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Identification of Structural Damage in Frame Bridge Using Mode Shape Curvature: Simulation on Laboratory-Scale Frame Bridge

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ABSTRACT

Bridge construction is known as one of the transportation means to connect two roads that are separated due to natural factors. Bridges also represent a nation's asset. Steel is chosen as the material because of its durability and strength. However, inadequate maintenance of steel bridges can lead to structural damage or failure. Structural failure can result in economic losses for a country and, more importantly, pose threats to human lives. Therefore, monitoring activities for structural health are necessary. In the past decade, the development of Structural Health Monitoring Systems (SHMS) has been underway. To address the challenges of SHMS, various methods are being researched, including Non-Destructive Testing (NDT). NDT methods are considered the best choice for inspection as they are easy and effective in detecting, analyzing, and diagnosing structural issues. Hence, this study aims to detect the location of damage in steel bridge structures using the Mode Shape Curvature (MSC) method with the assistance of accelerometer sensors to scan dynamic frequency extractions of the structure for monitoring and assessing the occurring damages. It is observed that from the designed damage scenarios, the MSC index indicates stiffness loss with increasing MSC values at the damage locations.

Keywords: Damage Detection; MSC; NDT; SHM; Truss Bridge

ABSTRACT

Konstruksi jembatan sudah dikenal sebagai salah satu sarana transportasi untuk menghubungkan dua jalan yang terputus karena faktor alam. Jembatan juga merupakan kekayaan nasional dari suatu negara. Pemilihan material baja dipilih karena kekuatannya yang tidak mudah rusak dan awet. Akan tetapi apabila kegiatan pemeliharaan terhadap jembatan baja kurang, akan berpotensi pada kerusakan bahkan kegagalan pada struktur. Kegagalan pada struktur dapat menimbulkan kerugian ekonomi bagi Negara, lebih dari itu dapat mengancam keselamatan jiwa manusia. Maka dari itu, dibutuhkan adanya kegiatan monitoring terhadap kondisi kesehatan struktur. Pengembangan kegiatan monitoring yang sedang dikembangkan pada dekade terakhir ini, yaitu Sistem Monitoring Kesehatan Struktur (SHMS). Untuk dapat menjawab tantangan SHMS, berbagai metode diteliti termasuk diantaranya yaitu Metode Non Destruktif Test (NDT). Metode NDT merupakan pilihan terbaik sebagai sarana inspeksi yang dinilai mudah dan efektif untuk mendeteksi, menganalisis, mendiagnosis sejumlah permasalahan pada struktur. Oleh karena itu, dalam penelitian ini, dilakukan deteksi lokasi kerusakan pada struktur jembatan baja dengan metode Mode Shape Curvature (MSC) dengan alat bantu sensor accelerometer untuk memindai ekstraksi frekuensi dinamis struktur agar dapat memonitoring dan menilai kerusakan yang terjadi pada struktur. Terlihat bahwa dari skenario kerusakan yang didesain, MSC index menunjukkan kehilangan kekakuan dengan meningkatnya nilai MSC pada lokasi kerusakan.

Keywords: Deteksi Kerusakan; MSC; NDT; SHM; Truss Bridge

INTRODUCTION

Steel bridges are a vital part of a nation's infrastructure. Most bridge constructions are dominated by steel bridges with various designs and structural types. Steel bridges are known as robust structures for long-span applications (spanning over 30m) that can connect two separate roads due to natural factors [1]. The choice of steel material is due to its known strength and durability. However, without proper maintenance to monitor the bridge's condition, steel bridges are susceptible to structural damage and failure due to aging [2]. In some countries, such as Japan, statistical data from 2012 estimated that 9% of all constructed bridges were over 50 years old, with 81% being less than 30 years old. These bridges require serious attention to maintenance to anticipate structural failures [3]. In the United States, data from 2013 indicated that approximately 11% of bridge structures were inefficiently aged, with a service life of over 65 years. Similarly, in Indonesia, many bridges built between 1945 and 1965 have a service life of over 50 years [4]. Hence, regular maintenance and monitoring activities are essential, especially for steel frame bridges, to prevent potential damages and failures that could lead to losses in various aspects [5]. Structural failures can result in significant economic losses and pose threats to human lives. Therefore, regular structural condition monitoring and maintenance are necessary at short intervals to prevent potential severe damages and failures in structures. Some common damages to steel bridges include corrosion, section bending, cracks, among others [6].

