CivilEng

MDPI

Review

A Review of Health Monitoring and Model Updating of Vibration Dissipation Systems in Structures

Neda Godarzi [1] and Farzad Hejazi [2,*]

[1] Department of Civil Engineering, University Putra Malaysia, Serdang 43400, Malaysia; neda.guodarzi@gmail.com
[2] Faculty of Environment and Technology, The University of The West England, Bristol BS16 1QY, UK
* Correspondence: farzad.hejazi@uwe.ac.uk

Abstract: Given that numerous countries are located near active fault zones, this review paper assesses the seismic structural functionality of buildings subjected to dynamic loads. Earthquake-prone countries have implemented structural health monitoring (SHM) systems on base-isolated structures, focusing on modal parameters such as frequencies, mode shapes, and damping ratios related to isolation systems. However, many studies have investigated the dissipating energy capacity of isolation systems, particularly rubber bearings with different damping ratios, and demonstrated that changes in these parameters affect the seismic performance of structures. The main objective of this review is to evaluate the performance of damage detection computational tools and examine the impact of damage on structural functionality. This literature review's strength lies in its comprehensive coverage of prominent studies on SHM and model updating for structures equipped with dampers. This is crucial for enhancing the safety and resilience of structures, particularly in mitigating dynamic loads like seismic forces. By consolidating key research findings, this review identifies technological advancements, best practices, and gaps in knowledge, enabling future innovation in structural health monitoring and design optimization. Various identification techniques, including modal analysis, model updating, non-destructive testing (NDT), and SHM, have been employed to extract modal parameters. The review highlights the most operational methods, such as Frequency Domain Decomposition (FDD) and Stochastic Subspace Identification (SSI). The review also summarizes damage identification methodologies for base-isolated systems, providing useful insights into the development of robust, trustworthy, and effective techniques for both researchers and engineers. Additionally, the review highlights the evolution of SHM and model updating techniques, distinguishing groundbreaking advancements from established methods. This distinction clarifies the trajectory of innovation while addressing the limitations of traditional techniques. Ultimately, the review promotes innovative solutions that enhance accuracy, reliability, and adaptability in modern engineering practices.

Keywords: structural health monitoring; damages detection; high damping rubber bearings (HDRB); model updating; frequency domain response

check for updates

Academic Editors: Angelo Luongo and Hugo Rodrigues

Received: 14 October 2024
Revised: 20 December 2024
Accepted: 9 January 2025
Published: 13 January 2025

Citation: Godarzi, N.; Hejazi, F. A Review of Health Monitoring and Model Updating of Vibration Dissipation Systems in Structures. *CivilEng* **2025**, *6*, 3. https://doi.org/10.3390/civileng6010003

1. Introduction

The structural health monitoring process (SHM) includes modal parameter variation identification, damage detection, time history analysis, and finite element model updating, which help to provide safety for structures. In the process of monitoring, to account for dynamic loads, accelerometers are installed at various structural locations to evaluate the isolation system performance. The acceleration data are used as input for the analytical program. Modal parameters, including frequencies, mode shapes, and damping ratios, acquired from both isolated and non-isolated systems show the effectiveness of dissipating devices on structural seismic performance. With the advancement of technology in the production of sensors and data capture and transmission, many efforts have been made to use this tool to control the performance of structures to increase service life and their safety. In addition, as isolators and energy-absorbing devices located in the superstructure make buildings resilient under strong ground motions, seismic isolation efficiency is discussed by structural health monitoring operations in this manuscript. This review paper aims to assist newcomers, practitioners, and researchers in navigating various techniques, including monitoring methods, their applications, and damage detection methodologies. The most prominent studies are reviewed and classified into the following subtopics: structural vibration dissipation systems, the effect of damaged dampers on structural frequencies, health monitoring of structures using frequency domain response, model updating of vibration dissipation systems, damage detection in structural systems, and health monitoring with satellites. Moreover, it offers a comprehensive review of prevalent anomaly detection, damage detection, damage localization, and residual life estimation in SHM approaches. Additionally, the paper addresses challenges in vibration-based methods and the application of various techniques. Tariq Amin Chaudhary, M. et al. (2000) applied the system identification method (SI) and acquired bridge parameters which are equipped with high damping rubber bearings (HDRB) and side stoppers at both sides of HDRB, considering several earthquake accelerations [1]. Using a multiple-input multiple-output (MIMO) health monitoring approach, Siringoringo, D., and Fujino, Y. (2017) evaluated the function of a cable-isolated bridge against ground vibrations during a 20-year period. The findings demonstrated that while long-term monitoring might reveal different parameters of rubber bearing, such as the lateral pounding phenomena caused by earthquakes, the majority of the recordings were redundant [2]. In order to determine the impact of damage on the isolated bridge's modal parameters as a result of ambient vibrations, pedestrian traffic, and hammer strikes, Tarozzi, M. et al. (2020) carried out the process of bridge damage detection both numerically and experimentally. Through the use of both Stochastic Subspace Identification (SSI-COV) and Frequency Domain Decomposition (FDD), they were able to extract the frequency and mode shapes [3].

Implementing a health monitoring system on a suspension bridge involves several systematic steps to ensure safety, functionality, and efficiency in detecting structural issues. Figure 1 illustrates the suspension bridge's health monitoring steps as follows:

(1) Accelerometers: To detect vibrations or movements.
(2) Installation Points: To place sensors strategically in critical areas (e.g., joints, supports, load-bearing elements).
(3) Data Acquisition System: To set up hardware and software for continuous or periodic data collection.
(4) Signal Processing: To filter and process raw data for clarity and accuracy.
(5) Condition Assessment and Maintenance Recommendations: To categorize the structure's health (e.g., good, at-risk, critical) and then propose repairs, reinforcements, or component replacements.

Iacovino, C. et al. (2018) introduced the Interpolation Evolution Method (IEM) for localizing damage in structures subjected to seismic excitation. IEM combines the Interpolation Method (IM) and the Curvature Evolution Method (CEM) to enhance accuracy in detecting and localizing damage. IM uses interpolation errors to identify changes in stiffness without calculating curvature, while CEM extracts nonlinear vibration modes using a band-variable filter. The combined method was tested on numerical models of multi-story buildings and experimental data from shaking table tests on reinforced concrete frames. Results demonstrate the effectiveness of IEM in accurately localizing damage in both controlled and real-world conditions, overcoming challenges of noise and nonlinearity [4].

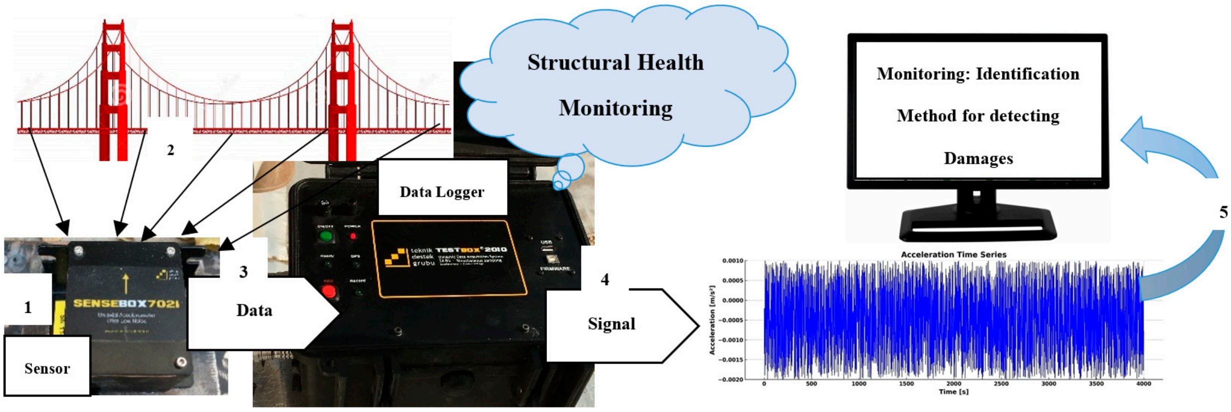


Figure 1. Various stages of this review's structural health monitoring mechanism.

Aloisio, A. et al. (2023) focused on vibration issues in timber structures, emphasizing their lightweight nature and resulting susceptibility to vibrations. It categorizes research into floor systems and whole buildings, highlighting challenges and advancements in vibration mitigation techniques, dynamic modeling, and serviceability criteria. Cross-Laminated Timber (CLT) floors and composite timber floors are extensively analyzed for their unique properties, vibration behaviors, and optimization strategies. The study underscores gaps in the current research, such as the need for improved modeling, better integration of acoustic and vibration factors, and multi-criteria optimization methods. It provides guidance for researchers, designers, and regulatory bodies to enhance the design and performance of timber structures [5].

Zar, A. et al. (2023) explored vibration-based structural damage detection (SDD) methods for civil engineering structures, highlighting advancements in Machine Learning (ML) and Deep Learning (DL) techniques. It emphasizes the transformative impact of Convolutional Neural Networks (CNNs) in feature extraction and computational efficiency. The study identifies challenges, such as data scarcity, algorithm overfitting, and the inherent nonlinearity of civil structures under diverse loads. It discusses limitations in validation metrics like MAC, MAE, and RMSE and the complexities of inverse analysis due to noise and limited data. Recommendations include integrating real-world data with simulated scenarios, developing universal validation standards, and adopting unsupervised algorithms to enhance SDD methodologies. The findings provide a comprehensive reference for improving structural health monitoring systems and advancing resilient infrastructure design [6].

Nakamura, Y et al. (2009) designed a six-story seismic isolated building by installing six base isolators on the upper of each column to protect the structure against earthquakes. A 3D model of the steel structure and the stiffness of the rubber bearings was created, and when an artificial earthquake was conducted, the reactions of the structure were discovered [7]. Siringoringo, D., Fujino, Y. (2015) examined the serviceability performance of a base-isolated from 2010 to 2012 against approximately 140 earthquakes. They evaluated the modal parameters of the structure before and after the earthquake to detect the damage and the effect of asymmetricity on the long-term seismic response [8]. On the other hand, by employing a structural health monitoring technique and input–output records, Siringoringo, D., and Fujino, Y. (2015) assessed the vibration dissipation building efficiency against real earthquakes and determined the structure's modal parameters over the course of a year [9].

Structural health monitoring is a proactive approach that not only ensures safety but also promotes sustainability, efficiency, and technological advancement. The most important benefits of structural health monitoring procedures are gathered in Figure 2.

Figure 2. Objectives of structural health monitoring.

To assess the bridge's seismic behavior under different seismic excitations in both the undamaged and damaged bearing states, Kim, S. et al. (2006) enhanced the bridge analytical model taking bearing damage into consideration. The results showed that while both flexible and rigid bearings may sustain damage from an earthquake's acceleration, the use of fixed bearings increased relative displacement [10]. Hedayati Dezfuli, F., Shahria Alam, M. (2017) extracted the probability of damage in a three-span steel bridge which was equipped with various isolation systems. The 3D bridge was modeled using software, and thirty excitations were applied. The seismic susceptibility of the bridge pier and elastomeric bearings was then assessed using fragility functions [11]. An inverse analytic technique was developed by Siringoringo, D. and Fujino, Y. (2018) to evaluate bearing behavior under a range of ground movements. Through the identifications approach, the bridge's modal parameters were obtained. The findings demonstrated that, at high acceleration intensities, the presence of friction force increases damping and decreases natural frequency because the bearing slid and stiffness decreased [12].

Figure 3 shows a schematic representation of the Structural Health Monitoring System's components.

In order to monitor and diagnose the condition of structures, vibration-based techniques are essential. The use of vibration-based approaches is being revolutionized by open-source algorithms, which provide accessibility, scalability, and potential for cooperation. The combination of vibration-based techniques with open-source algorithms offers immense potential for cost-effective, scalable, and accurate structural health monitoring. These methods enable engineers and researchers to monitor structural integrity, predict failures, and ensure safety efficiently. However, vibration-based techniques have been reviewed extensively, and this study classifies the methods for vibration-based evaluations and the application of various techniques, including the role of open-source algorithms, in Table 1.

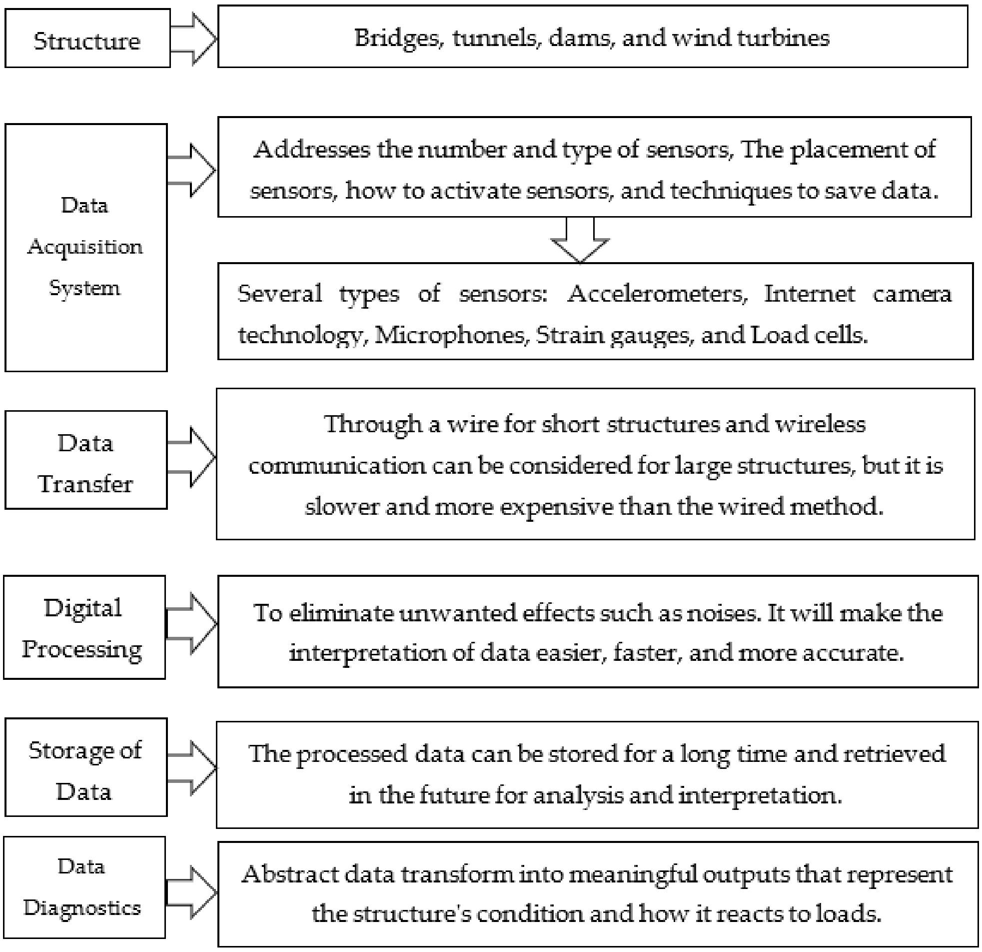


Figure 3. Structural Health Monitoring System's components.

