LOGIC
Journal of Engineering Design and Technology
Vol. 24 No.2 July 2024 ; p. 93 - 100

p-ISSN : 1412-114X
e-ISSN : 2580-5649
http://ojs2.pnb.ac.id/index.php/LOGIC

APPLICATION OF MODE SHAPE DATA BASE INDICATOR (MSDBI) FOR DAMAGE DETECTION OF STEEL FRAME BRIDGE STRUCTURE BASED ON MODAL ASSURANCE CRITERION (MAC)

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Abstract. The substantial expansion of the global economy and the extensive urbanization witnessed in recent decades have rendered bridge infrastructure as a vital component of transportation systems. Conducting structural damage detection is a vital strategy to prevent structural failures and avert bridge collapse. One popular approach for detecting damage is to use mode shapes as characteristics in structural dynamics analysis. In this study, the identification of the mode shapes in the damaged condition will utilize the Modal Assurance Criterion (MAC), while the location of the damage within the simulation will be identified using the Mode Shape Data Base Indicator (MSDBI). The study was carried out with the help of a finite element model using Midas Civil software with a case study of a steel frame bridge. Referring to the report studied, damage identification focused on damage caused by loose bolts. The results of the analysis show that the MAC analysis has consistent values on mode shapes in each damage simulation with the mode shapes produced by the healthy condition model. Meanwhile, damage location is detected by the MSDBI index value in each damage simulation. It can be seen that the MSDBI index changes according to the location of the damage
.

Keywords : Damage detection, steel bridge, MAC, MSDBI.

1. INTRODUCTION

The substantial expansion of the global economy and extensive urbanization in recent decades have rendered bridge infrastructure as a vital component of infrastructure aspect. Damaged or inadequate performance of bridges, leading to potential collapses, presents significant challenges within infrastructure networks and results in measurable losses [1], [2]. A significant portion of bridges in Japan, approximately 9%, have reached the end of their designed lifespan. Projections indicate that this percentage will rise up to 53% within the next 20 years, as most bridges were constructed following World War II [3], [4], [5]. It is estimated that around 5,000 bridges in the United States require some of restorative work, such as repairs, reinforcements, or complete replacements, on an annual basis to maintain their structural integrity and functionality [5]. The failure of the Kutai Kartanegara bridge in 2011 emphasized the critical need for routine inspections of infrastructure to mitigate the risk of structural collapses [6]. Conducting bridge structural damage detection has become important to identify and to prevent structural failures. Furthermore, identified damage on bridge also necessary to repair the bridge and to maintain bridges in good condition to become a reliable infrastructure to support rapid economic growth. However, due to financial limitations, bridge replacement is often not a feasible solution [3], [7], [8].

One popular approach for detecting damage is to use mode shapes as characteristics in structural dynamics. Conceptually, damage modifies the mechanical characteristics of a bridge, including stiffness and mass, resulting in alterations to the dynamic response and damage detection method that utilizes mode shapes is the Modal Assurance Criterion (MAC) [9] [10]. MAC is a scalar value that quantifies the consistency between two sets of modal data, enabling a direct comparison of mode shapes in healthy and damaged structural conditions. While this method cannot precisely identify the specific location of damage due to its insensitivity to minor changes in mode shapes; however, it can still serve as a valuable diagnostic tool, providing an overall indication of structural damage. The Mode Shape Data Base Indicator (MSDBI) is utilized to detect localized damage in bridge structures, with a simple beam structure as a case study [11]. MSDBI study findings demonstrate the sensitivity of this index to reductions in beam cross-sectional stiffness. Increases the index value correspond well with the locations of damage along the beam elements, providing reliable damage detection results [11].

The main objective in this study is to damage detection in steel bridges by comparing the mode shapes of the structure in both healthy and damaged conditions by creating a simulation model of damage due to loose bolts. The identification of the mode shapes in the damaged condition will be using Modal Assurance Criterion (MAC), while the location of the damage within the simulation will be identified by Mode Shape Data Base Indicator (MSDBI).

2. METHODS

The research method utilizes mode shapes as the one dynamic response characteristic of structure to detect the presence and location of damage. Changes in the observed mode shapes between before and after the occurrence of damage are analyzed as an indicator to identify structural damage. [11].