(a) (b) (c)

Figure 1. The Most Common Type of Damage in Bridge a) Corrosion, b) Buckling, c) crack.

Source: Dolati et al, 2021

Monitoring the structural condition of bridges poses a new challenge for experts to ensure that bridge structures remain in a safe condition [7]. Various inspection methods are being developed to assess the structural condition in real-time and with accuracy, providing early warnings to bridge users in the event of structural damage. Additionally, accurate and real-time structural inspections serve as a reference for making informed decisions in handling the structure, ensuring that it can withstand the applied loads. In the past decade, Non-Destructive Testing (NDT) methods have been developed and applied as inspection and assessment tools for bridge structures. These methods are considered easy, fast, and effective for detecting, analyzing, diagnosing various issues in structures such as cracks, voids, fatigue, corrosion, delamination, or even loss of section [7]. NDT techniques for monitoring and assessing damages in structures have been widely applied in various industries such as aerospace, space vehicles, power plant equipment, architecture, metallurgy, mechanical manufacturing, etc. Damage detection techniques in non-destructive testing (NDT) such as CT scanning, accelerometers, and ultrasonic testing, etc., are primarily used to detect local damage in structures and can determine the presence and location of damage [8].

This research is also developed to assess and identify damages in steel bridge structures to contribute to Structural Health Monitoring (SHM), which is a system for monitoring the health of structures. This technique is developed to extract bridge frequency data from dynamic responses recorded using accelerometers due to applied loading [9]. Structural Health Monitoring Systems (SHMS) installed on infrastructures record long-term behaviors. Information obtained from SHMS is mostly used to assess long-term damage processes due to physical aging and traffic loads [10]. Many studies seek to investigate the impact of structural damage on the physical properties of the structure. Damage assessment in structures is based on the idea that damaged structures will result in changes in the physical properties of the structure, which can be marked by changes in modal properties such as natural frequencies, modal damping, and mode shape [11]. Modal property variables are closely related to the stiffness of the structure. Therefore, changes in frequency or mode shape indicate a loss of stiffness in the structure [12][13]. Damage can also be interpreted as changes in geometric characteristics that can have adverse effects on the performance, safety, and reliability of the structure [14]. This research aims to complement previous studies, with the objective of detecting damage locations using the Mode Shape Curvature (MSC) method in bridge structures to contribute to SHM [12]. The MSC method is widely used because it shows good sensitivity to damage [15]. The MSC method used indicates peak curvature indices at the location of the damage. Therefore, in this study, intact or healthy bridge structures and damaged bridge models will be modeled. This research utilizes accelerometer sensors to read dynamic responses in both healthy and damaged structures.

LITERATURE REVIEW

Mode Shape Curvature (MSC) index

There are several methods available for detecting and localizing damage in structures. Researchers have extensively discussed these methods to address the contemporary challenge of assessing the structural health of bridges. This study focuses on the Mode Shape Curvature (MSC) method. The MSC method is applied by referencing the relationship between mode shape curvature and flexural stiffness [12].

$$v''(x) = \frac{M(x)}{EI} \qquad \text{…. (1)}$$

Where v'' Indicating the mode shape curvature at location x, M (x) represents the bending moment, and EI is the flexural stiffness of the structure. It can be observed from equation (1) that a damaged structure will have varying Young's modulus, affecting the curvature shape of the mode shape. MSC is defined as the absolute difference in curvature between the damaged and intact structures (2) [12].