Bandara, R. et al. (2014) developed a combination algorithm including artificial neural networks (ANNs), frequency response function (FRF), and principal component analysis (PCA) for structural damage identification without the need for considering noise uncertainty measurements. By simulating a two-story building, they investigated the processes and confirmed that, under various damage scenarios, the process of health monitoring and damage identification can be completed in a shorter amount of time with acceptable precision [13]. A 3D steel frame structure with four viscous dampers at the beam–column joints was built by Xie, B. et al. (2019) in order to assess multiple damage scenarios in structural health monitoring using two distinct sensors. They demonstrated that the results of monitoring processes using piezoelectric sensors and cellphones with acceleration response are the same [14]. Kildashti, K. et al. (2020) determined the location and degree of damage to cable-stayed bridges that are susceptible to dynamic stresses from moving cars. After formulating the association between the bridge and the car, they used bridge software modeling to apply many damage states and validate it numerically [15].

When monitoring a suspension bridge, Nagayama, T. et al. (2005) took into account ambient vibration. They employed measured records, using the ERA approach independent of damping and stiffness, to determine modal parameters. They then used an inverse methodology to extract noise from modal data [16]. A novel technique called refined Frequency Domain Decomposition (FDD) was created by Pioldi, F. et al. (2015) to identify the modal properties of structures using seismic recordings as an input. They used MATLAB software to design the rFDD method for a multi-story building and demonstrated its benefits over the FDD technique by demonstrating that rFDD can predict a high damping ratio whereas FDD requires white noise as input and is unable to display a damping ratio [17].

Table 1. Vibration-based methods and the application of various techniques.

Technique	Purpose	Open-Source Tools/Libraries	Algorithms	Applications
Frequency Domain Decomposition (FDD)	Identify natural frequencies and mode shapes	MATLAB Toolboxes (OpenModal), Python (SciPy)	Singular Value Decomposition (SVD), FFT (Fast Fourier Transform)	Bridges, buildings, and offshore platforms
Stochastic Subspace Identification (SSI)	Extract modal parameters (frequencies, damping, mode shapes)	MATLAB Toolboxes (OpenModal)	State-space modeling	High-rise buildings, wind turbines
Wavelet Transform Analysis	Detect localized anomalies or non-stationary signals	PyWavelets, WaveletComp	Continuous Wavelet Transform (CWT), Discrete Wavelet Transform (DWT)	Wind turbine blades, bridge cables
Modal Assurance Criterion (MAC)	Compare and validate mode shapes	MATLAB Toolboxes (OpenModal)	Correlation-based comparison	Modal shape validation in bridges and dams
Time Series Analysis	Predict and analyze trends in vibration data	Python (SciPy)	Auto-Regressive (AR) models	Time-varying systems like machinery or turbines
Peak-Picking Method	Quick estimation of natural frequencies	Python (NumPy, SciPy)	Peak detection in FFT	Preliminary analysis of simple systems
Energy-Based Methods	Evaluate changes in vibration energy	Python (Librosa, SciPy)	Short-Time Fourier Transform (STFT), Hilbert Transform	Machinery fault detection, seismic monitoring
Machine Learning Approaches	Pattern recognition and damage classification	Python (TensorFlow, PyTorch)	Neural networks, Support Vector Machines (SVM), Random Forests	Damage detection in complex structures
Frequency Response Functions (FRF)	Analyze structural response to dynamic loads	OpenSees, MATLAB Signal Processing Toolbox	Transfer function analysis	Earthquake response monitoring in buildings
Dynamic Time Warping (DTW)	Compare time-series signals for anomalies	Python	Elastic matching algorithms	Monitoring systems with repeated operational cycles

Implementing SHM in complex structural environments, such as high-rise buildings or infrastructure in seismically active zones, presents significant challenges. In high-rise buildings, traditional wired sensor systems are often impractical due to the difficulty in routing cables through large, complex structures. This challenge is addressed by wireless sensor networks (WSNs), which offer easier installation and greater flexibility. However, the deployment of these systems in tall buildings also involves considerations regarding sensor density, power supply, and data transmission distances. In seismically active areas, SHM systems must be robust enough to handle dynamic and unpredictable forces, which can complicate sensor calibration and data interpretation. Advanced techniques such as integrated monitoring systems and real-time data analytics are increasingly used to address these challenges. These systems can help detect damage in real time, improving safety and maintenance efficiency while reducing long-term costs. For instance, Ye, X. et al. (2012) explored the use of distributed strain sensor networks in a high-rise building construction project in China, where they installed 224 wireless strain gauges to monitor stress changes during critical construction phases. Their real-time monitoring system proved essential for assessing the safety of the structure [18]. Similarly, Yi, T. et al. (2012) demonstrated the effectiveness of GPS-based monitoring technology in tracking real-time deformations in high-rise buildings. By analyzing the building's response to environmental factors like wind and seismic activity, their study highlighted GPS as a reliable tool for assessing structural stability and detecting potential issues in real time. These studies underscore the importance of real-time SHM systems in ensuring structural safety and optimizing maintenance in challenging environments [19].

Pan, Y.. et al. (2020) conducted an ambient vibration test on a real building and used FDD and EFDD analysis to extract modal parameters. They then used software to model a complex tall building with a basic construction and obtained data on frequency, mode shapes, and damping ratio [20]. Hejazi, F. et al. (2016) developed a numerical viscous wall damper (VWD) model that not only decreases the structure responses and strengthens the building's performance against earthquakes, but also can detect damage in the structure. Their findings proved the significant role of the damping coefficient on VWD structure proficiency [21].

FDD is a robust algorithm used for modal identification in structural health monitoring. It analyzes the structural response in the frequency domain to extract modal parameters such as natural frequencies, damping ratios, and mode shapes. A summary of the mechanism of the FDD identification method is shown in Figure 4.

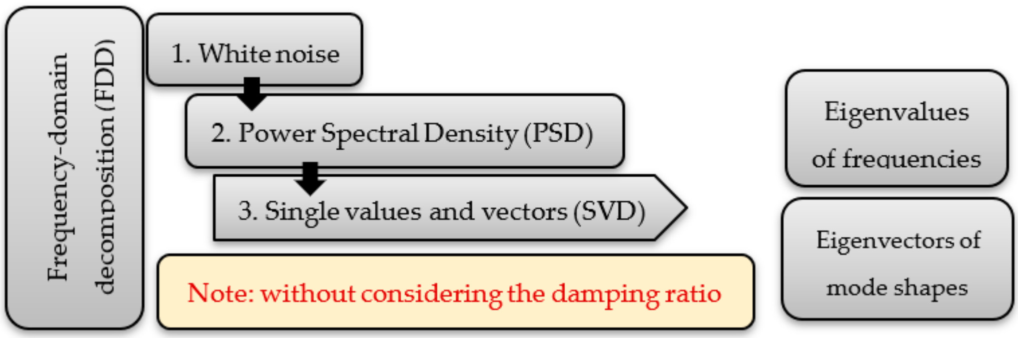


Figure 4. Frequency Domain Analysis Detection process algorithm (FDD).

The FDD algorithm is a powerful tool for modal analysis and structural health monitoring, particularly in systems with ambient excitation and limited resources for active testing. However, its effectiveness may be limited by its assumptions about linearity, excitation parameters, and frequency resolution. The FDD approach is highly accurate in estimating natural frequency values; however, it is not particularly accurate at calculating damping ratios. Unlike FDD, SSI works in the time domain and provides damping ratios directly. SSI is a time-domain method widely used in structural health monitoring (SHM) to identify a structure's modal properties (natural frequencies, damping ratios, and mode shapes) based on output-only data (response data). It is particularly effective for ambient vibration monitoring where external excitation forces are unknown or unmeasured. SSI involves processing vibration data to identify dynamic parameters of structures. It is based on a state-space representation of the structure's response and is particularly useful for monitoring large civil infrastructure like bridges, buildings, and towers. Steps in the SSI Process are summarized as follows:

(1) Time-series data, often under ambient excitation (e.g., wind, traffic, or seismic activity), are collected.
(2) The collected time-series data are organized into a structured matrix called the Hankel matrix; this matrix represents the dynamic behavior of the system. Modal parameters are extracted through these matrices.

Table 2 presents the results of a thorough comparison between FDD and SSI.

Table 2. Advantages, disadvantages, similarities, and differences between the two FDD and SSI methodologies.

	Advantages	
Aspect	**FDD**	**SSI**
Simplicity	Easy to implement and interpret.	Provides detailed results, including natural frequencies, mode shapes, and damping ratios.
Computational Efficiency	Fast and less resource-intensive compared to SSI.	Handles large datasets and can process complex systems accurately.
Visualization	Peaks in the frequency spectrum are straightforward to identify.	Stabilization diagrams enable precise validation of modal parameters.
Suitability for Ambient Vibration	Effective for ambient vibration monitoring where excitation forces are unknown.	Well-suited for ambient vibration monitoring, even under challenging conditions.
Applications	Ideal for preliminary modal analysis and quick frequency identification tasks.	Suitable for detailed modal analysis and systems with closely spaced modes or time-varying properties.
	Disadvantages	
Aspect	**FDD**	**SSI**
Damping Ratios	Cannot estimate damping ratios directly (requires Enhanced FDD for damping estimation).	Provides damping ratios directly but requires more computational effort.
Accuracy in Complex Systems	Struggles to resolve closely spaced modes or modes in high-noise environments.	Resolves closely spaced modes effectively but may require careful selection of model order.
Noise Sensitivity	Susceptible to significant noise in the frequency domain, potentially masking peaks.	Less sensitive to noise but relies on preprocessing and appropriate parameter selection for best results.
Mode Tracking	Does not explicitly track time-varying properties or systems under dynamic changes.	Can handle time-varying systems with appropriate modifications, making it more versatile for real-time monitoring.
Ease of Use	Simpler to implement but provides less comprehensive modal information.	Requires expertise for interpretation, particularly for stabilization diagrams and system matrix computations.
Visualization Challenges	Overlapping peaks in the frequency spectrum may make mode differentiation challenging.	Stabilization diagrams can be difficult to interpret for users without experience.
Applications to Nonlinear Systems	Less effective for nonlinear or time-varying systems.	While primarily designed for linear systems, it can adapt to nonlinear or time-varying conditions with suitable modifications.

Table 2. *Cont.*

	Similarities	
Aspect	**FDD**	**SSI**
Purpose	Both methods are used to extract modal parameters that extensively used in SHM applications for buildings, bridges, wind turbines, and other large-scale infrastructure.	
Output-Only Techniques	Both can work effectively with ambient vibration data (without requiring knowledge of excitation forces.)	
Non-Destructive	Both methods are non-invasive and allow for continuous monitoring without altering the structure or requiring a controlled excitation source.	
Applicable to Complex Systems	Both can handle multi-degree-of-freedom (MDOF) systems and structures with multiple modes.	
Noise Robustness	Both techniques are robust against moderate noise levels and can differentiate noise from true modal signals.	
Sensor Data Use	Both rely on data collected from sensors like accelerometers, strain gauges, or displacement sensors placed on the structure.	
Stability Checks	Both use tools to validate modal results, such as stabilization diagrams in SSI or peak analysis in FDD.	
	Differences	
Aspect	**FDD**	**SSI**
Operating Domain	Operates in the frequency domain, using the Power Spectral Density (PSD) matrix of the response.	Operates in the time domain, directly using time-series response data.
Input Requirement	Relies on response data with ambient excitation (assumes excitation is broadband or white noise).	Uses response data without assumptions about excitation type, though ambient excitation is typical.
Accuracy and Resolution	Good for identifying natural frequencies and mode shapes; less accurate for damping ratios.	High accuracy for natural frequencies, damping ratios, and mode shapes, even for closely spaced modes.
Computational Demand	Computationally efficient and quicker due to fewer data processing steps.	Computationally intensive, especially for large datasets or high model orders.
Suitability for Linear Systems	Best suited for linear, time-invariant systems under steady conditions.	Handles linear systems and can adapt to time-varying systems with proper modifications.
Closely Spaced Modes	Struggles to resolve closely spaced modes if peaks overlap in the frequency spectrum.	Accurately resolves closely spaced modes using advanced decomposition techniques.
Data Preprocessing	Requires preprocessing to compute the PSD matrix and filter noise.	Time-domain signals are processed directly; preprocessing focuses on noise reduction.
Visualization	Produces a singular value spectrum with peaks at natural frequencies.	Produces stabilization diagrams, showing stable poles across different model orders.

This is a brief review of the mechanism of damping against dynamic loads while implementing an identification method on raw vibration data acquired from structural health monitoring with accelerometers. Moreover, published results revealed damage existence by comparing structural property changes such as frequency before and after monitoring. Past findings revealed that there are various traditional techniques in the damage identification approach which are summarized and scrutinized in Table 1 including modal analysis, finite element model updating, non-destructive testing (NDT), and structural health monitoring

(SHM) method. Details in Table 3 in this review paper help researchers to broaden their horizons and tackle novel applications regarding monitoring techniques in the structural health monitoring domain. While SHM systems consist of various stages, feature extraction, and pattern recognition steps are the most important; therefore, the most optimal, practical, and reliable identification method can be defined in each project.

Table 3. Various monitoring techniques details.

Methods	Modal Analysis	Model Updating	Non-Destructive Testing (NDT)	Structural Health Monitoring (SHM)
Description	Based on how the modal parameters (frequency, mode shapes, and damping) of damaged and un-damaged structures differ from one another.	Modal parameters are extracted using a finite element computational method. Finite element model results are compared with the experimental results.	Through the use of wave parameters, damage within a structure can be identified by tracking how various wave types interact with the regarded building.	By vibration-based damage identification, any damage to a structure will change its mass, energy dissipation, or stiffness, which will change the structure's measured dynamic response.
Applications	High degree of accuracy.	Easily applicable in the real world.	Improve visual inspection to detect damage via manual operation.	Even in situations when the precise position of the damage is unknown or inaccessible, both damage locations and damage extents can be determined by vibration-based approaches.
Drawbacks	Susceptible to signal noise being present. Uncertainties brought on by variable environmental changes and inconsistent boundary conditions.	Need a thorough comprehension of the structure parameters as well as an excellent computational effort.	Be appropriate just for evaluating damage in local areas. Unapplicable in complex structures. damage location should be known.	It is essential that the structure's material properties be available precisely. In super-tall structures and complicated structures identification results show low accuracy in determining damage location and damage values.
Methodology	FDD-SSI-EFDD-rFDD-MIMO	Optimization algorithm like Genetic Algorithm—Ensemble method—Artificial neural network—Bayesian model updating.	Thermography—Electromagnetic methods-Global positioning system (GPS)	Fourier transform-Wavelet transform-Hilbert–Huang transform
Future recommendation	As it is only appropriate for damage localization and detection; damage quantification can be performed through further research.	It is important to choose the model updating parameters carefully, to estimate and determine structure's dynamic parameters precisely.	Stochastic modeling of loading circumstances is typically impossible because of the short time event of NDT. More work is required to improve the resilience of the technique.	It is necessary to conduct additional research to tackle the challenges of implementing vibration-based damage detection techniques, especially for high-rise and complex structures. Such as optimizing the sensors' placement for precise structural damage forecasts.

2. Structural Vibration Dissipation Systems

Nowadays, base isolation systems are used extensively in order to decrease both inter-story displacement and acceleration demands by hysteretic energy dissipation. There are many types of base isolation systems installed in structures to strengthen structures against dynamic loads, including rubber bearings, high damping rubber bearings (HDRB), and lead-core rubber (LRB) systems which dissipate considerable energy due to their hysteretic material properties. Systems equipped with rubber bearings, by means of several layers of rubber not only are capable of supporting the vertical loads and providing the necessary lateral flexibility but also the core portion provides a large hysteretic damping force.