2.1. Modal Assurance Criterion (MAC)

MAC is a popular method that uses a comparison of two mode shapes in the identification of damage to bridges. MAC compares two mode shapes such as mode shapes with different conditions. In this study, a mode shapes of healthy and damaged conditions were used from the analysis results. The value of MAC is a scalar value limited between zero and one, representing a linear relationship between two mode shape data sets [12]. In practice, MAC serves to assess the identification of variance conducted or to approximate the results from testing different variances. The MAC value is calculated based on two data of mode shape vectors using Equation (1) [13].

$$\mathrm{MAC}(r,q) = \frac{\left|\{\phi_A\}_r^T\{\phi_X\}_q\right|^2}{\left(\{\phi_A\}_r^T\{\phi_A\}_r\right)\left(\{\phi_X\}_q^T\{\phi_X\}_q\right)} \tag{1}$$

Where $\{\phi_X\}_q$ is mode shape vector healthy condition, mode q, $\{\phi_A\}_r$ is mode shape vector damage condition, mode r, $\{\phi_X\}_q^T$ is transpose of $\{\phi_X\}_q$, and $\{\phi_A\}_r^T$ is transpose of $\{\phi_A\}_r$.

MAC is primarily employed to evaluate the consistency among mode shape vectors, rather than to assess their validity or orthogonality [14]. However, the MAC has notable limitations in its ability to identify potential issues, as it cannot effectively capture the presence of consistent random or systematic errors across the variance estimation vectors. [13]. In addition, MAC is unable to distinguish between systematic errors and localized differences. This limitation is often attributable to the underlying assumptions or estimation techniques used for the variance parameters being invalid. Furthermore, MAC may be susceptible to the effects of measurement uncertainty, which can impact its reliability and usefulness [15]. Consequently, MAC is frequently utilized as a preliminary check prior to further analysis and only to identify which mode shape have consistent value of healthy condition or close to a value of one.

2.2. Mode Shape Data Based Indicator (MSDBI)

The MSDBI will be use to detects structural damage by analyzing changes in the mode shape data before and after the occurrence of damage in curvature plot. MSDBI utilizes the first and second derivatives from two mode shape data sets to identify the presence and location of structural damage. [11]. Equation (2) represents the modal data extracted from the structural model, which includes the nodal coordinates and mode shapes.

$$\left[x_{q,}\Phi_{(q,i)} = \left[x_{q,}\Phi_{(1,i)}, x_{q,}\Phi_{(2,i)}, \dots, x_{q,}\Phi_{(n+1,i)}\right]\right] \tag{2}$$

Where nodal coordinates, $x_{q,}$ $q = 1,2,\dots,n+1$ and mode shapes, $\Phi_{(q,i)}, q = 1,2,\dots,n+1$. The first and second derivatives of equation (2) are approximated using Equation (3) and Equation (4).

$$\boldsymbol{\Phi'}_{\mathbf{q,i}} = \frac{\boldsymbol{\Phi}_{\mathbf{q+1,i}} - \boldsymbol{\Phi}_{\mathbf{q-1,i}}}{\mathbf{2l_e}} \tag{3}$$

$$\boldsymbol{\Phi''}_{\mathbf{q,i}} = \frac{\boldsymbol{\Phi}_{\mathbf{q-1,i}} - 2\boldsymbol{\Phi}_{\mathbf{q,i}} + \boldsymbol{\Phi}_{\mathbf{q+1,i}}}{\mathbf{l_e^2}} \tag{4}$$

Where $\Phi_{q,i}$ is mode shape of the q[th] node in the i[th] mode shape and l_e is constant distance separating two consecutive nodes. From Equations (3) and (4) the MSDBI value is obtained using the Equation (5).

$$\mathbf{MSDBI_q} = \frac{\sum_{i=1}^{nm} \left| \left[\left| \Phi''_{d(q,i)} - \Phi''_{h(q,i)} \right| \times \left(\Phi_{d(q,i)} \right)^2 \right] - \left[\left(\left| \Phi'_{d(q,i)} \right| - \left| \Phi'_{h(q,i)} \right| \right)^2 \times \Phi_{h(q,i)} \right] \right|}{nm} \tag{5}$$

Where $\Phi_{h(q,i)}$ is mode shape of healthy condition, $\Phi_{d(q,i)}$ is mode shape of damage condition and nm is number of mode shapes. With the assumption that MSDBI values are obtained from all nodal from the model, $(MSDBI_q, q = 1,2, \dots, n+1)$ which represents a normally distributed sample, then the MSDBI form can be normalized as in equation (6).

$$\mathbf{nMSDBI_q} = \max \left[0, \left(\frac{\mathbf{MSDBI_q - mean\ (MSDBI)}}{\mathbf{std\ (MSDBI)}} \right) \right] \tag{6}$$

Where, $MSDBI_q$ is defined by Equation (5), mean (MSDBI) and std (MSDBI) is mean and standard deviation of MSDBI.