$$\Delta v_i'' = \left| v_{i,u}'' - v_{i,d}'' \right| \qquad \text{…. (2)}$$

v_i'' represents the mode shape curvature for mode i, u and d indicate the conditions of the healthy and damaged structures, respectively. Therefore, it can be stated that an increase in local curvature occurs when there is a local decrease in stiffness [12]. The Curvature can be calculated using the following equation (3) [12].

$$v_{i,j}'' = \frac{v_{i+1j} - 2v_{i,j} + v_{i-1j}}{h^2} \qquad \text{…. (3)}$$

Where, h is the constant distance separating two consecutive nodes, $v_{i,j}$ is the mode shape at coordinate *i* located in mode *j*.

Natural frequency

A structure will experience resonance if the frequency imposed on the structure approaches or equals its natural frequency. Typically, the first 3 or 4 modes are considered potential resonance modes. The natural frequencies for bridges are generally below 5Hz for vertical vibrations and 1.5Hz for horizontal vibrations. If the frequencies fall outside of these ranges, it is necessary to check the vibration tolerance of the structure [16].

Mode Shape

Generally, a bridge structure can have three main vibration modes: horizontal, torsional, and vertical. Modal analysis yields the shapes for each mode of the analyzed structure [16].

METHOD

Here are the steps taken in this study, as illustrated in Figure 2. The first step involves creating specimens of intact frame bridge structures, where the bridge model has no damage scenario (Figure 3). Subsequently, specimens of damaged frame bridges are created with damage scenarios applied at the center of the bridge span (Figure 4) and at one-quarter of the bridge span (Figure 5). The damage scenarios involve a damaged profile due to bending (Figure 6). This type of damage approximates the typical field damage [6]. The Non-Destructive Testing (NDT) is conducted using an accelerometer sensor placed at specific points, namely at the center and one-quarter span of the bridge.

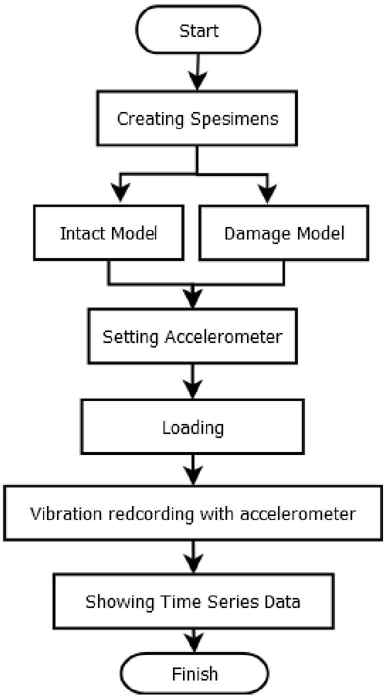

Figure 2. Research Flowchart.

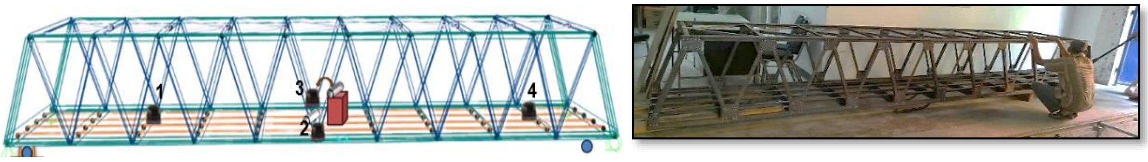

Figure 3. Intact Specimen.

Figure 4. Damage Specimen with Damage at the Center Span of the Bridge.

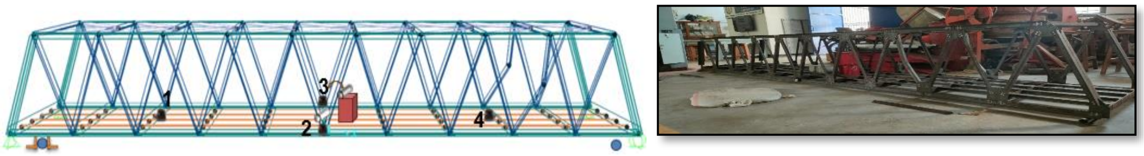

Figure 5. Damage Specimen with Damage at one-quarter span of the bridge.