Kikuchi, M. and Aiken, I. (1997) constructed a numerical hysteresis model to predict a structures' dynamic response considering the existence of an isolation system. Additionally, various rubber bearings were tested experimentally and modal parameters were carried out.

Results verified the accuracy of the proposed analytical model in detecting the maximum seismic response of the isolated system and the dependency between force and displacement [22]. Based on the function that depends on the rubber's stiffness, Eibl, J. (1999) developed a rule for the seismic design of base-isolated structures employing high damping rubber bearings (HDRB). Researchers demonstrated the dynamic behavior of the HDRB under shear and tension analysis by applying the formulation in software while taking a dynamic load into account [23].

The nonlinearity of the action of High Damping Rubber Bearings (HDRBs) under axial load fluctuations was studied by Jankowski, R. (2004). Using the least-squares method, HDRBs were modeled as a nonlinear elastic spring-dashpot that was dependent on the strain rate of shear to determine device horizontal responses. It was discovered that the suggested model accurately represented HDRB behavior in a range of experimental tests as it might be a good representation of HDRB stiffness in deformation quantities [24].

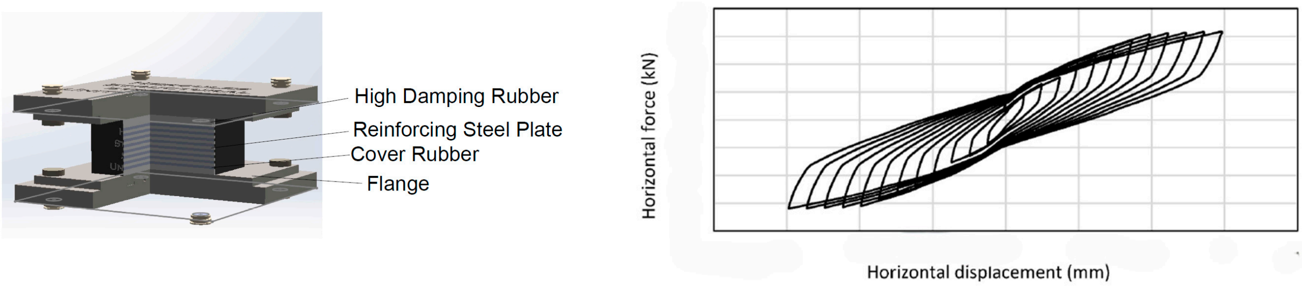
By adjusting the parameters of Wen's equation, Tsai, C. et al. (2003) proposed an analytical model that determines the properties of high damping rubber bearings (HDRB) under different excitations. Findings confirmed that, although the model can take velocity-dependent effects into account in the formulation, the experimental data exhibited a good consistency with the results of the analytical model [25].

In order to determine the HDR seismic performance under dynamic loads in the base-isolated system, Asta, A. and Ragni, L. (2006) proposed a model to simulate the behavior of HDR, which is made from natural rubber with additional damping nature and carbon filler. The model was then examined by shear strain and stretch tests. Studies on the Mullins effect on the stiffness, form, and energy-dissipating ability of rubber material came to the conclusion that more flexible rubber dissipates energy more effectively while deforming more readily [26].

The viscous wall damper (VWD) was used in a three-story building that Lu, X. et al. (2008) tested on a shaking table in order to determine the structure's seismic performance. According to reports, VWD may effectively dampen structural vibrations while simultaneously improving rigidity, which reduces structural reactions. By using SAP software 2000 v11 to simulate an analytical finite element model, they further validated the experimental results [27].

Using computer software, Hejazi, F. et al. (2009) examined the behavior of a non-isolated system and a seismically isolated three-story concrete building with a viscous damper under accelerations caused by earthquakes. They observed that the existence of a viscous damper in the structure not only dissipates energy significantly (approximately 80%) but also decreases structural seismic responses [28].

Figure 5 illustrates the HDRB dissipating device along with its force-displacement response.



(a) (b)

Figure 5. (**a**) High-damping rubber bearing (HDRB) and (**b**) shear behavior in HDRB.

In their 2011 study, Lu, C. et al. examined the phenomenon of sliding in a bridge equipped with a dissipating device. A nonlinear bridge model simulation was used to investigate the effectiveness of rubber bearings in the face of ground accelerations. Following the earthquake, the friction coefficient-dependent bearing sliding nature not only restricted transmission of the seismic load to the substructure but also transferred force-resisting capacity to the isolation system; therefore, damage in columns decreased [29].

Thiravechyan, P. et al. (2012) probed the superstructure's yielding due to the occurrence of a strong earthquake which may lead to a strike to walls in the vicinity of the isolation system. To simulate the seismic behavior of the structure an analytical model of a five-story building instrumented with isolators was developed. Findings verified that when the strength of the superstructure decreased, more energy was absorbed by the superstructure and caused that isolation displacement to reduce [30].

Li, Y. et al. (2013) examined the high damping rubber bearing's (HDRB) significant seismic function with regular rubber bearings' (RBs) in a multi-span bridge while taking earthquake excitations into account. Following time history analysis of the FE model, it was shown that RBs were vulnerable to shear and displacement failure, but HDRBs could tolerate failure against both shear and displacement, hence preventing residual deformation at bearings [31].

The effectiveness of additional damper devices such as base isolation, viscous damper, and friction damper independently on four-story steel structures subjected to ground vibrations was examined by Moghadam, A. et al. (2015). A comparison of the analytical findings showed that while friction dampers dispersed energy more than two other types of dampers, base isolation systems were more effective than other dissipating energy systems in lowering base shear in the structural system. Furthermore, although a base isolation system helps reduce drift on lower levels, friction and viscous dampers also contribute to a reduction in drift on upper floors [32].

In order to investigate the effectiveness of isolation system features on the seismic function of three, nine, and twenty-story structures equipped with dampers, Chimamphant, S., and Kasai, K. (2015) built a finite element model. The results from the dissipating system were compared to structures without additional damping devices, and it was found that high periods in the isolated building reduced acceleration and displacement regardless of the number of stories or amount of damping. This was because the flexible bearing in the isolated building dissipated energy instead of the superstructure, demonstrating the isolated building's superiority over the rigid structure [33].

Using nonlinear computational analysis in finite element software, Arya, G. et al. (2015) examined the seismic behavior of high damping rubber bearings (HDRB) under earthquake acceleration. Findings proved that the insulator, which is around 3.5 times thicker than the rubber layer, can tolerate movement while remaining stable [34].

Gajewski, M. et al. (2015) exhibited hyperelasticity properties through an elastomer model in ABAQUS software (6.12) to reveal the incompressible rubber feature. Findings defined that The Yeoh model gave more accurate and rational outputs in comparison to the neo-Hookean model since it showed elastomers function in the wide range of deformation data considering past results obtained from the experimental tests [35].

Using a shaking table and artificial excitations, Oh, J. et al. (2016) determined the bridge's damping capacity in two states: with and without a high damping rubber bearing (HDRB). Outputs revealed that the bridge with HDRB has a larger dissipation capacity, which allows it to reduce shear force more than the bridge without isolation equipment. The results demonstrated that the HDRB's damping ratio is dependent on both frequency and surface pressure, while shear stiffness depends on shear strain. Therefore, shear strain should be considered in designing the shear stiffness of an HDRB [36].

Figure 6 compares the deformation of the building under the two scenarios: without damping devices in the structure and with an isolation system.

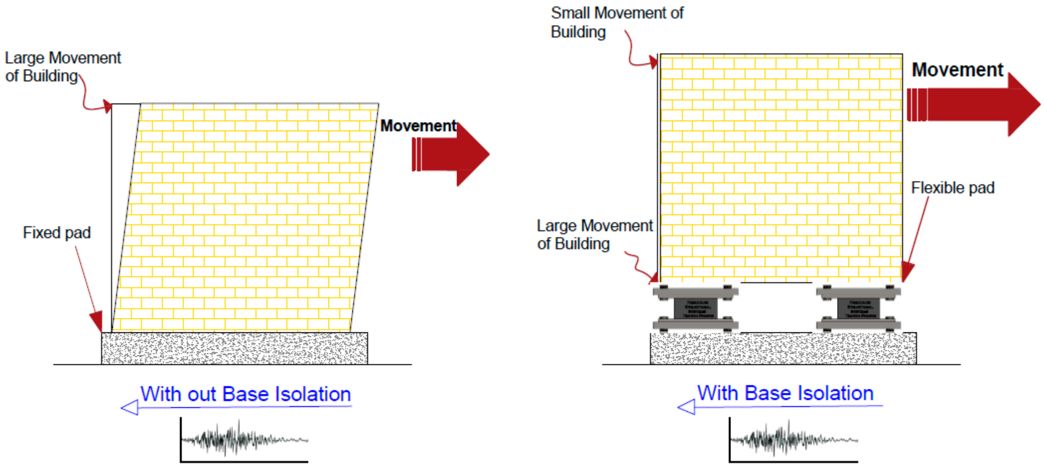


Figure 6. The act of base isolation.

The mechanical behavior of high damping rubber bearings (HDRBs) during shear and compression testing was investigated by Markou, A. et al. (2016). An HDRB model comprised four components: a nonlinear elastic spring, two elastoplastic elements, and a hysteretic damper, in that order, and was simulated under strain conditions with amplitudes of strain that were around 200% intense.

According to experimental findings, when strain intensity rose, damping and stiffness also increased, limiting the displacement when severe dynamic loads were taken into account [37].

Li, Y. et al. (2017) constructed a bridge equipped with a high damping rubber bearing (HDRB) to test its mechanism on the shaking table. The results showed that when the pressure stress reached to 10 MPa or shear strain exceeded from limitation, although the rubber bearing stayed stable but its large deformation did not back to its initial condition and then structural damage may happen [38].

In the beam–column connection, Ebrahimi, E. et al. (2018) suggested and tested a high damping natural rubber (HDNR) device, taking excitations into account. The results of the analytical model determined that the energy dissipation capability was reduced due to the increase in rubber thickness whereas, the amount of rubber layers had little bearing on HDNR performance [39]. Zhang, Y. (2018) compared the seismic behavior of high damping rubber bearing (HDRB) with laminated rubber bearing in a bridge by means of nonlinear time-history analysis in numerical software. Results revealed that considering

HDRB, bridge seismic response was reduced more than system isolated with laminated rubber bearing [40].

The structural seismic response to artificial excitations in both isolated and non-isolated states was studied by Xu, W. et al. (2019). Data acquired showed that while both the structure period and the damping ratio rose, the use of laminated rubber bearings in a two-story spatial structure decreased superstructure response in a horizontal direction. Furthermore, the efficacy of the isolation system in the lateral condition improved as the vibration intensity rose [41].

Zhang, Y. and Li, J. (2020) inspected the effects of various damping ratios in high damping rubber bearing (HDRB), by analyzing a two-span simply supported beam bridge with a time-history dynamic technique considering the Northridge earthquake. The extracted results discovered that not only did the increment of damping in the isolation system lead to the decrement in the superstructure's seismic response, but it also reduced rubber's horizontal shear force and displacement [42].

An analytical model was created by Grant, D. et al. (2004) to investigate the performance of a bridge with high damping rubber bearings (HDRB) under varied earthquake accelerations. The results proved the impact of pier flexibility in reducing structural displacement by extracting the nonlinear behavior of isolated bridge piers at strong earthquake intensity [43].

Labiba, A. and Muntasir, A. (2020) conducted a nonlinear time history analysis to examine the long- and short-term effects of ground excitations on the piers base shear, deck acceleration, bearing displacement, and rubber's ability to dissipate energy while taking into account different structural vibration dissipation systems. Findings represented that increasing the applied dynamic load's duration on the rubber bearing bridge caused an increase in seismic response, which in turn caused structural damage [44].

The base-isolated structure seismic response mechanism with a fluid viscous damper acting as an external damper device was assessed by Deringol, A. and Güneyisi, E. in 2021. An examination of the time history of a ten-story building was conducted considering different periods, damping coefficients, and damper installation sites. Hysteresis loops showed that drifts reduced, particularly at the lower damping coefficient values, whereas longer periods and higher damping coefficients showed increased displacement [45].

Also, the effectiveness of varying the isolation period, effective damping ratio, and post-yield stiffness ratio values on the seismic structure response were investigated analytically by Deringol, A. and Güneyisi, E. (2021). Findings showed that, under low post-yield stiffness ratio levels, the isolation period and effective damping ratio values increased, speeding up the energy dissipation process [46].

3. The Effect of the Damaged Damper on the Frequency of Structures

Health monitoring and damage detection in structures play an important role in improving the performance of structures and preventing their overall collapse. Buildings equipped with damper devices, like other civil structures, need maintenance. Research and experience of past earthquakes show that after various earthquakes, we need structures that have less damage in dissipating systems against wind and earthquake, due to construction costs, damage to the structure to be identified in the shortest time and easily repairable.

According to Pan, P. et al. (2004), base-isolated buildings exhibit seismic responses when subjected to intense earthquake excitations that cause excessive horizontal deformation and the formation of a stroke between the isolation system and the nearby existing wall. Therefore, the lead-rubber bearing behavior was determined by applying dynamic movements to the software's analytical model. Findings showed that while the impact did not alter base isolation reactions, it did raise drifts in the superstructure and substructure [47].

To identify and evaluate the generated bearing damages and their impact on the performance of structures subjected to dynamic vibrations, Kasai, K. et al. (2013) examined the seismic functions of structures outfitted with isolation devices. The findings showed that while many dampers suffered from numerous problems, including bolt misalignment from rotation and the flaking bearing phenomena, these defects decreased the rubber's ability to dissipate energy; nonetheless, fractures prevented the dampers' parts from yielding. Furthermore, as the damping ratio dropped, the isolation system's displacement and acceleration both increased [48].

The effects of a damaged damper resulting from aging, ambient temperature, and scragging recovery were examined by Gheryani, M. et al. (2015) using different acceleration excitations to examine the nonlinear dynamic response of a vibration dissipation system with high damping rubber bearings HDRBs. As the response of the structure is dependent on changes in HDRB natures, when temperature decreases, the stiffness and strength of rubber bearings increase in structural response. This was discovered after implementing time-history analysis on a six-story building using modified coefficients on the software [49].

Yue, L. et al. (2018) assumed material nonlinearity behavior and explored damage bearing in conjunction with limit device states and their impacts on the bridge. Calculations showed that it is compulsory to consider the friction effect in the performance of movable support to lead to structure safety in strong excitations. Additionally, because the bridge has a limit mechanism, the displacement in the beams and the seismic response in the pier has decreased, and the influence of the seismic forces in the piers has diminished [50].

Xiang, N. et al. (2018) evaluated the damages to the bridge caused by sliding in laminated rubber bearings during earthquakes in the link between the superstructure and the substructure. They used a shaking table test to evaluate the effectiveness of many restraint systems, including those without any restraints, concrete shear keys, and yielding steel dampers. They came to the conclusion that while sliding at the bearing increased the displacement of the bearing and hindered the transfer of dynamic loads, the presence of restraining devices lowered the displacement of the bearing because of their potent energy-dissipating capabilities [51].