2.3. Case Study

The case study will be remodel of the existing steel frame bridge structure, with data sourced from laporan Uji Respons 1 Jembatan Citarum issued by Pusat Litbang Jalan dan Jembatan (PUSJATAN). The case study is conducted through modeling using the Midas Civil software as shown in Figure 1.

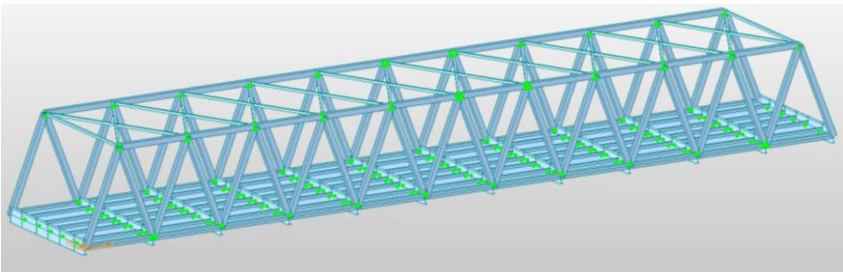


Figure 1. Steel bridge Structural Modeling in 3 Dimensions

The identified damage of the steel frame bridge structure is due to loose bolts, which reduce the stiffness of the steel bridge connections. The location for loose bolts connections to be considered are the downstream direction at upper and bottom chord sections as shown in Figure 2.

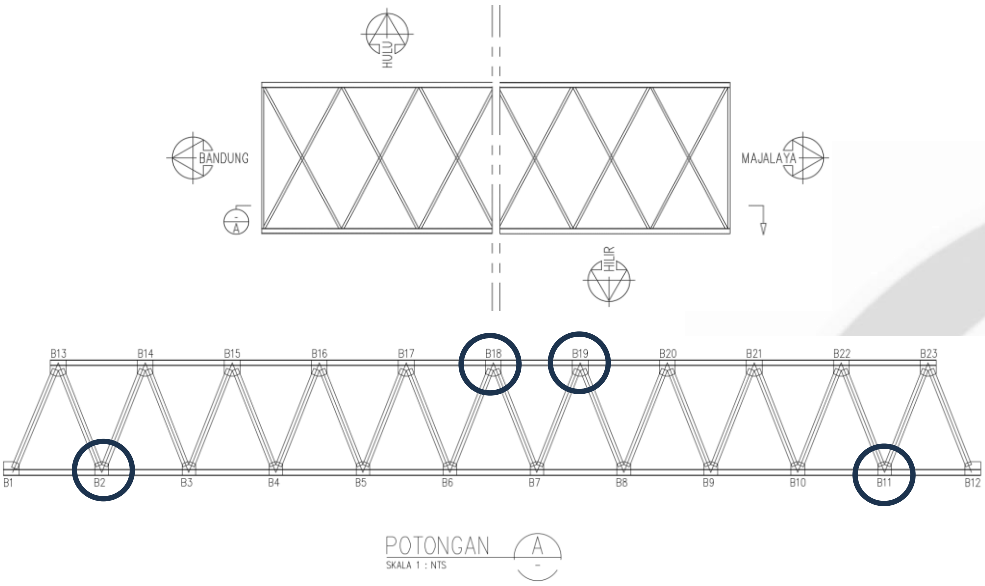


Figure 2. Location of loose bolts at downstream direction

From Figure 2, the locations of loose bolts are at bolt node (B), B2, B11, B18, and B19 in downstream and upstream directions. The percentconsage value of tight bolts included in the model is the smallest percentage value. Imperfections in bolt installation on the diagonal elements in this study are not modeled and some part of steel structural element in upper and bottom chord sections will designed as frame. The percentage of loose bolts in upstream and downstream directions is presented in Table 1. The damage that occurs at nodal points in bridge connections is characterized by a reduction in axial stiffness in the Z direction and lateral stiffness in the X direction, with the smallest percentage value identified. A simulation of the damage was conducted to obtain the mode shape data of damaged condition, which are presented in the Table 2.

