. It usually includes the following methods: (1) identification method based on dynamic fingerprint; (2) recognition method based on model modification; (3) recognition method based on measured time-domain signal; (4) recognition method based on neural network. Among them, three damage identification methods based on dynamic fingerprint, model correction, and measured time-domain signal are the main research directions.

The mass, stiffness, and damping of a structure are known as the physical parameters of the structure, which are determined by the structure's geometry and material properties, and determine the structure's static and dynamic properties. High damping rubber-bearing isolation systems have been used in buildings and bridges. Since they can significantly reduce the response of structures subjected to earthquakes and other dynamic loads, these base isolation systems will be used more and more widely in the future. In order to ensure the integrity and safety of the base isolation system, it is necessary to develop a matching structure health monitoring system. So far, little has been done. The hysteretic nonlinear mechanical properties of rubber isolation bearings are a challenging problem for health monitoring of rubber isolation bearings and their base isolation structures. Therefore, the hysteresis nonlinear model of the rubber isolation bearing must be established to accurately describe the nonlinear dynamic characteristics of the rubber isolation bearing, and the rubber isolation structure damage (including the damage of the superstructure and rubber isolation bearing damage) can immediately assess the operation state of the structure, that is, whether it is safe, and diagnose the damage of the structure, such as the damage location and degree.

The horizontal shear and displacement curves of rubber isolation bearing are nonlinear. At first, in order to simplify and facilitate analysis, scholars proposed an equivalent linear model, which mainly includes the equivalent stiffness and equivalent damping coefficient of the structure. According to the equivalent linear model, when the hysteresis nonlinear structure is excited by the earthquake, its motion equation is shown as follows:

$$m\ddot{x} + c_{\mathrm{eq}}\dot{x} + k_{\mathrm{eq}}x = -m\ddot{x}_0, \quad (1)$$

where M represents the mass of the hysteresis nonlinear structure; Ce and KE are the equivalent damping coefficient and equivalent stiffness of hysteresis nonlinear structure, respectively. Z, Z, and x are the response signals of acceleration, velocity, and displacement on the opposite planes of the structure, respectively. X_0 is the stimulated seismic acceleration signal.

Bilinear model is a kind of nonlinear model commonly used in structural analysis. It can be divided into three types: ideal elastic-plastic model, linear strengthening elastic-plastic model, and elastic-plastic model with negative stiffness; its stiffness is expressed as k_1 and k_2, respectively; the force-displacement relationship (unidirectional) of this bilinear model is shown as follows:

$$f(x) = \left\{ \begin{array}{cc} k_1 x, & x \le u_y, \\ (k_1 - k_2)u_y + k_2 x_2, & x > u_y. \end{array} \right\}. \quad (2)$$

Then, the motion equation of the hysteresis nonlinear structure modeled by the bilinear model is shown as follows:

$$m\ddot{x}(t) + c\dot{x} + f(x) = F(t). \quad (3)$$

Yield parameters are defined. $\alpha = k_2/k_1$, it reflects the postyield to preyield stiffness ratio, and we can simplify this. In the ideal elastic-plastic model, $\alpha = 0$; and in a general bilinear model, $0 < \alpha < 1$. See Figure 1.

In the seismic isolation calculation and analysis, the differential model (Bouc–Wen model) or bilinear model that does not consider the shear strain correlation is usually used to simulate the lead-core rubber bearing or the modified bilinear model that considers the shear strain correlation or corrected BRO model (corrected bilinear + RO model). Bilinear model is more studied in the piecewise linear model, and linear model trilinear model and multishear spring model are widely used, while piecewise linear model also includes multiple shear spring (MSS). Similar to the bilinear model, the trilinear model consists of three linear springs of different stiffness; it includes three linear springs whose stiffness is called the first stiffness, the second stiffness, and the third stiffness, respectively. The model contains two displacement and force yield points. Compared with the bilinear model, the parameters of the trilinear model increase, and the calculation complexity increases greatly, and it is difficult to define the two yield points effectively, so the practical application is limited. After the east-west and north-south displacements are obtained, the deformation and restoring force of each spring can be expressed by the increment of displacement along the east-west and north-south directions as shown in

$$\Delta x_{\mathrm{ew}} = x_{\mathrm{ew}}(t) - x_{\mathrm{ew}}(t-1), \quad (4)$$

$$\Delta x_{\mathrm{ns}} = x_{\mathrm{ns}}(t) - x_{\mathrm{ns}}(t-1), \quad (5)$$