Wang, S.H. et al. (2021) evaluated the damaged viscoelastic damper application in terms of both stiffness and energy dissipation performance subjected to uniaxial reversal loading tests. The proposed analytical model revealed that the existence of a damaged viscoelastic damper in a structure is significantly applicable rather than a structure without any damper devices since results proved damaged damper is capable of reducing both structure displacement and acceleration [52].

4. Health Monitoring of Structures Using Frequency Domain Response

Methods for identifying system parameters have been considered by researchers over the past few decades with the development of modal testing as one of the useful tools for determining mode specifications. In general, system modal identification methods can be divided into two parts: input–output and output only. Figure 7 explains the process of modal analysis to determine the intrinsic dynamic properties of a system. This literature review describes both operational modal analysis (OMA) and experimental modal analysis (EMA). In OMA, the vibration of the real structure is recorded under operating loads, and the modal parameters, which are the frequencies, mode shapes, and damping of the structure, are obtained.

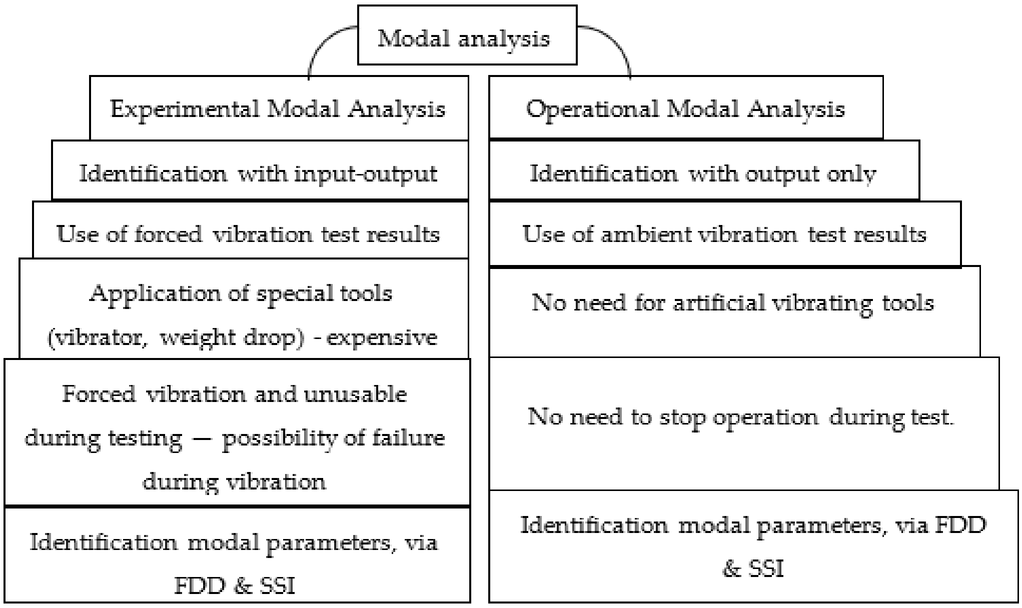


Figure 7. Modal analysis.

Brincker, R. et al. (2000) proposed the Frequency Domain Decomposition (FDD) method to identify modal parameters in the frequency domain by using ambient modal analysis. This method was surveyed to test on a two-story building and derived modal parameters even for close modes regarding the existence of signal noises [53].

Weng, J. et al. (2008) used wireless measuring equipment to identify the suspension bridge's dynamic properties using two approaches of random subspace and frequency domain analysis. Results shown that these approaches, when used in the process of health monitoring, are not only less expensive than other methods but also have the ability to accurately obtain modal properties [54].

Immediately following construction, Magalhães, F. et al. (2008) carried out a structural health monitoring test on a concrete bridge in both numerical and experimental modes to collect acceleration data due to ambient vibration. Then, using two analyses—one in the frequency domain, Frequency Domain Decomposition, and the other in the time domain, Stochastic Subspace Identification—the modal data were collected, including frequency, mode shapes, and damping ratio. Findings show that monitoring, by comparing modal findings from real monitoring with software outputs, is an effective technique to identify potential harm [55].

Altunisik, A. et al. (2012) compared two powerful methods of stochastic subspace and advanced frequency domain analysis, to identify a scaled model of a bridge beam in the laboratory. In this study, sensors were installed on the laboratory-made beam model utilizing the shock excitation function to cause vibrations. The research's findings also demonstrated the effectiveness of subspace techniques. Modal assurance criteria were used, which are well-recognized MAC criteria based on modal shape analysis, to indicate the occurrence of damage [56].

The dynamic properties of the Suspension Bridge were determined by Zhang, J. et al. (2013), taking into account uncertainties resulting from the ambient vibration testing. Therefore, the vibration analysis was used to derive modal parameters. The experimental data were then compared with the numerical model findings. The results presented good correspondence in the outputs, indicating that accurate subsystem connection modeling is crucial for reducing analytical uncertainty. Additionally, modal values from several identification techniques displayed the ambient test signal with the least amount of uncertainty [57].

Davis, N. and Sanayei, M. (2020) developed an identification method based on strain and acceleration data acquisition from bridge substructures subjected to traffic loads. Extracted results presented frequency response functions (FRFs), other structural parameters, and parameters of the foundation. Moreover, the proposed method showed a time-saving process while did not need specific experts for analysis [58].

Specific Frequency Shift Curves (FSCs) are a visual representation of the seismic performance of reinforced concrete structures based on frequency variation, as determined by Spina, D. (2021), who suggested an analytical model termed SMAV. The actual model with sensors that is subjected to dynamic loads is compared to the FSC's function caused by environmental vibrations, and the appropriate match in dynamic responses is demonstrated. However, the results showed that when utilizing SMAV, the presence of a single accelerometer on the last floor of a building is sufficient to extract acceleration data and calculate the structure's overall reaction [59].

A frequency response function (FRF)-based damage detection method was developed by Jalali, M. and Rideout, D. (2022) and is useful for monitoring structures. In order to detain specific areas as susceptible to damage, the identification process was implemented by decoupling various system components. The experimental results from the laboratory instruction were compared with the model outcomes generated by the finite element software, showing acceptable agreement. Also, the system was updated by determining the damage location and damage value [60]. Table 4 describes in detail how the monitoring approach examined in this research is applied to different types of buildings.

Table 4. List of application of various monitoring techniques.

Reference	Applied Monitoring Method	Structure	Type of Software and Analysis	Monitoring Results	Specification
Tariq Amin Chaudhary, M et al. (2000) [61]	SSI	Base-isolated bridge in Japan	Finite element software SAP2000 v8—Modal Analysis	Because of the excellent subsoil conditions, column stiffness dominates sub-structure stiffness, and the influence of SSI is negligible in this bridge.	The high amplitude of excitation has a significant impact on rubber's parameters, thus the effect of small amplitudes is a challenge to be considered.
Siringoringo, D., Fujino, Y. (2017) [2]	MIMO	Cable-stayed bridge in Japan	Finite element software SAP2000 v16—Time History Analysis	The performance of the seismic isolation system, response nonlinearity, and structural pounding Determined.	Supplying unknown parameters like transverse structural pounding which are required for retrofitting following intense events.
Tarozzi, M. et al. (2020) [3]	FDD-SSI	Composite bridge	Finite element software STRAND 7.x—Modal Analysis	The results of numerical calculations and the tests are extremely in good agreement.	The evolution of modal shapes and damping ratios obtained by altering the order of bolted cover plate removal is the subject of ongoing investigations.
Bandara, R. et al. (2014) [13]	Artificial neural network	2-story building	ANSYS Workbench 14.x—Transient analysis	Damage identification with real building data with high accuracy.	The capability of the proposed method in noise filtering.

Table 4. *Cont.*

Reference	Applied Monitoring Method	Structure	Type of Software and Analysis	Monitoring Results	Specification
Xie, B. et al. (2019) [14]	Wavelet transform	Steel Frame	D-viewer 4.x	Based on the findings, the errors are about 5% and the acceleration responses recorded by the cell phones closely resemble those of the conventional sensors.	The feasibility of tracking a building structure's reaction via smartphones.
Kildashti, K. et al. (2020) [15]	Ambient vibration test	Cable bridge	Finite element software ABAQUS (6.18)	Without using bridge response measurements, damage to the cables may be successfully detected, localized, and assessed.	Various parameters efficiency on the suggested approach's effectiveness is thoroughly examined.
Nagayama, T. et al. (2005) [16]	Ambient vibration test	Suspension Bridge	Finite element software SAP 2000 v10	The approach is capable of accurately identifying the features of both upper and lower modes, as well as of successfully detecting structural property changes.	It is not necessary to make assumptions about the structural damping or stiffness beforehand, to identify structural parameters.
Pioldi, F. et al. (2015) [17]	Ambient vibration test—FDD—rFDD	10-storey frame	Finite element software SAP 2000 v15-MATLAB R2012a	Results of both proposed rFDD algorithm and a classical FDD method compared.	A developed rFDD method is applicable even in structures equipped with high damping values.
Pan, Y. et al. (2020) [20]	Ambient vibration test—Finite element model updating	Super tall building	Finite element software ABAQUS (6.18)	Dynamic properties of the tall tower extracted through AV test and after that the simplified FE model proposed for model updating assessment.	The developed simplified FE model is fast computational tool with high accuracy. The finite element model updating technique is quite sensitive to chosen parameters.
Tan, R.Y., Weng, I.W., (1996) [62]	Modal Analysis	4-story isolated building	Mathematical model	Hysteretic nonlinear isolation system identified.	Calculation process minimized.
Okada, K. et al. (2009) [7]	non-destructive testing (NDT)	6-story isolated building	Finite element software SAP 2000 v11	Seismic-isolated structure monitored using series of sensors.	Safe and secure hardware and software earthquake early warning system.
Matsuda, K. et al. (2012) [63]	Modal Analysis	20-story isolated building	Finite element software SAP 2000 v14	Modal properties identified.	Vibration period and damping ratio are considered in the process of identification.
Astroza, R. et al. (2021) [64]	Ambient vibration test—SSI	5-story base-isolated building	Finite element software SAP 2000 v21-MATLAB R2020b	Natural frequencies and effective damping ratios identified.	Mullin's effect (softening) and amplitude dependency in identification.

5. Health Monitoring and Model Updating of Vibration Dissipation Systems in Structures

Today, health monitoring of critical structures is both essential and indispensable. Additionally, the more important and larger the structure, the more costly the damage it imposes on users during the period of operation. In designing and evaluating structures that are affected by fluctuations due to loads and vibrational stimuli, modal analysis is absolutely necessary. An isolation system's dynamic response is dependent on a number of variables, including the intensity of ground motion, the bearings, and the material of the structure. These variables cause nonlinear behavior, which is dependent on a number of variables, including the scale size, axial load, temperature, and loading rate, particularly during intense seismic shaking.

The Masing Criterion approach was presented by Tan, R.Y. and Weng, I.W. (1996) as a means of identifying a four-story structure that has laminated rubber bearings. The dynamic properties of the structure are computed numerically by simulating the superstructure as a linear state and using bilinear isolators as isolators. The method's intended performance was confirmed as the identification results matched the structure derived data considering dynamic loads [62].

Tariq Amin Chaudhary, M. et al. (2000) implemented the identifying process in two different isolation systems considering earthquake accelerations to assess the bearing's function. The results found that in both base-isolated bridge models, while the earthquake intensity increased, the natural frequencies decreased, since the stiffness of the bearing decreased. Moreover, outputs showed that the stiffness of the superstructure depends on metal bearing friction in weak vibration [61].

Later, three distinct scenarios were taken into consideration by Tariq Amin Chaudhary, M. et al. (2002) in order to optimize the location of bearings on the bridge and assess the bearing performance in an earthquake-prone bridge.

It was discovered by comparing the modal parameters from the two states—frequency domain system identification and models with different bearing locations—that installing bearings in two piers is at least required since the substructure's lateral load distribution will be symmetric [65].

A technique for determining the stiffness and hysteretic algorithm of isolation systems while taking seismic response data into account was presented by Huang, M. et al. in 2009. Monitoring using different soil conditions was carried out on a bridge using lead-rubber bearings (LRBs). Results showed how accurate the identification technique was in estimating structural parameters [66].

In order to prevent damage caused by earthquakes, wind, and temperature, Okada, K. et al. (2009) developed a seismically isolated building in Tokyo using a structural health monitoring system as an earthquake early warning system. This system consisted of hardware and software to detect and record vibrations, manage responses, and prevent damages gradually. The findings demonstrated the trend of variations in natural frequencies between 2004 and 2007 as well as the temperature's varying impact on the stiffness of the rubber bearings, which are temperature sensitive [7].

In order to monitor the structural health over an extended period of time in a 20-story structure with rubber bearings subjected to real dynamic loads, MATSUDA, K. et al. (2012) took into account two distinct monitoring states: an isolated building and a non-isolated building. After analysis, modal parameters were obtained using curve-fitting of the transfer function approach in both states. Subsequently, the noteworthy efficiency of the base-isolated system in dissipating energy was confirmed, as the acceleration was about twice as great in the structure without taking the isolation system into account, as opposed to the base-isolated system [63].

Lead-rubber bearings (LRBs) were used by Tafur, A. and Swailes, T. (2017) to optimize the performance of a concrete bridge that had been constructed over 50 years. A numerical bridge model was created using finite element software to examine the proposed construction with flexible connections as well as the current structure with fixed steel bearings. The analysis's findings showed that rubber isolators effectively balanced the transmission of seismic forces in piers and beams by raising the damping ratio and subsequently reducing the impact of those forces [67].

A suspension bridge was subjected to health monitoring by Siringoringo, D. and Fujino, Y. (2018) in order to determine the modal parameters over an 8-year period under various dynamic loads. Time-domain and time-frequency approaches were used to extract seismic data. The findings showed that the main crater's center is where the most vertical acceleration occurs [12].

In order to determine the link between the elastic center and elastomer layers while taking the coordinate system's position into account, Ramesh, R. et al. (2019) computationally discovered the properties of the isolation system. The use of the modal decomposition approach revealed that the diagonal stiffness matrix required the elastic center in order to be properly formulated. Furthermore, frequency response curves containing elastomer damping matrices were generated, clarifying the viscous parameters [68].

Astroza, R. et al. (2021) examined artificial excitations from a shaking table, white noise, and ambient vibration while analyzing a building isolated with high-damping rubber bearings (HDRBs) in order to assess the seismic performance of the isolated structure and pinpoint structural dynamic features. Records demonstrated that when more energy was released through vibrations, the isolated structure period lengthened. Additionally, health monitoring data revealed that, whereas higher modes were associated with the deformation of the upper stories, lower modes of the structure's base isolation indicated greater deformation [69].

In a study by Yu et al. (2023), a methodology was developed and implemented for updating the model of a full-scale base-isolated reinforced-concrete building using experimental data from a Japanese facility. The researchers addressed computational challenges in model updating by dividing the process into smaller, more efficient sub-problems. Their results demonstrated that the updated model accurately captured the dynamic behavior of the base-isolated structure, validating their approach through experimental observations. However, the method had limitations, including reliance on high-quality experimental data and a focus on specific structural types, which may restrict its generalizability to other building configurations or isolation systems [64]. In a study by Wen et al. (2021), a performance-based seismic design and optimization methodology was developed for damper devices in cable-stayed bridges. The researchers aimed to enhance the seismic performance of such bridges by strategically designing and positioning damper devices to mitigate earthquake-induced vibrations. Their results showed that the optimized dampers significantly improved the dynamic response of the bridge, reducing displacement and internal forces during seismic events. However, the approach had limitations, including a reliance on precise modeling of the bridge's dynamic behavior and the seismic forces, which might restrict its application in structures with complex or uncertain conditions [70].