Table 1. Percentage of stiffness reduction

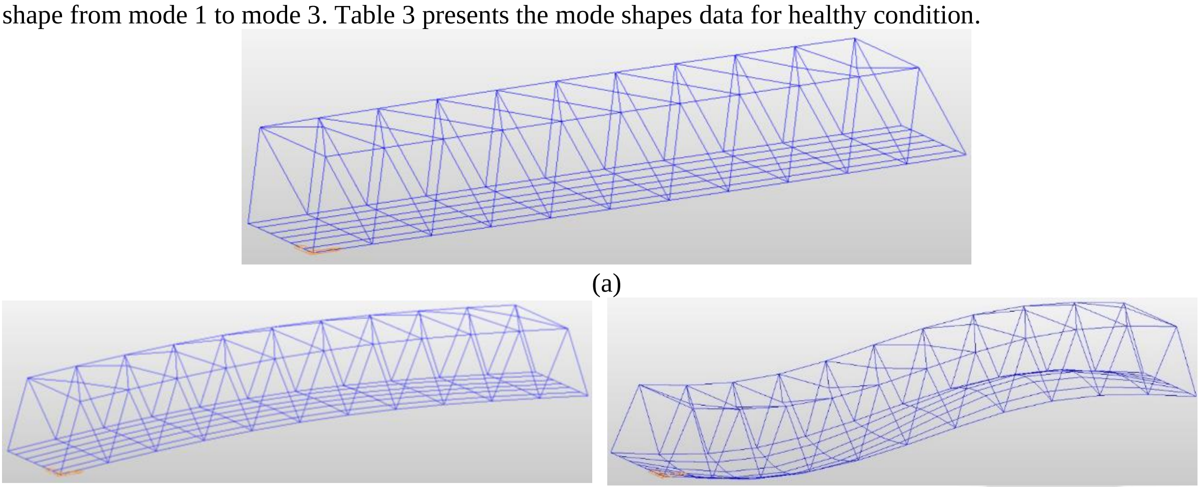
Downstream direction				
Node	B2	B11	B18	B19
Number of loose bolts/total bolts	3/10	2/20	8/20	12/20
Percent reduction (%)	70%	90%	60%	40%
Upstream direction				
Node	B2	B11	B18	B19
Number of loose bolts/total bolts	-	-	6/20	9/20
Percent reduction (%)	-	-	70%	55%

Table 2. Damage Simulation

Simulation	Damage description
Healthy	Healthy condition
Damage 1	B2 and B11 at downstream direction
Damage 2	B18 and B19 at downstream direction
Damage 3	B18 and B19 at upstream direction
Damage 4	B2, B11, B18 and B19 at downstream direction
Damage 5	B2 and B11 at downstream position; B18 and B19 at upstream direction
Damage 6	B2 and B11 at downstream direction; B18 and B19 at downstream and upstream direction

3. RESULTS AND DISCUSSION

The output from the model are natural frequencies and mode shapes, within Figure 3 illustrate the mode shape from mode 1 to mode 3. Table 3 presents the mode shapes data for healthy condition.



(a) (b) (c)

Figure 3. Bridge Structure on (a) Mode shape 1; (b) Mode shape 2; (c) Mode shape 3

Table 3. Natural frequency and mode shape healthy condition

Mode Shapes	Direction	Frequency (Hertz)
1	Y Dir.	1.427863
2	Z Dir.	2.020688
3	Z Dir.	2.783113

3.1. MAC Analysis

The condition of the bridge is assessed using equation (1) to obtain data on damage based on the MAC method by analyzing the mode shape of the bridge structure. The analysis results can determine the MAC value for each simulation on Table 4.

