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Structural Damage Identification Methods in Truss Bridge Structures Using Vibration Analysis: A Review

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Abstract. Developing countries will always engage in infrastructure development in various regions, and one notable aspect of this development is the construction of steel frame bridges. Bridges are complex structures with a myriad of challenges. The increasing number of cases of steel frame bridge collapses has prompted humans to become more conscious of Structural Health Monitoring (SHM) activities. In order to implement this, the development of a straightforward structural damage detection method has been pursued, suitable for both simple and highly complex structures, commonly referred to as Vibration-Based Damage Detection (VBDD). Various algorithms have been proposed to achieve the goal of identifying structural damage, enabling prompt and accurate decision-making in handling such situations. This article delves into the discussion of several proposed algorithms for achieving this objective.

1. Introduction

The Developing countries will always engage in infrastructure development across various regions. One of the key projects in this development is the construction of steel frame bridges[1]. Bridges are integral parts of infrastructure, and as such, bridge collapses can have significant impacts on both the economy and human safety [2][3]. For instance, the collapse of the Silver Bridge in Ohio in 1967 resulted in 46 deaths, and the failure of the I-35W bridge in Minnesota in 2007 due to overload during repairs and gusset plate failure[4][5] led to 13 deaths and 145 severe injuries. This resulted in a loss of $26 billion for the United States from 2007 to 2008. The U.S. reported 503 cases of bridge collapse causing substantial losses to the country between 1989 and 2000[3]. In 2007, a steel frame bridge in Japan was found to have corrosion in some of its sections[6]. In Indonesia, there were two cases of steel frame bridge collapses in 2018, namely the Ponulele bridge in Palu, which collapsed due to an earthquake and tsunami, and the collapse of a steel frame bridge on the Tuban - Lamongan border due to excessive load[1].

The increasing number of bridge collapses has prompted researchers to seek detailed information about the causes and mechanisms of bridge failure[3] A research study indicates that there are two main factors causing bridge collapses: natural factors and human factors. Natural factors include floods, earthquakes, landslides, storms, hurricanes, extreme conditions, and others. Human factors encompass design flaws, incorrect construction methods, collisions, overloading, fires, inadequate inspection and maintenance, and others. These factors contribute to the deterioration and collapse of bridge structures [3][7].

As a consequence, engineers are researching optimal methods for detecting bridge damage to provide early information about deterioration, thus minimizing bridge collapse incidents that can result in fatalities and economic losses for the country [8]. Visual inspection methods are considered less effective. Visual methods provide valuable information when monitoring protocols are in place, but their weakness lies in the dependence on the skills and experience of inspection operators to identify damage[9]. Consequently, the concept of structural health, also known as Structural Health Monitoring (SHM), has been developed in the field of Structural Engineering[10]. SHM involves observing the structure or system's behavior over time through periodic measurements, extracting measurements that are sensitive to damage, and conducting static analysis to determine the health status of the system[11]. SHM is also used to validate design assumptions, enabling decision-making regarding maintenance issues and maintenance management [12]. SHM can contribute to assessing five levels of damage [11][13][14]:

1) Existence: Is there damage to this system?
2) Location: Where is the damage in this system?

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3) Type: What type of damage?
4) Size: How severe is the damage?
5) Prognosis: How much remaining service life does this system have?

To achieve these contributions, various studies are being developed, and a vibration-based damage detection (VVDB) method has been proposed. This method has gained prominence due to the increasing complexity of structural damage cases [15]. Essentially, the idea behind vibration-based damage identification is that damage is caused by changes in the physical properties of the object. These physical properties, such as mass, damping, and stiffness, can be indicated by changes in natural frequencies, modal damping, and mode shapes [16]. Damage can also be defined by changes in geometric or material characteristics that adversely affect the performance, safety, and reliability of the structure [17]. Assessing structural conditions based on vibrations (VVDB) is considered effective in detecting structural damage using modal parameters such as natural frequencies, mode shapes, damping ratios, curvature mode shapes, and others [18][19]. The VVDB method is highly effective for use in short and medium-span bridges, as well as complex structures with easily modeled finite elements [20]. Several formulations for applying vibration-based damage detection (VVDB) methods are being developed.