Figure 8 shows how the model updating method works. It shows that after numerically modeling the structure, model updating is initiated when the discrepancy between the modal parameters in the numerical model and the existent structure is more than 5%. The optimization process begins with simultaneous work on programming code and finite element software. Every time the model is updated, the optimization variable values are varied within a specified space domain. Minimizing the difference between the replies produced by the developed analytical model and the actual outcomes of experimental testing is the primary goal of the optimization method. In order to reduce the inaccuracy, the optimization algorithm modifies the analytical model's optimization parameters sufficiently.

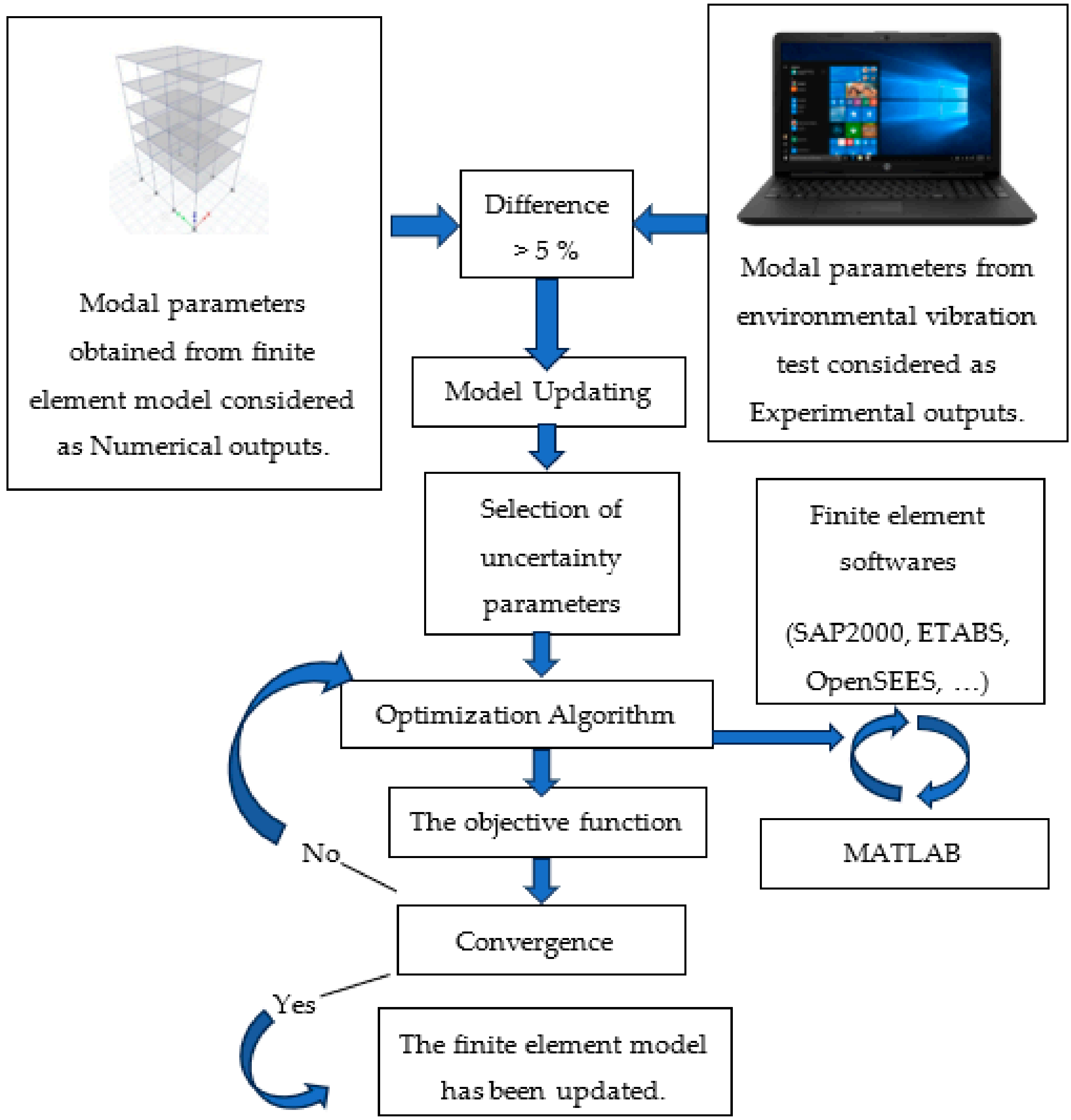


Figure 8. The steps of the model updating process in this review.

6. Damages Detection in Structural Systems

Identification of damage and monitoring of the health of structures is an important issue in the structural engineering field. During a structures' useful life, it is always affected by various operating loads, including live and dead loads, earthquake loads, environmental loads such as wind, and accidental loads such as explosions. While the nature of these loads is often dynamic, it may cause damage to the structural systems. Most failures that occur in structures are usually limited and occur in one or more structural elements. But over time or without paying attention to this issue, the damage extends, which may lead to more breakdowns in the structure. Due to the high cost of construction and the importance of some structures, the diagnosis of damage and mechanism of failure in structures has become an important issue in structural engineering. By correctly identifying the damaged elements in the structure and strengthening or replacing them, the useful life of the structure can be increased. The comparison of several damage detection techniques is categorized in Table 5.

Table 5. A Comparative classification of damage detection methodologies for SHM.

Methodology	Principle	Key Features	Advantages	Disadvantages	Applications
Visual Inspection	Manual identification of visible damage or deterioration	Simple, cost-effective	Immediate results, no specialized equipment required	Subjective, requires expertise, not applicable for internal damage	Bridges, buildings, aircraft inspections
Acoustic Emission (AE)	Detects stress waves produced by crack growth or material failure	High sensitivity to active damage	Early damage detection, real-time monitoring	Complex signal interpretation, sensitive to noise	Pressure vessels, pipelines
Vibration-Based Methods	Analyzes changes in natural frequencies, mode shapes, or damping	Global damage identification, non-invasive	Effective for large structures, suitable for long-term monitoring	Requires baseline data, may not detect minor local damage	Bridges, turbines, offshore platforms
Ultrasonic Testing (UT)	High-frequency sound waves used to detect internal flaws	Precise detection of internal defects	Accurate, applicable to a wide range of materials	Requires access to both sides of the material, surface prep	Aircraft components, welding, composites
Thermography	Detects heat distribution anomalies caused by damage	Non-contact method, suitable for large areas	Rapid scanning, detects subsurface defects	Limited depth of penetration, sensitive to environmental conditions	Concrete structures, composites
Magnetic Particle Testing (MPT)	Detects surface and near-surface defects in ferromagnetic materials	Simple and effective for magnetic materials	High sensitivity to surface cracks	Limited to ferromagnetic materials, requires surface prep	Welding, pipelines
Modal Analysis (e.g., FDD, SSI)	Monitors dynamic properties of structures to detect changes	Global structural assessment, non-invasive	Effective for large-scale systems, long-term monitoring	Requires advanced equipment and expertise	Bridges, skyscrapers
Wavelet Transform Analysis	Detects localized anomalies in time-frequency domain	High resolution for non-stationary signals	Effective for damage localization	Requires extensive computational resources	Wind turbines, cables
Machine Learning (ML) Models	Uses algorithms to classify or predict damage from data	Can process large datasets, adaptable	Highly accurate with sufficient training data	Requires labeled datasets and computational resources	Any structure with sensor data
Fiber Optic Sensors (FOS)	Detects strain or temperature changes using fiber optic technology	High sensitivity, distributed sensing	Lightweight, immune to electromagnetic interference	High initial cost, requires expertise	Bridges, tunnels, aerospace

Also, early structural damage detection can prevent severe and hazardous failures in the long term and under dynamic loads such as earthquakes. Therefore, identifying the amount and location of failure in structures is very important.

In order to locate damage in a beam model statistically, Pandey, A. et al. (1991) established the curvature mode shape by taking into account two states: undamaged and damaged parts. Findings revealed that damage is identified when natural frequencies shift in addition to the damage size increasing with the curvature mode shapes increment. Conversely, several investigations demonstrated that the shape of the curvature mode could be empirically derived by bending stresses, in contrast to previous findings that suggested the curvature mode shape depended on both acceleration and structural displacement [71].

Alvin, K.F. et al. (2003) surveyed various damage detection methods that utilize system identification techniques based on numerical calculations. Their comparison of different health monitoring procedures demonstrated that each method—whether subjected to ambient vibrations or artificial excitations—has its own advantages for extracting modal parameters, diagnosing damage presence, quantifying damage size, and determining damage location to predict the remaining life of the structure [72].

In order to identify damage in terms of locations and intensities quantitatively, Choi, S. and Stubbs, N. (2004) carried out a time-domain reaction. In the structural elements of a beam, the damage index is regarded as a mean strain energy measure. In light of noise vibrations, damage output results were obtained with a satisfactory degree of precision. Furthermore, the minimal degree of element damage was identified using the time-domain response process [73].

Two techniques based on frequency and mode shape changes were employed by Kannappan, L. (2008) to enhance system monitoring and identify structural deterioration while taking modal parameter fluctuations into account. According to numerical results, the frequency-based approach was superior since its measurements relied only on a single location's outputs, but the dynamic parameters derived from the technique of based mode shapes included noise [74].

Malekzehtaba, H. and Golafshani, A. A. (2013) detected damage by using an optimization algorithm of genetics in order to minimize the error between the modal parameters extracted from the real structural model compared to the finite element model in software. Under various damage states, the results proved the appropriate performance of the Genetic Algorithm, especially in the existence of noise data [75].

By analyzing changes in the modal parameters of both intact and damaged structures over time, Kaveh, A. and Zolghadr, A. (2014) optimized a charged system search (CSS) method to find structural damage to truss components. They were able to acquire numerical changes in modal parameters in the form of objective function curves [76].

A vibration measuring technique was presented by Siriwardane, S. (2015) to track structural conditions and identify areas of deterioration in bridge component parts. Modal parameters are obtained through the real bridge, which has accelerometers placed at certain locations to record accelerations under trains' dynamic loads. Comparing the software's 3D finite element model with the real bridge revealed differences in trends brought on by the damage [77].

Chisari, C. et al. (2015) implemented the Genetic Algorithm (GA) as a damage detection method on a bridge equipped with an isolation system considering both static and dynamic analysis. Results obtained a model updating data values based on the existence of uncertainty on elasticity modulus and stiffness which proved acceptable outputs in comparison to past findings in the forms of discrepancy curves [78].

He, W. and Ren, W. (2018) developed a novel method of damage identification that can identify damage while accounting for variations in frequency amounts brought about by the presence of parked cars at different points along the bridge. After adding damage to the bridge model, findings proved the method's accuracy and demonstrated that it was helpful in detecting both structural damage and natural frequencies, as relying solely on frequency changes for damage identification was unreliable [79].

In order to sustain additional dissipating energy systems during severe seismic excitations while taking damper parameters into consideration, Sepehri, A. et al. (2018) devised a clever approach. Three different types of steel structures with varying numbers of floors were numerically designed to evaluate the effectiveness of this trend. The results showed that, in contrast to previous procedures, the developed process can reduce damper damage while enduring the highest level of earthquake intensity without the need to strengthen the dampers [80].

Yuan, C. et al. (2022) manufactured a comprehensive device to detect damage in reinforced concrete buildings and also, verified the proposed method with an experimental model of the reinforced concrete column which failed under cyclic loading. The obtained data in terms of segment, localization, quantification, and accuracy proved that this procedure is an applicable, human-independent, and safe method in damage detection [81].

Moreover, structural health monitoring (SHM) encompasses several critical phases aimed at ensuring the safety and functionality of engineering structures. Anomaly detection serves as the initial step, identifying deviations from normal behavior through advanced sensor data and statistical methods. Once an anomaly is detected, damage detection focuses on confirming the presence of damage by analyzing structural responses. Damage localization further pinpoints the specific area affected, utilizing techniques such as vibration analysis or wave propagation methods. Finally, residual life estimation predicts the remaining service life of the structure, considering the detected damage, operational conditions, and material degradation models. Together, these interconnected phases form a comprehensive framework for proactive maintenance and reliability assessment of critical infrastructure, including bridges, buildings, and aerospace systems. Table 6 provides a comparative analysis of the key methodologies used in anomaly detection, damage detection, damage localization, and residual life estimation within the realm of SHM. It also offers valuable insights into how different methodologies are applied and evolved in real-world applications to enhance the reliability and longevity of infrastructure.

The ability to achieve and implement each phase—anomaly detection, damage detection, damage localization, and residual life estimation—depends on technological advancements, sensor networks, data analysis techniques, and the domain of application. Table 7 classifies some of the most significant contributions made by researchers in the phases of anomaly detection, damage detection, damage localization, and residual life calculation in SHM.

Table 6. The comparison of Anomaly Detection, Damage Detection, Damage Localization, and Residual Life Estimation in SHM.

Aspect	Anomaly Detection	Damage Detection	Damage Localization	Residual Life Estimation
Objective	Identify deviations from expected behavior or patterns	Determine the presence of damage in a structure	Pinpoint the exact location of the damage	Predict the remaining usable life of a structure
Scope	General abnormalities, not specific to structural damage	Structural changes due to cracks, corrosion, etc.	Spatial identification of damage	Time-based assessment for maintenance or replacement
Key Techniques	Statistical analysis, machine learning, signal analysis	Modal analysis, vibration-based methods, AE	Ultrasonic testing, thermography, wave propagation	Fatigue analysis, material degradation models
Input Data	Sensor outputs, system performance metrics	Structural response, modal properties, strain data	High-resolution inspection data, wave propagation	Historical usage, environmental factors, load data
Complexity	Moderate	Moderate to High	High	Very High
Accuracy	Identifies patterns but may have false positives	High for detecting significant damage	Highly accurate for localized damage	Depends on model assumptions and input data
Tools	Machine learning libraries, statistical analysis tools	Accelerometers, strain gauges, fiber optic sensors	Ultrasonic scanners, thermographic cameras	Finite element analysis (FEA), ML-based prediction tools
Advantages	Early warning of potential issues	Non-invasive, effective for global assessments	Precise damage location, aids targeted maintenance	Supports proactive planning, reduces maintenance costs
Disadvantages	Limited to general anomalies, not specific to damage	May require baseline data for comparison	Requires detailed inspection, may be costly	Complex calculations, sensitive to input inaccuracies
Applications	Monitoring structural health, identifying unusual events	Bridge monitoring, aircraft maintenance	Locating cracks in pipelines, turbines	Lifespan prediction of bridges, aircraft components

Non-Destructive Testing (NDT) is essential for ensuring the safety and durability of structures, as it allows for inspecting materials without causing damage. This approach is cost-effective and efficient, helping to maintain systems in a sustainable way. New technologies like smart sensors, laser tools, and advanced monitoring systems have made NDT more accurate and flexible. These innovations expand its uses, from finding tiny cracks to understanding how environmental and operational factors affect structures.

By combining traditional methods with modern tools, NDT helps solve challenges like environmental changes and the need for real-time analysis. This progress not only tracks trends but also helps create better and more reliable ways to monitor and protect infrastructure.