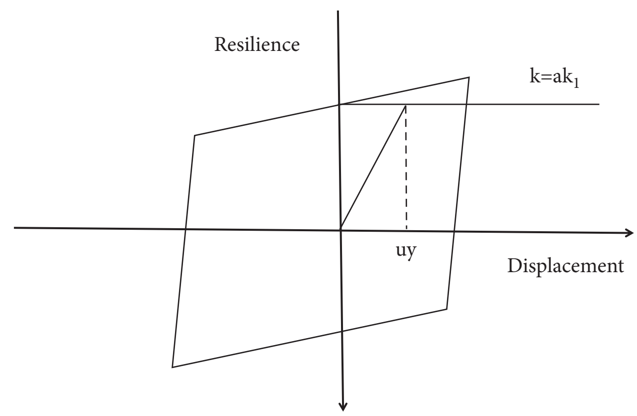

Figure 1: Displacement-restoring force curve of the bilinear model.

where $x_{\mathrm{ew}}(t)$ is the east-west displacement, and $x_{\mathrm{ns}}(t)$ is the north-south displacement.

The sensitivity analysis of model parameters is to study the change of model output response value through the change of input parameter value, and it can be divided into proportional change of parameter value, quantitative change of parameter value, and qualitative change of parameter value. The influence of parameter variation of the hysteresis model on structural response was analyzed by the single parameter variation method. Among them, the parameter value proportional change analysis method is easier to implement, and the result analysis is more intuitive and simple. Therefore, this paper adopts the parameter value proportional change analysis method to analyze the parameter sensitivity in the generalized Bouc–Wen model of the rubber isolation bearing and only changes each time. One parameter, the one-parameter proportional change analysis method, is proportional to the change of the parameter, while the other parameters are fixed. This method has the advantages of small calculation and easy graphical analysis. With the increase of shear deformation, the vertical displacement also increases gradually; that is, the vertical displacement increases with the increase of shear deformation, and the horizontal shear displacement at this time has a certain influence on the vertical stiffness; that is, the vertical stiffness increases with the increase of shear deformation. There is a decreasing trend with the increase of shear deformation. In the implementation process of this method, a parameter variation interval, namely parameter domain, should be defined for each parameter first. Generally, these parameter domains should consider the variation range of model parameters describing the hysteresis characteristics of the structure and be selected and determined in combination with the test. There is no fixed limit. According to the existing literature, the parameter variation range is set as 50% of the base value.

3. Experimental Analysis

In order to verify the practical feasibility and effectiveness of the AEKF method proposed in Chapter 3, this chapter conducts experimental verification research on structural damage identification. In the experiment, the rubber isolation bearing is first used to establish the experimental model of the rubber isolation layer, and the Bouc–Wen model is used to simulate the hysteresis nonlinear characteristics of the isolation layer, using excitation equipment to apply foundation excitation to the isolation layer, and the acceleration signal of the foundation and the acceleration response signal of the isolation layer are measured, the measured data are analyzed by using EKF method, and the parameters of the isolation layer, including stiffness, damping, and hysteresis parameters, are identified. Secondly, a superstructure is added to the rubber isolation layer to build the rubber isolation structure. The high damping rubber bearing absorbs and consumes seismic energy through shear deformation and has obvious viscoelastic properties under dynamic action. The restoring force curve refers to the force-deformation relationship curve formed by the support under the action of dynamic force. Since the hysteresis curve in the test results of the high damping rubber bearing is usually crescent-shaped, it is difficult to define this curve accurately and cannot meet the requirements of structural analysis, so this actual restoring force curve is usually not used in earthquake analysis, but it is to seek a kind of restoring force curve model which is equivalent to its characteristics and convenient for mathematical expression. The experimental model of the rubber isolation layer is a mass block structure supported by four groups of eight rubber isolation bearings. The mass of the mass block is m = 110 kg. Two different seismic waves (El Centro and Kobe seismic waves) are used in the experiment. The vibration exciter and the sliding rail shaking table are used to simulate the foundation excitation. PCB3701 G3FA3 G acceleration sensor (sensitivity is 102 mV/g) and ASM WS10-250-1OV-L10 displacement sensor (sensitivity is 40 mV/mm) are installed. Acceleration response and displacement response are measured, in which the measured displacement curve is used to verify the feasibility and accuracy of the EKF method for parameter identification of rubber isolation bearings. The sampling frequency of all signals in the experiment is 500 Hz. The ultimate performance of the rubber bearing includes three aspects: the ultimate failure mode of axial compression is the tensile fracture of the internal steel plate; the ultimate failure mode of axial tension is the bonding failure between the rubber layer and the steel plate; the bearing appears as a whole under the compression shear state. Buckling is the limit sign.