Table 4 MAC Analysis for All Damage Simulation

Simulation	X Dir.		Y Dir.		Z Dir.	
	Mode	Value	Mode	Value	Mode	Value
Damage 1	1	0.997	1	0.887	2	0.585
Damage 2	1	0.783	1	0.888	2	0.725
Damage 3	1	0.806	1	0.888	2	0.562
Damage 4	1	0.776	1	0.888	2	0.725
Damage 5	1	0.803	1	0.888	2	0.562
Damage 6	1	0.943	1	0.888	2	0.589

From Table 4 it is observed that mode shape 1 have consistent values or close to 1 in Damage 1 to Damage 6 simulations under the healthy condition of the bridge structure in both the X and Y directions. The MAC analysis in the Z direction indicates that mode shape 2 is closest to a healthy condition. Damage 2 and Damage 4 simulations share the same MAC value of 0.725, reflecting similar damage characteristics. Similarly, Damage 3 and Damage 5 simulations also have identical MAC values due to comparable damage patterns. The values for Damage 1 and Damage 6 simulations are also similar, as both involve damage to the bottom chord section.

3.2. MSDBI Analysis

Detecting bridge structural damage of MSDBI relies on the mode shape values of the bridge structure from the damaged simulation, with the mode shape analyzed through the dominant modes produced by the MAC method. In Damage 1 Simulation, the MSDBI graph indicates an increase in MSDBI values on both the left and right sides where the damage location are, as shown in Figure 4. The MSDBI values are also present at the nodes that experienced damage, consistent with the assumptions in the simulation and across all examined directions.

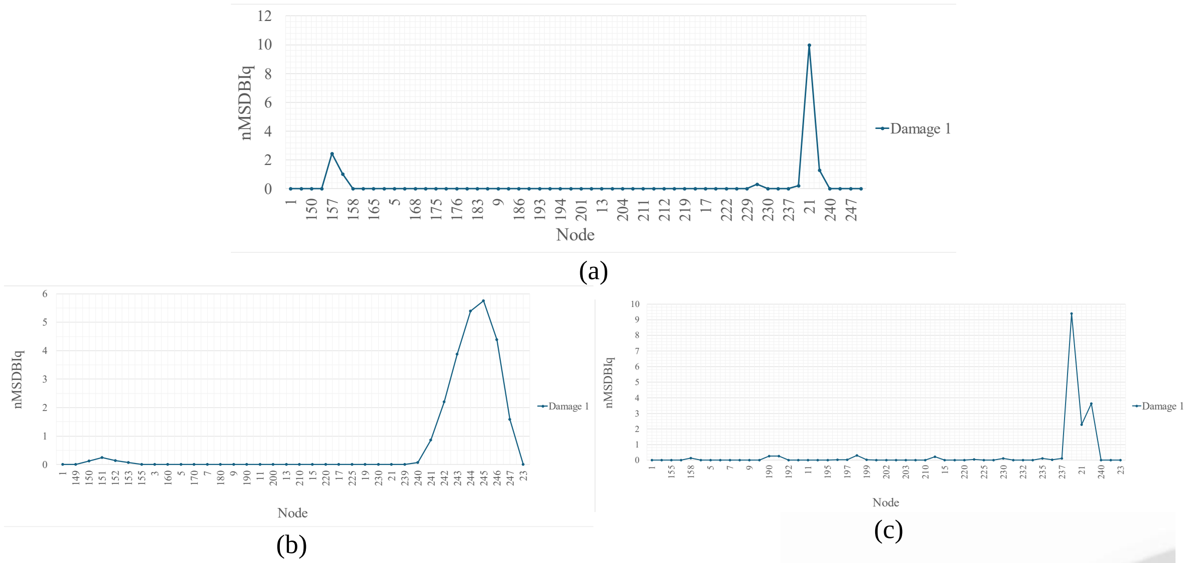


Figure 4. MSDBI Damage 1 simulation at (a) X direction; (b) Y direction; (c) Z direction

A comparison Damage 2 and Damage 3 simulations resulted in damage occurring in the middle of the span and having a tendency graph with a sharp shape in the middle of the span indicating that the damage occurred in the middle. However, Damage 3 displays more damage index than Damage 2 that lead to the MSDBI curve has numerous values along upstream direction. In Z direction, simulation 2 shows a sharp graphical trend at the mid-span, while simulation 3 has a fluctuating pattern. The differences in these damage patterns indicate that the shape of the curve varies depending on the downstream direction which is presented in Figure 5.

Damage 2 and Damage 4 simulations show a similar damage pattern in the X direction, much like the comparison Damage 2 and Damage 3 simulations. The Y direction also has the same pattern where the MSDBI value makes the damage graph in the middle of the span. Likewise, in the Z direction, the damage value has similar values in both simulations as in the curve in Figure 6.