Table 7. The contributions of various researchers in advancing the critical phases of anomaly detection, damage detection, damage localization, and residual life estimation in SHM.

Aspect	Researchers	Contributions
Anomaly Detection	Azimi, M. et al. (2020) [82]	Due to the inefficiency in traditional SHM methods, which rely on manual feature extraction and are not well-suited for large-scale, real-world applications, the use of deep learning (DL) approaches to identify anomalies in structural behavior, through vibration-based data analysis, was reviewed. The results proved DL techniques, such as Convolutional Neural Networks (CNNs), significantly enhanced the capabilities of SHM systems by providing faster and more reliable results for damage detection, localization, and life estimation [82].
	Zhang, Z., Sun, Ch. (2020) [83]	A physics-guided neural network (PGNN) method used to analyze deviations in structural responses and detect anomalies through model-based predictions [83].
	Qu, Ch. et al. (2023) [84]	Proposed a novel approach using data migration techniques between different bridges to balance datasets, which helps improve the performance of anomaly detection models. This approach is crucial for handling the data imbalance often found in real-world monitoring systems, where anomalies are rare [84].
	Samudra, Sh. et al. (2023) [85]	A machine learning-based framework was developed to enhance anomaly detection in acceleration data gathered from real-world bridge structures. The key challenge addressed was the presence of anomalies, such as noise, drift, or outliers, in SHM data, which can mislead assessments of the structure's health [85].
	Kim, S., Mukhiddinov, M. (2023) [86]	They addressed the challenge of sensor anomalies, which can arise due to environmental conditions, sensor failures, or damage, complicating the analysis of real-time data from civil structures like bridges. Their solution involved using a convolutional neural network (CNN) to detect these anomalies in time-series vibration signals, a common data type in SHM [86].
Damage Detection	Jia, J., Li, Y. (2023) [87]	Reviewed the development of the Structural Health Monitoring Digital Twin (SHMDT) method, which is capable of real-time damage detection, while highlighting the need for better generalization of DL models and more robust datasets to address complex real-world conditions [87].
	Zhang, Z., Sun, Ch. (2020) [83]	Detected damage by integrating measured data and physics-based models to identify discrepancies in structural parameters [83].
	Huang, Q. et al. (2012) [88]	The study discussed a method for system identification and damage detection in buildings equipped with semi-active friction dampers. The authors employed frequency response functions (FRF) for model updating and stiffness parameter identification, which helps detect damage by comparing the original and damaged states of the building. The study shows that this method effectively detects and quantifies structural damage, even in the presence of measurement noise, making it a valuable tool for real-world applications in damage detection for buildings with dampers [88].
	Guo, L. et al. (2022) [89]	The challenge of assessing seismic damage in buildings equipped with isolation systems, which are designed to mitigate earthquake forces but complicate traditional damage detection methods, was addressed. They introduced a substructure method that separates the building structure from the foundation to allow for more accurate damage detection during seismic events. This method models the building and isolation system separately, enabling a clearer assessment of damage in both components [89].
Damage Detection, Damage Localization, Residual Life Estimation	Brownjohn, J. et al. (2011) [90]	Explored the role of vibration-based monitoring in structural health. They identified challenges such as noise in real-world data, environmental factors, and difficulties in interpreting complex vibration data. Various monitoring techniques and highlighted advancements in damage detection, localization, and residual life estimation were reviewed [90].

Table 7. *Cont.*

Aspect	Researchers	Contributions
Damage Localization, Residual Life Estimation	Rabi, R. et al. (2024) [91]	Various vibration-based techniques were examined for their effectiveness in identifying damage locations and predicting the remaining service life of bridges. The findings reveal that when integrated with advanced computational tools, these techniques significantly enhance the precision of damage localization and provide robust lifetime predictions, although challenges persist in adapting them to large-scale and complex structures [91].
	Zacharakis, I., Giagopoulos, D. (2022) [92]	This study utilized finite element (FE) modeling combined with a particle swarm optimization (PSO) algorithm to enhance vibration-based damage detection. By optimizing FE models, it effectively localized and quantified structural damage, even under noise and nonlinearities, using examples like composite beams. The approach demonstrates strong potential for SHM and lifetime prediction by assessing stiffness and dynamic property changes over time [92].
	Zhang, M. et al. (2023) [93]	The study focused on damage identification in seismic-isolated structures using a Convolutional AutoEncoder (CAE) network and vibration monitoring data. The challenge was accurately detecting and localizing damage in systems with seismic isolation, where complex dynamics can interfere with traditional methods. The researchers utilized the CAE network to analyze vibration data, effectively identifying damage patterns and changes in structural properties. This approach enhanced damage localization by detecting anomalies in dynamic characteristics, and it also provided insights into lifetime prediction and predictive maintenance of seismic-isolated structures [93].
	Mita, A., Yoshimoto, R. (2003) [94]	The study utilized the subspace identification approach to address challenges in assessing damage in base-isolated buildings, overcoming limitations of traditional methods. It successfully localized damage and evaluated its long-term effects on structural performance, demonstrating the potential of advanced techniques for precise structural health monitoring [94].

Keshmiry, A. et al. (2023) reviewed how environmental and operational conditions affect SHM and NDT. They focused on advanced techniques like laser scanning and ground-penetrating radar, which offer precise, non-invasive structural evaluations despite challenges like temperature or humidity changes. The study highlighted a trend toward hybrid systems that combine multiple methods to improve reliability and accuracy. It also emphasized the need for better data processing to handle environmental noise and identified areas for improving next-generation monitoring systems [95].

Svendsen, B. et al. (2022) developed a hybrid structural health monitoring (SHM) approach to detect damage in steel bridges, combining numerical simulations with experimental data under simulated environmental conditions. They applied this approach to assess the structural integrity of bridges by simulating various environmental factors, such as temperature and humidity, that could impact the accuracy of damage detection. The results showed that the hybrid method effectively improved damage detection reliability by leveraging both simulation-based predictions and real-world experimental data, offering a more robust and adaptable solution for monitoring the condition of steel bridges. This research highlights the potential of combining advanced sensor technologies with simulation models to enhance the precision and efficiency of SHM systems [96].

A summary of the research steps in this literature review is depicted in Figure 9.

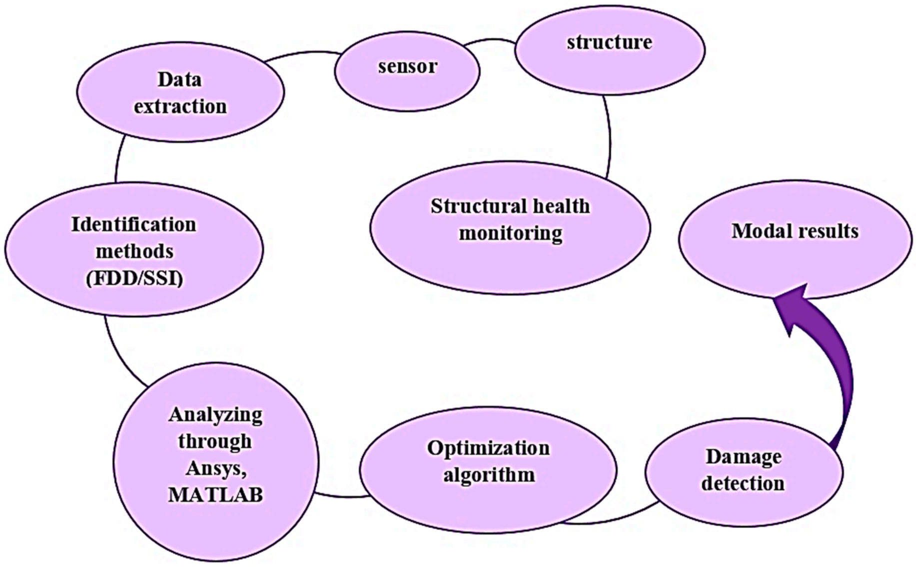


Figure 9. A summary of the research steps in this literature review.

7. Health Monitoring with Satellite

Satellite-based technologies have been widely utilized for health monitoring and damage detection in various structural and vibration dissipation systems due to their ability to capture deformation trends and structural behaviors. Systems, such as those used for vibration isolation and energy harvesting, can significantly impact the deformation of structures, making them identifiable through satellite data. The integration of satellite methods like DInSAR (Differential Interferometric Synthetic Aperture Radar) offers a non-invasive and cost-effective solution for monitoring and identifying structural changes in response to temperature fluctuations, seismic activity, and other environmental factors. Various studies have leveraged satellite-based approaches to assess structural health and detect damage, demonstrating the effectiveness of these techniques in a range of applications, including bridges, buildings, and infrastructure subjected to vibrations and other external forces. The following papers highlight the use of satellite technologies in these contexts, showcasing their potential for long-term monitoring and damage detection in engineering systems:

Ponzo et al. (2024) investigated the structural health monitoring of the "Ponte della Musica" in Rome by combining the DInSAR–SBAS satellite interferometry method with a calibrated 3D digital twin model to analyze temperature-induced deformations. Due to rapid thermal variations, satellite data struggled to capture the central span of the bridge. The authors integrated environmental vibration data to simulate temperature effects on structural deformations, finding that combining satellite and experimental data was effective for long-term infrastructure monitoring [97].

Kwon and Oh (2016) developed a dual-purpose system for satellite applications, combining micro-jitter isolation with energy harvesting. They proposed a tuned mass damper-type electromagnetic energy harvester integrated with a passive vibration isolator, reducing jitter by a factor of 10.8 and harvesting a net electrical output of 5.84 mW, sufficient for a low-consumption accelerometer. Optimized harvesters increased the output to 95 mW, showcasing the system's potential for renewable energy generation in spaceborne applications [98].

Caprino et al. (2023) compared MT-InSAR satellite data with on-site structural health monitoring (SHM) of the Civic Tower in L'Aquila, Italy, after the 2009 earthquake. Using COSMO-SkyMed images (2010–2013) and inclinometers, they found a high correlation (0.86) between the two methods in detecting tower displacement. While MT-InSAR proved cost-effective for monitoring large urban areas post-earthquake, on-site measurements provided more accuracy. They concluded that MT-InSAR is a useful preliminary tool for detecting anomalies but requires on-site validation for precise analysis, with future improvements for nonlinear behaviors and post-earthquake scenarios [99].

Sciortino et al. (2024) analyzed post-seismic deformations in L'Aquila, Italy, using A-DInSAR data from COSMO-SkyMed images (2010–2021) and historical seismic damage maps. They observed that subsidence rates were correlated with higher building damage intensity, highlighting subsidence's influence from underground geological structures. Their study emphasized the value of long-term satellite SAR data for mapping seismic risk zones, and future research focused on pre-seismic data validation and geological influences [100].

Di Carlo et al. (2022) presented a method for monitoring modern bridges using DInSAR data integrated with historical structural documents. This method was applied to two Gerber bridges in Rome—Marconi and Magliana—using COSMO-SkyMed data (2011–2019). Historical records aided 3D modeling and Permanent Scatterer (PS) positioning within GIS, reducing the need for on-site surveys. Displacement analyses identified key factors such as PS groupings and structural scheme boundaries. Despite challenges, this approach proved effective for assessing structural behavior, suggesting a promising solution for low-cost, remote bridge monitoring [101].

Giordano et al. (2022) proposed the SAND method for detecting structural damage using DInSAR data. The method identifies anomalies like settlement in bridge piers while filtering out environmental effects. Applied to the Palatino Bridge in Rome, it detected settlements due to soil subsidence with an accuracy of 1–2 mm after 20–30 days, eliminating the need for on-site sensors. This cost-effective method also allows large-scale monitoring and can be integrated into alert systems for identifying potentially deficient structures [102]. Miano et al. (2022) discussed structural health monitoring (SHM) in Italy, particularly in areas with diverse hazard sources. They combined DInSAR measurements, geological investigations, historical surveys, and 3D modeling to assess ground displacement and structure conditions. Applied to the Valco San Paolo residential area in Rome (2011–2019), the study revealed settlement variations due to materials, foundations, and building age. They also proposed a quick damage assessment procedure to prioritize further investigations, demonstrating the methodology's utility in large-scale monitoring [103].

In another study, Miano et al. (2022) used DInSAR data to monitor landslide-affected buildings and assess the damage progression in reinforced concrete structures, offering rapid evaluation methods for landslide-prone regions [104].

Confuorto et al. (2019) explored the use of DInSAR techniques, specifically the Coherent Pixel Technique (CPT), to monitor remedial works on landslide-affected slopes in Quercianella, Italy. The integration of DInSAR data with ground-based tools such as inclinometers and piezometers showed the effectiveness of geotechnical interventions and guided further stabilization efforts, emphasizing remote sensing's advantages in challenging terrains for real-time monitoring and planning [105].

Meng et al. (2020) developed a methodology to identify and classify active loess landslides in Northwestern China using deformation data from Sentinel-1 InSAR. By combining ascending and descending SAR data, they decomposed the displacement into horizontal and vertical components, classifying various landslide types. The study validated the method with UAV surveys, detecting over 30 landslides and providing a reliable tool for hazard risk assessment and landslide management [106].

Tonelli et al. (2023) applied Multi-Temporal InSAR (MT-InSAR) to remotely monitor the A22 Po River Bridge in Italy, analyzing displacement data from 109 COSMO-SkyMed SAR images over eight years. The study examined how displacements correlated with temperature variations and environmental factors like river water flow. It demonstrated that InSAR is effective for large-scale, cost-effective SHM of bridges, providing insights into structural behavior and the influence of environmental factors, without the need for traditional sensors. Further research was recommended to explore the impact of bridge orientation on monitoring accuracy [107].

Deng et al. (2023) reviewed recent advancements in bridge health monitoring (BHM) systems, focusing on sensor technologies and data processing techniques. They highlighted the progress in fiber optic sensors (FOS), wireless sensor networks (WSN), and vibration-based damage identification methods. FOS and WSNs showed promise, though challenges remain in installation durability and optimal deployment. The review also discussed the growing role of satellite technologies like InSAR for bridge risk assessment and early warning systems, suggesting that integrating multiple damage identification methods could improve monitoring accuracy. The paper emphasized the need to account for temperature effects on structural monitoring and proposed future directions for more reliable and cost-effective BHM systems [108].

In conclusion, various studies have explored the use of satellite data in health monitoring and damage detection across different applications. These studies employed techniques like DInSAR and other satellite imaging methods to simulate structural changes in response to factors such as vibrations, temperature fluctuations, seismic damage, and other environmental changes. The data obtained from satellites in these studies can help identify damages and deformations in structures. Since damping devices have a significant impact on the behavior and deformations of structures, the same satellite data can be leveraged to identify damages and analyze the performance of these systems. In other words, satellite data can serve as an effective tool for detecting damage and evaluating the performance of damping devices in structures.