The parameters of the Bouc–Wen model used to simulate the rubber vibration isolator mainly include six parameters $c, k, \alpha, \beta, \gamma$, and n through the parameter sensitivity analysis and the mechanical performance test of the rubber vibration isolator. Several Bouc–Wen hysteresis models and seismic wave excitations of different sizes were used to model the rubber isolation layer and identify parameters. Before the experiment, the frequency of the experimental model was measured, and its first-order frequency was 3.42 Hz, and the model was regarded as a shear beam model; according to the finite element method, the stiffness of the model can be obtained as 50.8 kN/m, and this finite element value will be used as a reference in the analysis of the experimental results of the isolation layer parameter identification.

During the experiment, El Centro seismic wave and Kobe seismic wave were, respectively, applied to the model foundation, and the measured foundation acceleration and the acceleration response of the isolation layer mass block are shown in Figures 2 and 3.

Considering that the Bouc–Wen model contains four hysteresis parameters, the motion equation of the isolation layer can be written as follows:

$$\left\{ m\ddot{x} + c\dot{x} + \alpha k x + (1-\alpha)kz = -m\ddot{x}\dot{z} = \dot{x} - \beta|\dot{x}||z|^{n-1}z - \gamma\dot{x}|z|^{n} \right\}. \tag{6}$$

The unknown structural parameter is $c, k, \alpha, \beta, \gamma, n$, and the generalized state vector is $Z(t) = \{x, \dot{x}, z, c, k, \alpha, \beta, \gamma, n\}^{T}$, and then, the system state equation and observation equation can be written as follows:

$$\dot{z} = \left\{ \begin{matrix} \dot{k} \\ \dot{\alpha} \\ \dot{x} \\ \ddot{x} \;\; \dot{z}\dot{c}\dot{\beta} \\ \dot{\lambda} \\ \dot{n} \end{matrix} \right\} = \left\{ \begin{matrix} & o \\ & o \\ \dot{x} & \\ -\ddot{x} \;\; -\dfrac{(c\dot{x} + \alpha k x) + (1-\alpha)kz}{m}\dot{x} - \beta|\dot{x}||z|^{n-1}z - \gamma\dot{x}|z|no & o \\ & o \\ & o \end{matrix} \right\} + w, \tag{7}$$

$$y = \ddot{x} + \ddot{x}_0 + v = -\frac{(c\dot{x} + \alpha k x + (1-\alpha)kz)}{m+v}, \tag{8}$$