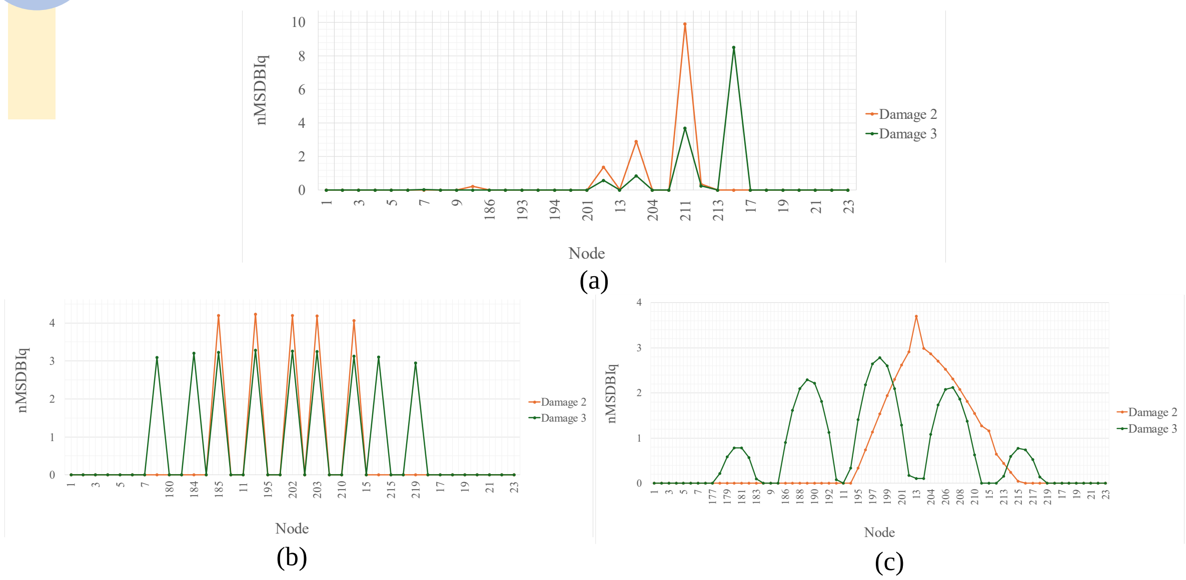


Figure 5. Comparison of MSDBI Damage 2 and Damage 3 simulations at (a) X direction; (b) Y direction; (c) Z direction