8. Conclusions

This review discusses numerous articles on SHM and model updating of vibration dissipation systems in structures, highlighting the importance of differentiating between recent advancements and traditional techniques. It emphasizes the value of comparing older methods, such as vibration analysis, with newer approaches like DL, CNN, and CAE to evaluate improvements in efficiency, accuracy, and applicability. This comprehensive review ensures a balanced perspective, grounding novel contributions within the broader context of SHM developments. Also, the importance of gathering methodologies together lies in creating a unified resource that facilitates comparative analysis, highlights best practices, and identifies gaps in existing approaches. Hence, by consolidating diverse techniques, researchers and practitioners gain a clearer understanding of the field, enabling the development of more effective and innovative solutions. This synthesis also promotes interdisciplinary collaboration and ensures that knowledge is accessible and applicable, ultimately accelerating progress and enhancing the impact of the methodologies on real-world challenges. This review paper emphasizes the importance of identifying damage in structures subjected to dynamic loads such as wind, earthquakes, or ambient vibrations. Early damage detection, such as in dampers, joint failure, member cracks, or section crushing, is critical for the timely replacement of damaged components and for ensuring structural safety. This research evaluates various vibration-based damage detection methods, including non-destructive testing (NDT), SHM, model updating, and modal analysis. However, as each structure is unique and complex, further work is needed to enhance vibration-based damage detection techniques for real-world applications. Though successfully applied to many engineering structures, most experiments use linear models, while nonlinearity due to connections, assembly, and damage requires additional investigation into damage detection systems for nonlinear structures. On the other hand, for future research on SHM in base-isolated structures, a promising direction is the development of hybrid SHM techniques that integrate multiple data sources. These techniques could combine vibration data with information from sensors such as temperature, displacement, and environmental monitoring, enhancing the robustness of damage detection. Additionally, integrating machine learning algorithms could improve the predictive capabilities of SHM systems, allowing them to adapt to real-time data. Addressing the challenge of data inconsistencies due to environmental variability and incorporating nonlinear models for a more accurate representation of isolation systems are also crucial steps in advancing SHM technologies. To address the limitations of environmental variability in SHM data, future research should focus on developing adaptive algorithms capable of filtering out noise from environmental factors like temperature, humidity, and vibrations caused by external sources. Researchers can explore the use of advanced signal processing techniques, such as wavelet transforms, to separate useful data from environmental disturbances. Additionally, incorporating sensor fusion techniques, where data from different types of sensors (e.g., accelerometers, strain gauges, and environmental sensors) are integrated, can improve robustness and reliability in dynamic monitoring. This approach would enhance the precision of SHM systems, particularly in fluctuating conditions.

The following is a summary of the study's primary findings:

(1) The results of the literature review clarified that based on comparing identified outputs with experimental results, HDRB had a significant performance in terms of higher stiffness, damping ratio, and energy dissipation.
(2) In addition, by comparing analytical and actual test results it is obvious that damage occurred because of existing differences in values of modal parameters between outputs.
(3) Researchers concluded that the base isolator has an effective performance in the building versus ground motions considering structural health monitoring which reported responses and deformations.
(4) However, the amount of acceleration response in top floors was high due to the torsional building parameters, so after the strong shock, because of the stiffness reduction in rubber, the first modes' natural frequencies were low for a period of time.
(5) Moreover, since the flexibility of the isolation system increased under strong vibration, damping increased due to the existence of deformation in shear at rubber, while the frequency of structure decreased. As the frequencies of both dynamic load and the building's torsional modes were coincident, the amplification occurred.
(6) Also, measured results showed that the maximum seismic response was related to the last story and its acceleration was almost 250% of earthquake acceleration. Authors believe that by adding damping devices upstairs, the vibration dissipating process will be increased.
(7) Satellite data, especially through methods like DInSAR, has proven effective in detecting structural damage and evaluating damping device performance, making it a valuable tool for health monitoring by identifying structural changes caused by environmental factors such as vibrations and seismic events.

Author Contributions: Conceptualization, N.G. and F.H.; methodology, N.G. and F.H.; software, N.G.; formal analysis, N.G.; investigation, N.G.; resources, F.H.; data curation, N.G.; writing—original draft, N.G.; writing—review and editing, F.H.; visualization, N.G.; supervision, F.H.; project administration, F.H.; funding acquisition, F.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All data generated or analyzed during this study are included in this published article.

Acknowledgments: The authors express their gratitude for the support provided by the University of the West of England, in facilitating this research. This support is gratefully acknowledged.

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

1. Chaudhary, M.T.A.; Abé, M.; Fujino, Y. Performance evaluation of base-isolated Yama-agé bridge with high damping rubber bearings using recorded seismic data. *Eng. Struct.* **2001**, *23*, 902–910. [CrossRef]
2. Siringoringo, D.M.; Fujino, Y. Over twenty years seismic monitoring experience of cable-stayed bridge: Lessons learned on structural assessments. In Proceedings of the 16th World Conference on Earthquake Engineering, Santiago, Chile, 9–13 January 2017. Available online: https://scholar.google.com/citations?view_op=view_citation&hl=en&user=8opLCHAAAAAJ&cstart=500&pagesize=100&citation_for_view=8opLCHAAAAAJ:kcGNQN_anIUC (accessed on 9 January 2017).
3. Tarozzi, M.; Pignagnoli, G.; Benedetti, A. Identification of damage-induced frequency decay on a large-scale model bridge. *Eng. Struct.* **2020**, *221*, 111039. [CrossRef]
4. Iacovino, C. The Interpolation Evolution Method for damage localization in structures under seismic excitation. *Earthq. Eng. Struct. Dyn.* **2018**, *47*, 2117–2136. [CrossRef]
5. Aloisio, A.; Ponzo, F.C.; Auletta, G.; Ielpo, P.; Ditommaso, R. Vibration issues in timber structures: A state-of-the-art review. *J. Civ. Struct. Health Monit.* **2023**, *76*, 107098. [CrossRef]
6. Zar, A.; Hussain, Z.; Akbar, M.; Ahmed, B. Towards vibration-based damage detection of civil engineering structures: Overview, challenges, and future prospects. *J. Civ. Struct. Health Monit.* **2024**, *20*, 591–662. [CrossRef]
7. Okada, K.; Nakamura, Y.; Saruta, M. Application of Earthquake Early Warning System to Seismic-Isolated Buildings. *J. Disaster Res.* **2009**, *4*, 570–578. [CrossRef]
8. Siringoringo, D.M.; Fujino, Y. Seismic response analyses of an asymmetric base-isolated building during the 2011 Great East Japan (Tohoku) Earthquake. *Struct. Control Health Monit.* **2015**, *22*, 71–90. [CrossRef]
9. Siringoringo, D.M.; Fujino, Y. Long-term seismic monitoring of base-isolated building with emphasis on serviceability assessment. *Earthq. Eng. Struct. Dyn.* **2015**, *44*, 637–655. [CrossRef]
10. Kim, S.H.; Mha, H.S.; Lee, S.W. Effects of bearing damage upon seismic behaviors of a multi-span girder bridge. *Eng. Struct.* **2006**, *28*, 1071–1080. [CrossRef]
11. Hedayati Dezfuli, F.; Alam, M.S. Effect of different steel-reinforced elastomeric isolators on the seismic fragility of a highway bridge. *Struct. Control Health Monit.* **2017**, *24*, e1866. [CrossRef]
12. Siringoringo, D.M.; Fujino, Y. Seismic response of a suspension bridge: Insights from long-term full-scale seismic monitoring system. *Struct. Control Health Monit.* **2018**, *25*, e2252. [CrossRef]
13. Bandara, R.P.; Chan, T.H.T.; Thambiratnam, D.P. Frequency response function based damage identification using principal component analysis and pattern recognition technique. *Eng. Struct.* **2014**, *66*, 116–128. [CrossRef]
14. Xie, B.; Li, J.; Zhao, X. Research on damage detection of a 3D steel frame model using smartphones. *Sensors* **2019**, *19*, 745. [CrossRef]
15. Kildashti, K.; Makki Alamdari, M.; Kim, C.W.; Gao, W.; Samali, B. Drive-by-bridge inspection for damage identification in a cable-stayed bridge: Numerical investigations. *Eng. Struct.* **2020**, *223*, 110891. [CrossRef]
16. Nagayama, T.; Abe, M.; Fujino, Y.; Ikeda, K. Structural identification of a nonproportionally damped system and its application to a full-scale suspension bridge. *Struct. Eng.* **2005**, *131*, 1536–1545. [CrossRef]
17. Pioldi, F.; Ferrari, R.; Rizzi, E. Output-only modal dynamic identification of frames by a refined FDD algorithm at seismic input and high damping. *Mech. Syst. Signal Process.* **2016**, *68–69*, 265–291. [CrossRef]
18. Ye, X.W.; Ni, Y.Q.; Xia, Y.X. Distributed strain sensor networks for in-construction monitoring and safety evaluation of a high-rise building. *Int. J. Distrib. Sens. Netw.* **2012**, *8*, 685054. [CrossRef]
19. Beskhyroun, S.; Wegner, L.D.; Sparling, B.F. Integral resonant control scheme for cancelling human-induced vibrations in light-weight pedestrian structures. *Struct. Control Health Monit.* **2012**, *19*, 55–69. [CrossRef]
20. Pan, Y.; Ventura, C.E.; Xiong, H.; Zhang, F.L. Model updating and seismic response of a super tall building in Shanghai. *Comput. Struct.* **2020**, *239*, 106285. [CrossRef]
21. Hejazi, F.; Shoaei, M.D.; Tousi, A.; Jaafar, M.S. Analytical model for viscous wall dampers. *Comput.-Aided Civ. Infrastruct. Eng.* **2016**, *31*, 381–399. [CrossRef]

22. Kikuchi, M.; Aiken, I.D. An analytical hysteresis model for elastomeric. *Earthq. Eng. Struct. Dyn.* **1997**, *26*, 215–231. [CrossRef]
23. Eibl, J. Dynamic behaviour of high damping rubber bearings for building seismic isolation. In *Dynamic Behaviour of High Damping Rubber Bearings for Building Seismic Isolation*; Springer: Dordrecht, The Netherlands, 1999; pp. 207–214.
24. Jankowski, R. Non-linear model of high damping rubber bearing. *Indian Concr. J.* **2004**, *78*, 74–76. Available online: https://www.semanticscholar.org/paper/NON-LINEAR-MODEL-OF-HIGH-DAMPING-RUBBER-BEARING-Jankowski/cd461a61a8916e4ecdec809f06296196108af529 (accessed on 1 August 2004).
25. Tsai, C.S.; Chiang, T.C.; Chen, B.J.; Lin, S.B. An advanced analytical model for high damping rubber bearings. *Earthq. Eng. Struct. Dyn.* **2003**, *32*, 1373–1387. [CrossRef]
26. Asta, A.D.; Ragni, L. Experimental tests and analytical model of high damping rubber dissipating devices. *Eng. Struct.* **2006**, *28*, 1874–1884. [CrossRef]
27. Lu, X.; Zhou, Y.; Yan, F. Shaking Table Test and Numerical Analysis of RC Frames with Viscous Wall Dampers. *J. Struct. Eng.* **2008**, *134*, 64–76. [CrossRef]
28. Hejazi, F.; Noorzaei, J.; Jaafar, M.S.; Abang Abdullah, A.A. Earthquake analysis of reinforced concrete framed structures with added viscous dampers. *World Acad. Sci. Eng. Technol.* **2009**, *33*, 762–767.
29. Lu, C. Seismic performance of bridges with rubber bearings: Lessons learnt from the 1999 Chi-Chi Taiwan earthquake. *J. Chin. Inst. Eng.* **2011**, *34*, 889–904. [CrossRef]
30. Thiravechyan, P.; Kasai, K.; Morgan, T.A. Response of Base Isolated Structures Considering Inelastic Behavior of Superstructure. In Proceedings of the 15th World Conference on Earthquake Engineering, Lisbon, Portugal, 24–28 September 2012; p. 9.
31. Li, Y.; Wang, J.; Liu, J. Seismic performance of a multi-span RC highway bridge with high damping rubber bearings. *Eng. Mater.* **2013**, *540*, 69–78. [CrossRef]
32. Moghadam, A.S.; Zare, M.; Habibi, M.; Jamali, M. The Effect of Energy Dissipation Systems on the Four-Story Steel Structure by Comparing Them. *Int. J. Eng. Res. Dev.* **2015**, *3*, 149–157.
33. Baker, J.W. Measuring bias in structural response caused by ground motion scaling. In Proceedings of the Pacific Conference on Earthquake Engineering, Singapore, 5–7 December 2007; Volume 56, pp. 1–6. [CrossRef]
34. Arya, G.; Alice, T.V.; Mathai, A. Seismic analysis of high damping rubber bearings for base isolation. *Int. J. Res. Eng. Technol.* **2015**, *4*, 321–327. [CrossRef]
35. Gajewski, M.; Szczerba, R.; Jemioło, S. Modelling of elastomeric bearings with application of Yeoh hyperelastic material model. *Procedia Eng.* **2015**, *111*, 220–227. [CrossRef]
36. Oh, J.; Jang, C.; Kim, J.H. Seismic behavior characteristic of high damping rubber bearing through shaking table test. *J. Vibroeng.* **2016**, *18*, 1591–1601. [CrossRef]
37. Markou, A.A.; Manolis, G.D. Mechanical models for shear behavior in high damping rubber bearings. *Soil Dyn. Earthq. Eng.* **2016**, *90*, 221–226. [CrossRef]
38. Li, Y.; Zong, Z.; Huang, X.; Xia, J.; Liu, L. Experimental study on mechanical properties of high damping rubber bearing model. *IOP Conf. Ser. Earth Environ. Sci.* **2017**, *61*, 012105. [CrossRef]
39. Ebrahimi, E.; Hejazi, F.; Jafar, M.S. Evaluate performance of rubber damper connector in structures subject to dynamic load. In Proceedings of the 11th National Conference on Earthquake Engineering, Los Angeles, CA, USA, 25–29 June 2018; Volume 9, pp. 5765–5775.
40. Zhang, Y. Study on seismic behavior for high damping rubber bearings of continuous beam bridges. *IOP Conf. Ser. Earth Environ. Sci.* **2018**, *153*, 052049. [CrossRef]
41. Xu, W.; Du, D.; Wang, S.; Liu, W.; Li, W. Shaking table tests on the multi-dimensional seismic response of long-span grid structure with base-isolation. *Eng. Struct.* **2019**, *201*, 109802. [CrossRef]
42. Zhang, Y.; Li, J. Effect of Material Characteristics of High Damping Rubber Bearings on Aseismic Behaviors of a Two-Span Simply Supported Beam Bridge. *Adv. Mater. Sci. Eng.* **2020**, *2020*, 9231382. [CrossRef]
43. Grant, D.N.; Fenves, G.L.; Auricchio, F. Bridge Isolation with High-Damping Rubber Bearings—Analytical Modelling and System Response. In Proceedings of the 13th World Conference on Earthquake Engineering, Vancouver, BC, Canada, 1–6 August 2004; Volume 1002, pp. 1–15.
44. Labiba, A.; Muntasir, A.H.M. Influence of ground motion duration and isolation bearings on the seismic response of base-isolated bridges. *Eng. Struct.* **2020**, *222*, 111129. [CrossRef]
45. Deringöl, A.H.; Güneyisi, E.M. Influence of nonlinear fluid viscous dampers in controlling the seismic response of the base-isolated buildings. *Structures* **2021**, *34*, 1923–1941. [CrossRef]
46. Deringöl, A.H.; Güneyisi, E.M. Seismic Response of Base-Isolated Buildings with High Damping Rubber Bearings Having Different Design Characteristics. *Res. Sq.* 2021, *Under Review*. [CrossRef]
47. Pan, P.; Nakayasu, N.; Nakashima, M. Response and damage of base-isolated buildings. In Proceedings of the 13th World Conference on Earthquake Engineering, Vancouver BC, Canada, 18–21 June 2018; Volume 3493, pp. 1–15.