Figure 6. Buckling Profile Model.

Subsequently, loading is applied in the form of vibration excitation generated by a dropping weight. The vibrations from the dropping weight are captured by an accelerometer sensor. The time-domain data is then received by a gateway for processing using the Fast Fourier Transform (FFT) algorithm, transforming it into the frequency domain. The natural frequency values for each test specimen are extracted from the data. At each accelerometer point on the bridge model, acceleration values are recorded to determine the modal displacement at that point. Modal displacement values are used as variables in MSC analysis to detect damage locations in the structure. The assessment parameters for damage can be observed through an increase in local curvature, indicating a localized reduction in stiffness.

RESULTS AND DISCUSSION

Natural Frequencies of the Bridge Model

Here are the natural frequencies (Table 1) obtained from the testing of the intact bridge model and the damaged bridge model based on the accelerometer sensor recordings.

Table 1. Natural Frequencies of Each Bridge Model

Num	Specimen	Condition	Natural Frequencies (Hz)			
			I	II	III	Average
1	Intact	Undamaged	2,18	2,06	2,06	2,10
2	Damage-1	Buckling	1,96	1,91	1,91	1,93
3	Damage-2	Buckling	1,96	1,91	1,81	1,89

Note: The specimen conditions can be observed in Figures 3 to 5.

Modal Acceleration of the Bridge Model

According to the recorded vibration signal data from each accelerometer, modal acceleration data was obtained as shown in Tables 2-4.

Tabel 2. Modal Acceleration of the Intact Bridge Model

Time (s)				**Acceleration (m/s²)**				
Intact Model				**Intact Model**				
				Experimental				
1	2	3	Avg	1	2	3	Avg	m/s²
0,15	0,15	0,2	0,17	0,1919	0,2325	0,2536	0,226	2,2173
0,16	0,21	0,15	0,17	0,1186	0,2660	0,2459	0,2102	2,0619
0,16	0,175	0,1	0,15	0,1065	0,2164	0,2001	0,1743	1,7104
0,18	0,3	0,1	0,19	0,1968	0,3042	0,1387	0,2132	2,092

Tabel 3. Modal Percepatan Pada Model Jembatan Damage-1

Time (s)				**Acceleration (m/s²)**				
Damage-1 Model				**Damage-1 Model**				
				Experimental				
1	2	3	Avg	1	2	3	Avg	m/s²
0,15	0,03	0,1	0,09	0,2701	0,0933	0,2533	0,2056	2,0168
0,25	0,175	0,25	0,23	0,2077	0,2473	0,1456	0,2002	1,9642
0,25	0,175	0,25	0,23	0,1348	0,1205	0,2232	0,1595	1,5649
0,1	0,18	0,25	0,18	0,1384	0,1343	0,2559	0,1762	1,7287

Tabel 4. Modal Percepatan Pada Model Jembatan Damage-2

Time (s)				**Acceleration (m/s²)**				
Damage-2 Model				**Damage-2 Model**				
				Experimental				
1	2	3	Avg	1	2	3	Avg	m/s²
0,07	0,2	0,06	0,11	0,2682	0,2246	0,1048	0,1992	1,9544
0,05	0,15	0,06	0,09	0,1089	0,1804	0,1112	0,1335	1,3098
0,06	0,05	0,02	0,04	0,095	0,1939	0,1659	0,1516	1,4873
0,25	0,06	0,16	0,16	0,1246	0,0909	0,1749	0,1301	1,2767

With reference to Tables 2-4, the data can be used to calculate the modal displacement values that occur in both the intact and damaged models. Subsequently, the modal displacement data is utilized to detect damage locations in the structure using the MSC algorithm with the application of equations 2 and 3. The assessment parameters are determined by the high curvature at specific points, indicating a reduction in stiffness at those points.