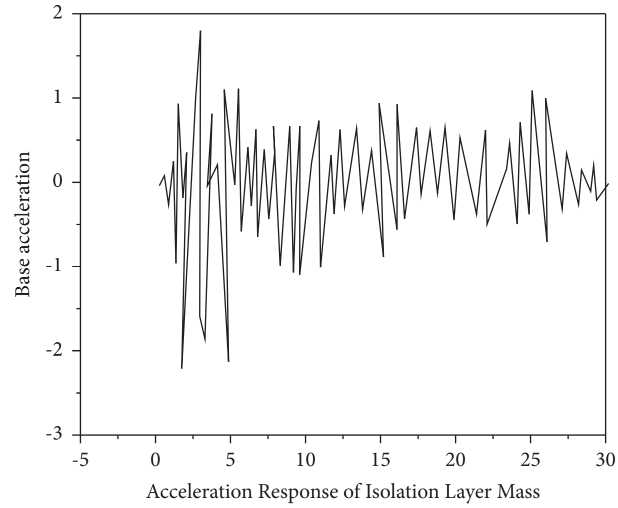

Figure 2: El Centro seismic wave excitation acceleration and response acceleration.

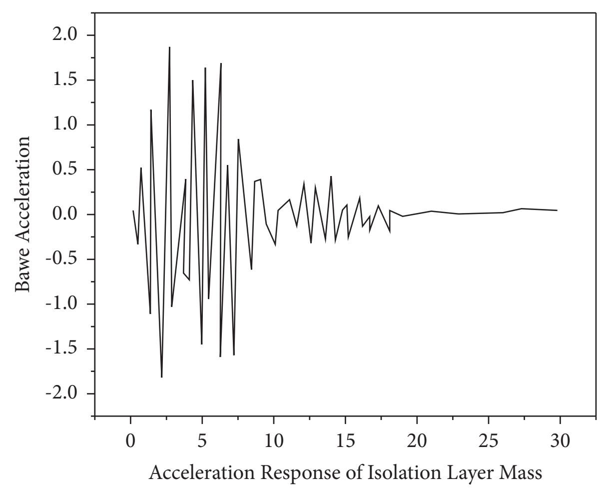

Figure 3: Excitation acceleration and response acceleration of Kobe seismic wave.

Table 1: Parameter identification results of rubber isolation layer model with different number of parameters under different seismic wave excitation.

Model parameter	Damp c (kNs/m)	Rigidity k (kN/m)	α	β	γ	n
The hysteresis parameters are known	El centro	0.26	52	-	-	-
	Kobe	0.21	49.8	-	-	-
Single-hysteresis parameter	El centro	0.23	48.6	-	-	-
	Kobe	0.26	49.0	-	-	-
Two-hysteresis parameters	El centro	0.21	49.2	-	-	2.00
	Kobe	0.26	49.1	-	-	2.01
Three-delay parameters	El centro	0.25	49.6	0.51	0.51	-
	Kobe	0.23	49.3	0.50	0.52	1.92

where $m = 125.53$ kg is the mass of the mass block, and v is the measured noise vector. The initial values of undetermined parameters are, respectively, $c_0 = 0.1\,\text{kN}\cdot\text{s/m}$, $k_0 = 40\,\text{kN/m}$, $\alpha_o = 5$, $\beta_0 = 0.5$, $\gamma_0 = 0.5$, $n_0 = 2$, all the other state variables start at 0, namely, $x_0 = 0$, $\dot{x}_0 = 0$, $z_o = 0$, and the initial value of the generalized state vector can be obtained.

In addition, taking the Kobe seismic excitation as an example, the parameter identification of isolation layer with different number of parameters under different excitation is studied, and the following four scenarios were considered: (i) the Bou–Wen model contains four unknown hysteresis parameters, namely α, β, γ, n, all the unknown, (ii) the BouO-WAN model contains three unknown hysteresis parameters, α, β, γ is unknown, $n = 2$, (iii) the BouO-WAN model contains only one unknown hysteresis parameter, α is unknown, $\beta = 0.5$, $\gamma = 0.5$, $n = 2$. The results of parameters identified in various cases are shown in Table 1. As can be seen from Table 1, when the excitation of local shock wave increases, the damping of the isolation layer decreases slightly and has little influence on other parameters of the isolation layer.