48. Kasai, K.; Mita, A.; Kitamura, H.; Matsuda, K.; Morgan, T.A.; Taylor, A.W. Performance of Seismic Protection Technologies during the 2011 Tohoku-Oki Earthquake. *Earthq. Spectra* **2013**, *29* (Suppl. S1), 265–293. [CrossRef]
49. Gheryani, M.H.; Razak, H.A.; Jameel, M. Dynamic Response Changes of Seismic Isolated Building Due to Material Degradation of HDRB. *Arab. J. Sci. Eng.* **2015**, *40*, 3429–3442. [CrossRef]
50. Li, Y.; Shan, H.; Li, Z.; Wu, Q. Effect of bearing damage on the seismic response of girder bridges. In Proceedings of the 10th International Conference on Measurement Technology and Mechatronics Automation, ICMTMA 2018, Changsha, China, 10–11 February 2018; pp. 32–35. [CrossRef]
51. Xiang, N.; Alam, M.S.; Li, J. Shake table studies of a highway bridge model by allowing the sliding of laminated-rubber bearings with and without restraining devices. *Eng. Struct.* **2018**, *171*, 583–601. [CrossRef]
52. Wang, S.-J.; Zhang, Q.-Y.; Yu, C.-H. Effectiveness of damaged viscoelastic dampers in seismic protection of structures under main shocks and aftershocks. *Eng. Struct.* **2021**, *242*, 112424. [CrossRef]
53. Brincker, R.; Zhang, L.; Andersen, P. Modal Identification from Ambient Responses using Frequency Domain Decomposition. In Proceedings of the 18th International Modal Analysis Conference, San Antonio, TX, USA, 7–10 February 2000; pp. 625–630.
54. Weng, J.H.; Loh, C.H.; Lynch, J.P.; Lu, K.C.; Lin, P.Y.; Wang, Y. Output-only modal identification of a cable-stayed bridge using wireless monitoring systems. *Eng. Struct.* **2008**, *30*, 1820–1830. [CrossRef]
55. Magalhães, F.; Cunha, Á.; Caetano, E. Dynamic monitoring of a long span arch bridge. *Eng. Struct.* **2008**, *30*, 3034–3044. [CrossRef]
56. Altunişik, A.C.; Bayraktar, A.; Sevim, B. Operational modal analysis of a scaled bridge model using EFDD and SSI methods. *Indian J. Eng. Mater. Sci.* **2012**, *19*, 320–330.
57. Zhang, J.; Prader, J.; Grimmelsman, K.A.; Moon, F.; Aktan, A.E.; Shama, A. Experimental Vibration Analysis for Structural Identification of a Long-Span Suspension Bridge. *J. Eng. Mech.* **2013**, *139*, 748–759. [CrossRef]
58. Davis, N.T.; Sanayei, M. Foundation identification using dynamic strain and acceleration measurements. *Eng. Struct.* **2020**, *208*, 109811. [CrossRef]
59. Spina, D.; Acunzo, G.; Fiorini, N.; Mori, F.; Dolce, M. A probabilistic simplified Seismic Model from Ambient Vibrations (SMAV) of existing reinforced concrete buildings. *Eng. Struct.* **2021**, *238*, 112255. [CrossRef]
60. Jalali, M.H.; Rideout, D.G. Substructural damage detection using frequency response function based inverse dynamic substructuring. *Mech. Syst. Signal Process.* **2022**, *163*, 108166. [CrossRef]
61. Chaudhary, M.T.A.; Abe, M.; Fujino, Y.; Yoshida, J. System identification of two base-isolated bridges using seismic records. *J. Struct. Eng.* **2000**, *126*, 1187–1195. [CrossRef]
62. Tan, R.Y.; Weng, I.W. Identification of dynamic properties of isolated structures. *Eng. Struct.* **1996**, *18*, 240–246. [CrossRef]
63. Matsuda, K.; Kasai, K. Responses of base-isolated buildings in Tokyo during the 2011 Great East Japan Earthquake. In Proceedings of the 15th World Conference on Earthquake Engineering, Lisbon, Portugal, 24–28 September 2012.
64. Yu, T.; Johnson, E.A.; Brewick, P.T.; Christenson, R.E.; Sato, E.; Sasaki, T. Modeling and model updating of a full-scale experimental base-isolated building. *Eng. Struct.* **2023**, *280*, 114216. [CrossRef]
65. Tariq, M.; Chaudhary, A.; Abe, M. Investigation of atypical seismic response of a base-isolated bridge. *Eng. Struct.* **2002**, *24*, 945–953.
66. Huang, M.-C.; Wang, Y.-P.; Chang, J.-R.; Chang Chien, C.-S. Physical system identification of an isolated bridge using seismic response data. *Struct. Control Health Monit.* **2009**, *16*, 241–265. [CrossRef]
67. Tafur, A.; Swailes, T. Effectiveness of rubber isolators for the seismic retrofitting of a Peruvian highway concrete bridge. In Proceedings of the Structural Engineers World Congress, Cancún, Mexico, 14–17 November 2017. [CrossRef]
68. Ramesh, R.S.; Fredette, L.; Singh, R. Identification of multi-dimensional elastic and dissipative properties of elastomeric vibration isolators. *Mech. Syst. Signal Process.* **2019**, *118*, 696–715. [CrossRef]
69. Astroza, R.; Conte, J.P.; Restrepo, J.I.; Ebrahimian, H.; Hutchinson, T. Seismic response analysis and modal identification of a full-scale five-story base-isolated building tested on the NEES@UCSD shake table. *Eng. Struct.* **2021**, *238*, 112087. [CrossRef]
70. Wen, J.; Han, Q.; Xie, Y.; Du, X.; Zhang, J. Performance-based seismic design and optimization of damper devices for cable-stayed bridge. *Eng. Struct.* **2021**, *237*, 112043. [CrossRef]
71. Pandey, A.; Biswas, M.; Samman, M. Damage detection from mode changes in curvature. *J. Sound Vib.* **1991**, *145*, 321–332. [CrossRef]
72. Alvin, K.F.; Robertson, A.N.; Reich, G.W.; Park, K.C. Structural system identification: From reality to models. *Comput. Struct.* **2003**, *81*, 1149–1176. [CrossRef]
73. Choi, S.; Stubbs, N. Damage identification in structures using the time-domain response. *J. Sound Vib.* **2004**, *275*, 577–590. [CrossRef]
74. Laxmikant, K. Damage Detection in Structures Using Natural Frequency Measurements. Ph.D. Thesis, UNSW Sydney, Sydney, Australia, 2008.
75. Malekzehtab, H.; Golafshani, A.A. Damage detection in an offshore jacket platform using genetic algorithm-based finite element model updating with noisy modal data. *Procedia Eng.* **2013**, *54*, 480–490. [CrossRef]

76. Kaveh, A.; Zolghadr, A. An improved CSS for damage detection of truss structures using changes in natural frequencies and mode shapes. *Adv. Eng. Softw.* **2014**, *80*, 93–100. [CrossRef]
77. Siriwardane, S.C. Vibration measurement-based simple technique for damage detection of truss bridges: A case study. *Case Stud. Eng. Fail. Anal.* **2015**, *4*, 50–58. [CrossRef]
78. Chisari, C.; Bedon, C.; Amadio, C. Dynamic and static identification of base-isolated bridges using Genetic Algorithms. *Eng. Struct.* **2015**, *102*, 80–92. [CrossRef]
79. He, W.; Ren, W. Structural damage detection using a parked vehicle-induced frequency variation. *Eng. Struct.* **2018**, *170*, 34–41. [CrossRef]
80. Sepehri, A.; Taghikhany, T.; Ahmadi Namin, S.M.R. Seismic design and assessment of structures with viscous dampers at limit state levels: Focus on probability of damage in devices. *Struct. Des. Tall Spec. Build.* **2018**, *28*, 1–15. [CrossRef]
81. Yuan, C.; Xiong, B.; Li, X.; Sang, X.; Kong, Q. A novel intelligent inspection robot with deep stereo vision for three-dimensional concrete damage detection and quantification. *Struct. Health Monit.* **2022**, *21*, 788–802. [CrossRef]
82. Review, S. Data-driven structural health monitoring and damage detection through deep learning. *Sensors* **2020**, *20*, 2778. [CrossRef] [PubMed]
83. Zhang, Z. Structural damage identification via physics-guided machine learning: A methodology integrating pattern recognition with finite element model updating. *Struct. Health Monit.* **2021**, *20*, 1675–1688. [CrossRef]
84. Qu, C.; Zhang, H.; Zhang, R.; Zou, S.; Huang, L.; Li, H. Multiclass anomaly detection of bridge monitoring data with data migration between different bridges for balancing data. *Appl. Sci.* **2023**, *13*, 7635. [CrossRef]
85. Samudra, S.; Barbosh, M.; Sadhu, A. Machine learning-assisted improved anomaly detection for structural health monitoring. *Sensors* **2023**, *23*, 3365. [CrossRef] [PubMed]
86. Kim, S.Y.; Mukhiddinov, M. Data anomaly detection for structural health monitoring based on a convolutional neural network. *Sensors* **2023**, *23*, 8525. [CrossRef] [PubMed]
87. Jia, J.; Li, Y. Deep learning for structural health monitoring: Data, algorithms, applications, challenges, and trends. *Sensors* **2023**, *23*, 8824. [CrossRef] [PubMed]
88. Huang, Q.; Xu, Y.L.; Li, J.C.; Su, Z.Q.; Liu, H.J. Structural damage detection of controlled building structures using frequency response functions. *J. Sound Vib.* **2012**, *331*, 3476–3492. [CrossRef]
89. Method, S. Seismic damage assessment for isolated buildings with a substructure method. *Buildings* **2022**, *12*, 1185. [CrossRef]
90. Brownjohn, J.M.W.; De Stefano, A.; Helmut, Y.X.; Emin, W.A. Vibration-based monitoring of civil infrastructure: Challenges and successes. *J. Civ. Struct. Health Monit.* **2011**, *1*, 79–95. [CrossRef]
91. Rabi, R.R.; Vailati, M.; Monti, G. Effectiveness of vibration-based techniques for damage localization and lifetime prediction in structural health monitoring of bridges: A comprehensive review. *Buildings* **2024**, *14*, 1183. [CrossRef]
92. Zacharakis, I.; Giagopoulos, D. Vibration-based damage detection using finite element modeling and the metaheuristic particle swarm optimization algorithm. *Sensors* **2022**, *22*, 5079. [CrossRef] [PubMed]
93. Zhang, M.; Guo, T.; Zhu, R.; Zong, Y.; Liu, Z.; Xu, W. Damage identification of seismic-isolated structure based on CAE network using vibration monitoring data. *Eng. Struct.* **2023**, *283*, 115873. [CrossRef]
94. Mita, A.; Yoshimoto, R. Damage assessment of base-isolated building using subspace identification approach. *WIT Trans. Built Environ.* **2003**, *72*, 179–189.
95. Keshmiry, A.; Hassani, S.; Mousavi, M.; Dackermann, U. Effects of environmental and operational conditions on structural health monitoring and non-destructive testing: A systematic review. *Buildings* **2023**, *13*, 918. [CrossRef]
96. Svendsen, B.T.; Øiseth, O.; Frøseth, G.T.; Rønnquist, A. A hybrid structural health monitoring approach for damage detection in steel bridges under simulated environmental conditions using numerical and experimental data. *Struct. Health Monit.* **2023**, *22*, 540–561. [CrossRef]
97. Ponzo, F.C.; Auletta, G.; Ielpo, P.; Ditommaso, R. DInSAR–SBAS satellite monitoring of infrastructures: How temperature affects the "Ponte della Musica" case study. *J. Civ. Struct. Health Monit.* **2024**, *14*, 745–761. [CrossRef]
98. Kwon, S.; Oh, H. Experimental validation of satellite micro-jitter management strategy in energy harvesting and vibration isolation. *Sens. Actuators A Phys.* **2016**, *249*, 172–185. [CrossRef]
99. Caprino, A.; Puliero, S.; Lorenzoni, F.; Floris, M.; da Porto, F. Satellite SAR interferometry and on-site traditional SHM to monitor the post-earthquake behavior of the Civic Tower in L'Aquila (Abruzzo Region, Italy). *Remote Sens.* **2023**, *15*, 1587. [CrossRef]
100. Sciortino, A.; Marini, R.; Guerriero, V.; Mazzanti, P.; Spadi, M.; Tallini, M. Satellite A-DInSAR pattern recognition for seismic vulnerability mapping at city scale: Insights from the L'Aquila (Italy) case study. *GIScience Remote Sens.* **2024**, *61*, 1–12. [CrossRef]
101. Di Carlo, F.; Giannetti, I.; Romualdi, A.; Meda, A.; Rinaldi, Z. On the DInSAR technique for the structural monitoring of modern existing bridges. In *Proceedings of the Institution of Civil Engineers—Bridge Engineering*; Thomas Telford Ltd.: London, UK, 2022. [CrossRef]
102. Giordano, P.F.; Turksezer, Z.I.; Previtali, M.; Limongelli, M.P. Damage detection on a historic iron bridge using satellite DInSAR data. *Struct. Health Monit.* **2022**, *21*, 2291–2311. [CrossRef]

103. Miano, A.; Di Carlo, F.; Mele, A.; Giannetti, I.; Nappo, N.; Rompato, M.; Striano, P.; Bonano, M.; Bozzano, F.; Lanari, R.; et al. GIS integration of DInSAR measurements, geological investigation, and historical surveys for the structural monitoring of buildings and infrastructures: An application to the Valco San Paolo urban area of Rome. *Infrastructures* **2022**, *7*, 89. [CrossRef]
104. Miano, A.; Mele, A.; Calcaterra, D.; Di Martire, D.; Infante, D.; Prota, A.; Ramondini, M. The use of satellite data to support the structural health monitoring in areas affected by slow-moving landslides: A potential application to reinforced concrete buildings. *Struct. Health Monit.* **2021**, *20*, 3265–3287. [CrossRef]
105. Confuorto, P.; Di, D.; Infante, D.; Novellino, A.; Calcaterra, D.; Ramondini, M. Catena monitoring of remedial works performance on landslide-affected areas through ground- and satellite-based techniques. *Catena* **2019**, *178*, 77–89. [CrossRef]
106. Meng, Q.; Confuorto, P.; Peng, Y.; Raspini, F.; Bianchini, S.; Han, S.; Liu, H.; Casagli, N. Regional recognition and classification of active loess landslides using two-dimensional deformation derived from Sentinel-1 interferometric radar data. *J. Geophys. Res. Earth Surf.* **2020**, *129*, 1541. [CrossRef]
107. Tonelli, D.; Caspani, V.F.; Valentini, A.; Rocca, A.; Torboli, R.; Vitti, A.; Perissin, D.; Zonta, D. Interpretation of bridge health monitoring data from satellite InSAR technology. *Remote Sens.* **2023**, *15*, 5242. [CrossRef]
108. Deng, Z.; Huang, M.; Wan, N.; Zhang, J. The current development of structural health monitoring for bridges: A review. *Buildings* **2023**, *13*, 1360. [CrossRef]