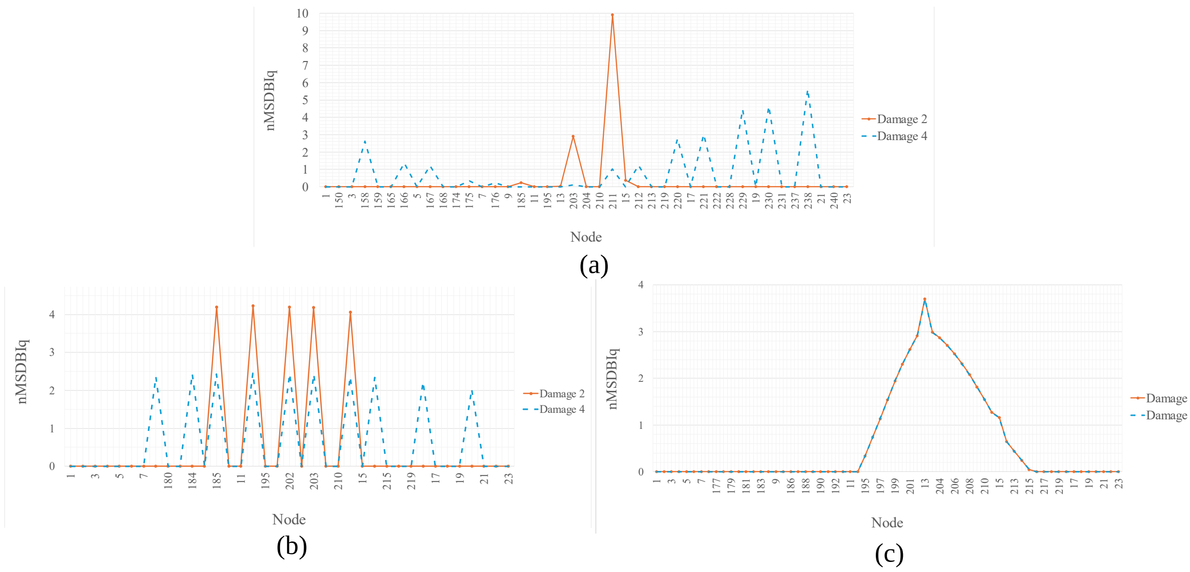
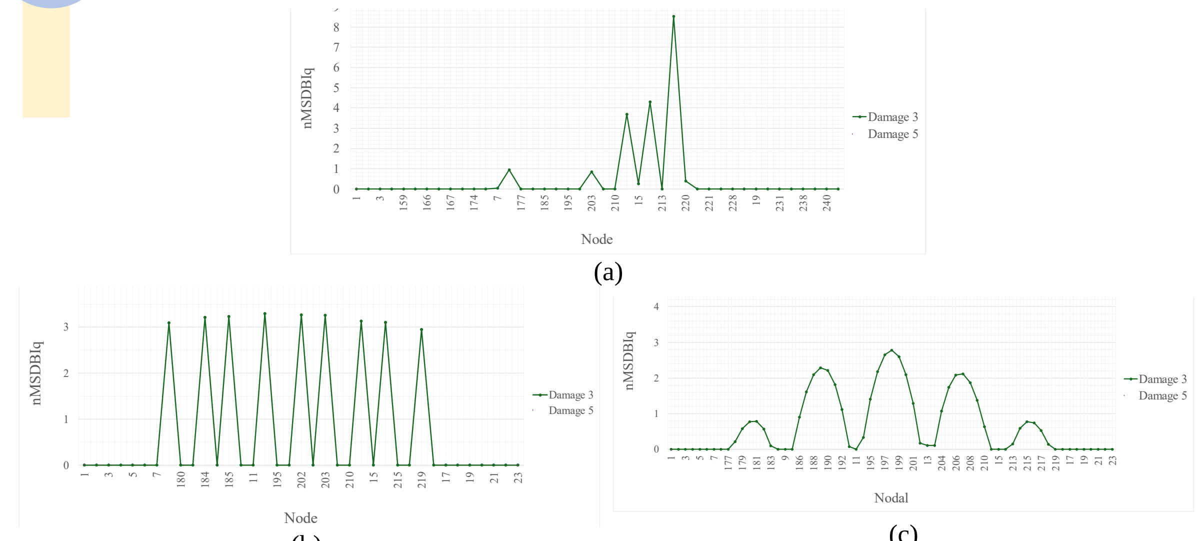


Figure 6. Comparison of MSDBI Damage 2 and Damage 4 simulations at (a) X direction; (b) Y direction; (c) Z direction

The comparison of the Damage 3 and Damage 5 simulations also has the same pattern as in the comparison of Damage 2 and Damage 4 simulations where the MSDBI index value shows an increase at the node simulated damage that illustrated in Figure 7. The key difference between the comparison Damage 3 and Damage 5 simulations and comparison Damage 2 and Damage 4 simulations, is the shape of the curve in the Z direction, as comparison Damage 3 and Damage 5 simulations are assessed in upstream direction.