4. Conclusion

By using the Bouc–Wen hysteresis nonlinear model to analyze the hysteresis characteristics of rubber isolation bearings, the sensitivity of nonlinear parameters of the Bouc–Wen hysteresis model is analyzed, and the order of nonlinear parameters of the hysteresis model under different sizes of excitation is obtained. The adaptive sequential nonlinear least-squares (ASNLSE) method based on genetic optimization algorithm is derived; firstly, the numerical simulation of hysteresis nonlinear structures and base-isolated structures is carried out, and simulation results demonstrate the effectiveness and accuracy of the ASNLSE method in nonlinear structural parameter identification and damage tracking; then, the experimental research on damage identification of rubber isolation structure was carried out by using this method. Different seismic waves were used to carry out basic excitation on the experimental model of rubber isolation structure, a rectangular identification frame with a certain probability guarantee rate is used to realize multitype seismic damage classification and location, the average accuracy of the identification of concrete cracking and spalling, steel bar exposure, and buckling is more than 80%, and the average coverage rate is more than 88%. During the use of civil engineering structures, the working environment is constantly changing. Combined with the current damage identification and detection methods, the structure health monitoring system is established to accurately monitor the structure in real time, and rapid and accurate diagnosis of structural damage is of great significance to promote the practical development of structural damage identification methods.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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References

[1] D. C Du, H. H. Vinh, V. D. Trung, N. Quyen, and N. T. Trung, "Efficiency of jaya algorithm for solving the optimization-based structural damage identification problem based on a hybrid objective function," *Engineering Optimization*, vol. 50, no. 8, pp. 1233–1251, 2017.

[2] Y. Gao and K. M. Mosalam, "Deep transfer learning for image-based structural damage recognition," *Computer-Aided Civil and Infrastructure Engineering*, vol. 33, no. 9, pp. 748–768, 2018.

[3] T. Silva and N. Maia, "Detection and localisation of structural damage based on the error in the constitutive relations in dynamics," *Applied Mathematical Modelling*, vol. 46, no. jun, pp. 736–749, 2016.

[4] R. Ghiasi and M. R. Ghasemi, "Optimization-based method for structural damage detection with consideration of uncertainties- a comparative study," *Smart Structures and Systems*, vol. 22, no. 5, pp. 561–574, 2018.

[5] Z. Luo, L. Yu, H. Liu, and C. Pan, "Structural damage detection based on norm normalization and sparse regularization constraints," *Zhendong yu Chongji/Journal of Vibration and Shock*, vol. 37, no. 18, pp. 30–35, 2018.

[6] A. Kerschbaumer, D. Baker, J. S. Smolen, and D. Aletaha, "The effects of structural damage on functional disability in psoriatic arthritis," *Annals of the Rheumatic Diseases*, vol. 76, no. 12, pp. 2038–2045, 2017.

[7] L. W. Kong, M. Zang, and A. G. Guo, "Structural damage effect on dynamic shear modulus of zhanjiang clay and quantitative characterization," *Chinese Journal of Geotechnical Engineering*, vol. 39, no. 12, pp. 2149–2157, 2017.

[8] H. A. Ahmad, J. F. Baker, M Østergaard, J. Ye, P. Emery, and P. G. Conaghan, "Fri0513validating mri-detected inflammation thresholds predictive of structural damage progression in patients with rheumatoid arthritis in a randomized placebo-controlled trial," *Annals of the Rheumatic Diseases*, vol. 75, no. 2, pp. 624.2–624, 2016.

[9] S. Tayfur, C. Yüksel, N. Alver, O. Akar, and Z. Andi-Akr, "Evaluation of alkali–silica reaction damage in concrete by using acoustic emission signal features and damage rating index: damage monitoring on concrete prisms," *Materials and Structures*, vol. 54, no. 4, pp. 1–17, 2021.

[10] J. J. Marini, "Dissipation of energy during the respiratory cycle," *Current Opinion in Critical Care*, vol. 24, no. 1, pp. 16–22, 2018.

[11] S. K. Barman, M. Mishra, D. K. Maiti, and D. Maity, "Vibration-based damage detection of structures employing bayesian data fusion coupled with tlbo optimization algorithm," *Structural and Multidisciplinary Optimization*, vol. 64, no. 4, pp. 2243–2266, 2021.