Tabel 5. MSC Index in the Damage-1 Bridge Model

Node.	**Measurement Result**			**Measurement Result**			$\Delta vi''^2$
	Intact Model			Damage 1 Model			
	a	v	d	a	v	d	
	m/det²	m/det	m	m/det²	m/det	m	
57062	2,2173	0,37	3,08	2,0168	0,19	0,88	8,71
56489	2,0619	0,36	3,10	1,9642	0,44	4,97	15,12
56490	1,7104	0,25	1,80	1,5649	0,35	3,96	12,46
57060	2,0920	0,40	3,91	1,7287	0,31	2,70	8,01

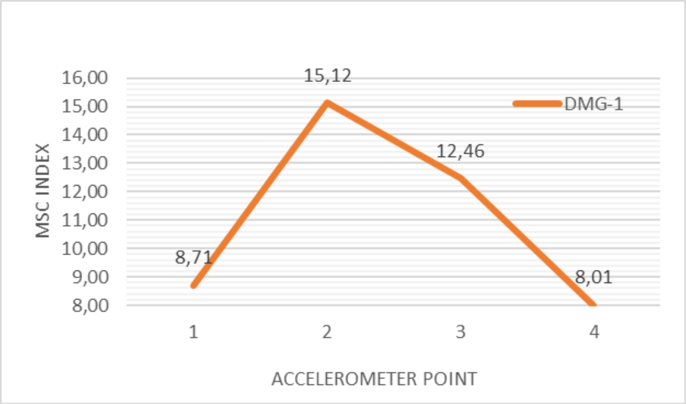

Figure 7. MSC Index Pada Model Damage-1.

Tabel 6. MSC Indeks Pada Model Jembatan Damage-2

Node.	**Measurement Result**			**Measurement Result**			$\Delta vi''^2$
	Intact Model			Damage 2 Model			
	a	v	d	a	v	d	
	m/det²	m/det	m	m/det²	m/det	m	
57062	2,2173	0,37	3,08	1,9544	0,21	1,18	8,09
56489	2,0619	0,36	3,10	1,3098	0,11	0,49	9,35
56490	1,7104	0,25	1,80	1,4873	0,32	3,44	8,58
57060	2,0920	0,40	3,91	1,2767	0,20	1,57	12,83

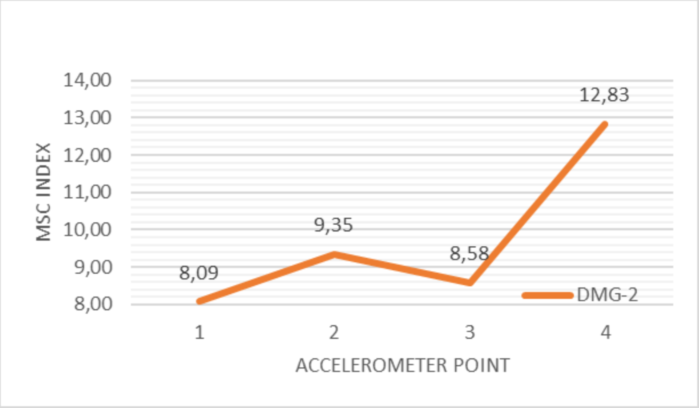

Figure 8. MSC Index Pada Model Damage-2.

From Figure 7, it is indicated that accelerometers at points 2 and 3 show a loss of stiffness in the structure due to damage. This can be validated in the damage-1 structure model (Figure 3), where the loss of stiffness is caused by a bend in the profile at the center of the span. Meanwhile, in Figure 8, an increase in MSC value occurs at accelerometer point 4. This can be validated in Figure 4, where the bending damage model is created at one-quarter span of the bridge, placed at accelerometer point 4. This suggests that MSC analysis can be utilized to detect damage locations in bridge structures.

CONCLUSION

Based on the discussion in Figures 7 and 8, it is evident that the MSC method can be applied to localize damage in complex bridge structures.

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