2. Comparative Study of Literature and Methods

Research related to the development of vibration-based damage detection (VVDB) methods has been conducted by numerous researchers. Among them, Moradipour [15] developed the MSE method and tested it on a numerical and experimental steel frame bridge structure model. The results showed that the MSECR method can be proposed for the monitoring of complex bridge health and accurately identifying damage in the steel frame bridge structure model. Zhou [20] conducted a comparison of algorithms for identifying and locating damage in a detached box girder test model from a bridge. All algorithms were able to detect and localize damage using six uniformly distributed accelerometers [20][21] (as seen in Figure 1), but they were susceptible to errors when detecting damage located in the support area. From the comparison, the CMS interpolation method showed the highest accuracy in locating damage for broader damage cases. Frigui [22] tested algorithms for detecting and locating damage in building structures using the Finite Element Method (FEM). In their research, damage detection methods using Eigenfrequencies and the Modal Assurance Criterion (MAC) were applied, followed by localization using the Modal Strain Curvature (MSC) and Cross Modal Assurance Criterion (CDF) methods. The results indicated that the MAC method could detect damage in the 16th mode, while the MSC method could localize damage in low modes. Chang [21] applied the MAC and COMAC methods for damage identification in a steel frame bridge using the FEM. The results showed that the MAC method was effective in detecting damage because it was sensitive to specific damage scenarios. Rucevskis [23] conducted a comparative test of the MSC, MSCS, and MSCSM algorithms to identify damage in an experimental beam. The beam structure was prepared in both intact and damaged conditions with various damage locations. The results showed that the MSC and MSCS damage index methods, as well as the proposed MSCSM damage index method, successfully indicated the size and location of damage. The advantage of the MSCS method was that it only required data from the damaged structure to detect damage in the studied damaged beam structure.

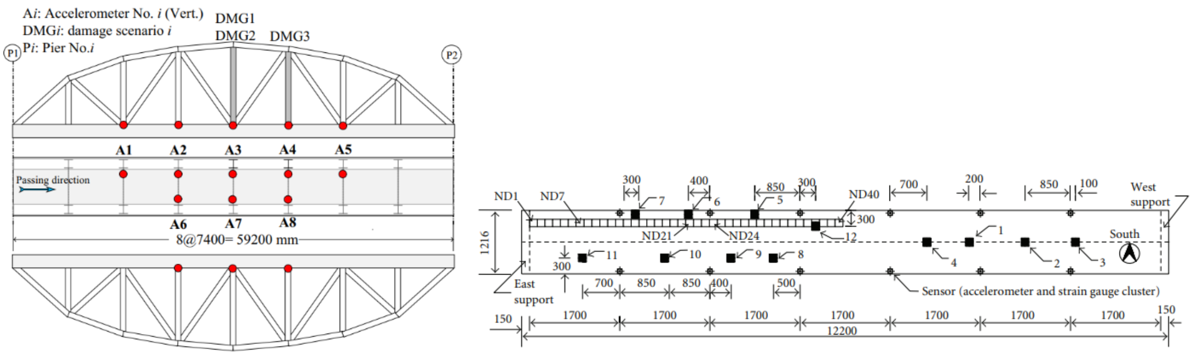

Fig. 1. The Uniform distribution of accelerometer sensors [20][21]

From the various comparative studies discussed in the previous paragraphs, each researcher has formulated several algorithms for vibration-based damage detection (VVDB), which are commonly used to detect structural damage. These include the following methods: Change in Mode Shape (CMS) method [20], modal assurance criterion (MAC) method [22][21], mode shape curvature (MSC) method [20], modal strain energy change ratio (MSECR) method [15], and mode shape curvature square (MSCS) method [23]. The detailed formulations provided in the literature are as follows:

2.1. Change in Mode Shape Method (CMS): This method calculates the simple difference values between the mode shapes of the damaged and intact structures.

$$\Delta\phi = |\phi^*| - |\phi|$$

Where the evaluation result is represented by the symbol of the absolute value, indicating the evaluation of the absolute values of each component of the damaged and intact structural vectors [20].

2.2. Modal assurance criterion (MAC)

$$MAC_{jk} = \frac{\left(\sum_{i=1}^{n} [\psi_u]_i^j [\psi_d]_i^k\right)^2}{\sum_{i=1}^{n}\left([\psi_u]_i^j\right)^2 ([\psi_d]_i^k)^2}$$

Where $[\psi_u]$ and $[\psi_d]$ represent the respective mode shapes of the intact and damaged structures. MAC_{jk} is a factor that indicates the relationship between the j^{th} and k^{th} modes, and n is the number of measurement nodes [22].

2.3. Mode shape curvature (MSC)

$$\Delta v_i'' = \left|v_i''^d - v_i''\right|$$

In this algorithm, the indication of damage location can be assessed by the difference in curvature shapes between the nodes of the intact structure and the damaged structure. The curvature shape of the mode is calculated from the measured experimental mode shape or numerically using the central difference approximation approach [23], as follows:

$$v_i'' = \frac{(v_{i+1} - 2v_i + v_{i-1})}{h^2}$$

The number of damage indices for each mode is determined by the following formula:

$$MSC_i = \frac{1}{N}\sum_{n=1}^{N}\left(\Delta v_i''\right)_n$$

2.4. Modal strain energy change ratio (MSECR)

Modal strain energy ratio can detect damage location by applying calculations (2.4a) and (2.4b).

$$MSECR_{ij} = \frac{\left|MSE_{ij}^d - MSE_{ij}\right|}{MSE_{ij}} \quad (2.4a)$$

$$MSECR_j = \frac{1}{5}\sum_{i=1}^{5}\frac{MSECR_{ij}}{MSECR_{i,max}} \quad (2.4b)$$

Where i is the mode; j is the element dan $MSECR_j$ is the average value of the sum of $MSECR_{ij}$ for the first five modes, taken in absolute value for the $MSECR_{i,max}$ value in each mode.