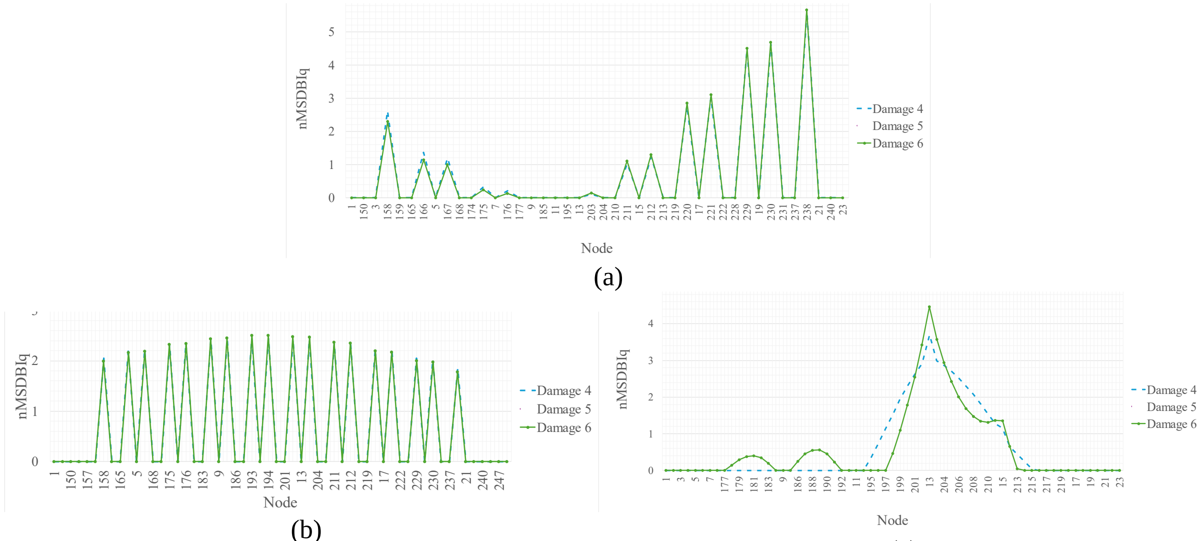
Figure 8 shows a similar graphic shape in the Damage 4, 5 and 6 simulations in the X direction simulations where the graphs of all three simulations have the same pattern. This indicates that the damage on the left and right sides is more dominant compared to the damage in the center. Comparison in Y direction also reveals a similar MSDBI graph shape across the three simulations, as well as in the previously described in MAC analysis, where the MAC values for all three simulations are the same at 0.888, making the Y direction graphs tends to be similar. In the Z direction, it is observed that the graph for simulation Damage 6 takes the shape of the two previous simulations, leading to the conclusion that simulation Damage 6 is a combination of the graph from the two prior simulations and has the highest MSDBI value among the three simulations.



(a)

(b) (c)

Figure 7. Comparison of MSDBI Damage 3 and Damage 5 simulations at (a) X direction; (b) Y direction; (c) Z direction



(a)

(b) (c)

Figure 8. Comparison of MSDBI Damage 4, Damage 5 and Damage 6 simulations at (a) X direction; (b) Y direction; (c) Z direction

From the results obtained, MAC analysis can determine the mode shapes in damage conditions that are close to healthy conditions more accurately. With MAC analysis, it is hoped that the data of mode shapes from test result in the field can be faster to identifying a consistent mode shapes that will be used for the next analysis. From the results of the MSDBI analysis, it was found that the MSDBI analysis could provide a damage curve that was in accordance with the simulated damage with a consistent mode shape from MAC analysis so that the location of the damage could be known more quickly in the test field.

4. CONCLUSION

Based on the analysis and comparison of the two previous methods, several conclusions were obtained as follows:

1. The Modal Assurance Criterion analysis indicates that the dominant modes correspond to the healthy condition, which are mode 1 in the Y direction and mode 2 in the Z direction. The MAC results in the Y direction are the most consistent, with values around 0.88 or 0.9, suggesting a strong correlation throughout the damage simulation. Simulations with similar damage locations exhibit comparable MAC values in each direction, such as Damage 2 and Damage 4, as well as Damage 3 and Damage 5, where the simulations with greater damage have slightly smaller MAC values.
2. The comparison of the MSDBI curves indicates that the MSDBI curve in the X direction exhibits a shape consistent with the specified damage locations across the simulations. However, the upstream direction of the

curve shows greater curvature than the downstream side, as evidenced by the alignment of the MSDBI values with the designated damage points, such as in the comparison of Damage 2 and Damage 4 simulations. The MSDBI curve in the Y direction also corresponds to the specified damage location, displaying a sharper curve but with a more distinct pattern compared to the X direction across all simulations. The MSDBI curve pattern in the Z direction varies between directions, with sharp curvatures observed in the downstream direction for Damage 1, Damage 2, and Damage 4 simulations, while the upstream direction exhibits a fluctuating curve, as seen in simulations 3 and 5. In simulation 6, a combination of curves from Damage 4 and Damage 5 is observed, which corresponds with the assumption that damage occurs on both sides.

3. Identifying the mode shapes from damage condition will more accurately using MAC analysis and the results of the MSDBI analysis for each damage simulation show a change in the curve value according to the damage simulation, which conlcude that the MSDBI analysis can identify the location of damage more accurately.

5. ACKNOWLEDGEMENT

The author would like to thank the Civil Engineering Department of Parahyangan Catholic University and PT Midasindo Teknik Utama for support of MIDAS CIVIL software steel bridge modeling.

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