2.5. Mode shape curvature square (MSCS)

The damage index is determined by this formula:

$$\Delta v_i''^2 = \left|v_i''^{d2} - v_i''^2\right|$$

For multiple modes, the index formula is used as follows:

$$MSCS_i = \frac{1}{N}\sum_{n=1}^{N}\left(\Delta v_i''^2\right)_n$$

Some methods require data from the intact structure; therefore, this method can be used to detect damage location in the damaged structure. This method is proposed because it only requires damage indices from the damaged structure [23]. Based on the previously researched formulations, the explanation is as follows (Table 1).

Table 1. Application of the VBDD method to be able to contribute to SHM

Algorithm	Parameter input	SHM Countribution		
		Level 1	Level 2	Others
CMS	Mode shape	Yes	-	-
MAC	Mode shape and natural frequency	Yes	Yes	-
MSC	Mode shape and natural frequency	Yes	Yes	-
MSECR	Mode shape and stiffness matrix	Yes	Yes	-

MSCS	Mode shape	Yes	Yes	Yes

Explanation:
Level 1 contribution of SHM is to identify the presence of damage in the structure.
Level 2 contribution of SHM is to detect the location of damage in the structure.
Other contributions imply SHM capabilities beyond levels 1 and 2.

In the comparison of the literature studies, it is also necessary to assess the algorithm's ability to detect damage for the modeled scenarios of damage in the research object. This can be observed in Table 2.

Table 2. Algorithm Comparison for Damage Detection

Algorithm	Single damage detection	Multiple damage detection	Noise immunity
CMS	Yes	No	N/A
MAC	Yes	Yes	N/A
MSC	Yes	Yes	Excelent
MSECR	Yes	Yes	Excelent
MSCS	Yes	Yes	Excelent

The explanations provided in the two tables above will be discussed in point 3 as a reference for designing a structural monitoring system for easy damage identification and localization.

3. Results and Discussion

Based on the literature review study conducted earlier and referring to Tables 1 and 2, the following points can be discussed:

• **Change in Mode Shape Method (CMS):** CMS requires mode shape data from both intact and damaged structures to detect damage in the researched object. Unfortunately, CMS is effective in detecting damage for scenarios where the damage is close to the vibration measurement devices. Thus, implementing the CMS algorithm necessitates a sufficient number of vibration measurement devices placed adequately close (as shown in Figure 1) to provide optimal information.

• **Modal Assurance Criterion (MAC):** MAC utilizes mode shape and natural frequency data from intact and damaged structures. This algorithm excels in identifying and localizing damage in complex structures. MAC is proficient in representing various damage scenarios. It requires mode shape and natural frequency data from both intact and damaged structures as input.

• **Mode Shape Curvature (MSC):** MSC is also proficient in effectively detecting and localizing damage in complex structures with low noise.

• **Modal Strain Energy Change Ratio (MSECR):** MSECR employs several features as parameters and also requires data from an intact structural model for comparison. However, this algorithm is capable of accurately identifying and localizing damage even with 3 to 5% noise present.

• **Mode Shape Curvature Square (MSCS):** MSCS was proposed by previous researchers as it requires minimal data, specifically mode shapes generated from the damaged structure. MSCS is effective in representing various damage scenarios in complex structures with low noise.

These observations emphasize the strengths and limitations of each algorithm in detecting and localizing damage in different scenarios. Depending on the specific requirements of the structural monitoring project, such as the degree of damage localization needed, the availability of data, and the complexity of the structure, engineers and designers can make informed choices about which SHM method to employ. The comparison and insights provided by the tables help guide the selection of an appropriate algorithm for effective and accurate damage detection and localization.

4. Conclusions

1. The increasing number of structural failures, particularly in bridge structures, has prompted engineers to investigate the root causes of these collapses. Studies derived from various research efforts have categorized these structural failures into two main factors: human-related factors and natural factors.

2. Vibration-Based Damage Detection (VBDD) has been extensively proposed by researchers for identifying damage. This method is considered effective and cost-efficient, making it suitable for application to structures with high levels of complexity.
3. In order to implement the concept of vibration-based damage detection, research has been conducted on various algorithms aimed at identifying and localizing damage in a simple and cost-effective manner.
4. Among the algorithms explored through literature study, some of them require data from intact structures as input for comparison with the analysis of damaged structures.

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