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Real Time Bridge Dynamic Response: Bridge Condition Assessment and Early Warning System

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***Abstract*— The present study investigates the use of wireless sensor networks (WSNs) in the assessment of bridge conditions as well as an early warning system. The WSNs are used to measure the acceleration that occurred on the bridge and the mode shape of the bridge as the excitation loads passing through the bridge. Fast Fourier Transform (FFT) is applied to transform the measured acceleration to get the frequency of the dynamic bridge response. Numerical integration is applied to determine the acceleration to get the displacement of the bridge dynamic response. Implementing the structural dynamics equation, the effective stiffness of the bridge can be determined using the frequency. The effective stiffness and the bridge dynamic response are then used to obtain the bridge condition and load ratings. A scaled model of steel truss bridge and miniature truck with various loads were used to simulate the use of WSNs in bridge assessment, which were also used to validate the finite element model. The finite element model was then used to simulate various scenarios, including the scenarios in which the bridge elements had the various level of damages. The behaviors of bridge with various level of damages can be used to identify the location and the level of damages in the bridge and were found to be useful as early warning system for bridges condition and load ratings.**

***Keywords*— structural health monitoring; bridge condition assessment; bridge load rating; structural dynamics; fast fourier transform.**

I. INTRODUCTION

Bridges are among the most important infrastructure to support social and economic activities in a region. It is even more so in Indonesia, an archipelago with many rivers crossing the land. Indonesia also lies along the pacific ring of fire; thus, earthquakes and ground tremors occur frequently. These natural challenges, often added by the low quality of infrastructure plus the lack of adequate bridge monitoring and management, often result in deterioration or even fatal bridge collapses.

Like other structures, bridge deterioration could be caused by various factors. Besides environmental conditions and natural disasters, such as earthquakes, factors like aging and additional loads also cause significant effects. The deterioration usually results in a reduction in the bridge's capability to withstand the loadings or to perform within its requirements. Therefore, for safety and continuous availability reasons, measuring the level of deterioration of a bridge is necessary.

In the past, measuring the level of structural deterioration in Indonesia is carried out periodically and manually; for example, once in every five years. A team of experts carries out a visual inspection and sometime conducts loading tests and measures the displacement that occurs to the bridge. However, these approaches have several disadvantages. Visual inspection relies on the individual capabilities of the experts, and the loading test with measurements is expensive and complicated. In addition to that, because it was carried out only once in every few years, any deterioration that happens before the scheduled inspection may not be detected. Consequently, the rate of deterioration may significantly increase, or the necessary maintenance works may not be done in time.

Analyzing the dynamic response of a structure, including a bridge, to a certain load, is one way to determine the characteristic of the structure, namely its stiffness. The stiffness of a structure relates to its capability to withstand loads as well as its deformation to the corresponding loads. This characteristic has been used to assess the condition of the structure [1]–[3], or in the case of a bridge, the rating criteria are based on bridge condition and load ratings [4]. By finding out the bridge response and the corresponding loads in real-time, the bridge conditions (or rating) assessment can be done continuously. The bridge condition is determined based on the difference between the actual and the initial dynamic response (see [5] and [6]). Any changes to the bridge response (indicating change in the bridge characteristics) can be detected immediately.

Among the methods to measure the dynamic response of a bridge is by using wireless sensor networks or WSNs [7]. It was shown in some studies, such as [8]–[11], that WSNs are cost-effective for this purpose. However, these studies focus more on the bridge condition evaluation based on its response to the excitation loads, namely the relationship between the bridge conditions and the frequency and displacement that occurred. Moreover, the effect of the bridge's supports condition may have some effect on the overall bridge's dynamic response [12].

The present study examines other aspects of the bridge's dynamic response. Not only the relationship between bridge conditions and its response but also between bridge conditions and the traffic conditions. Furthermore, in the case where the bridge has some damage, the relationship between the bridge dynamic response and the location of the damage will also be studied. This will facilitate real-time bridge condition assessment and early warning systems for various aspects of bridge operations.

II. MATERIALS AND METHOD

Bridge rating is determined based on the difference between the initial and the actual bridge's dynamic characteristics [4]. The actual bridge's dynamic characteristics can be different from the initial due to the deterioration. Ideally, the initial bridge's dynamic characteristics should be obtained from the measurement of the bridge response under a certain load when the bridge was newly constructed. However, if the initial dynamic characteristics are not available, they can be assumed using the computer model.

The dynamic characteristics are the bridge response frequency and its mode shape. From the structural dynamics, one can also derive the structural stiffness of the bridge from its dynamic characteristics. Using statics, which shows the relationship between the load, the stiffness, and the deformation, one can quickly determine the load capacity of the bridge given the stiffness and the maximum allowable deformation.

There are two critical parameters of the dynamic characteristics bridge, namely the bridge's response frequency and the maximum displacement. These two parameters need to be calculated from the measurement of the dynamic bridge response, which is in the form of time-domain acceleration. To identify the dominant frequency of the bridge response, the time-domain response needs to be converted into frequency-domain. One way to achieve this is by implementing the Fast Fourier Transform (FFT) [13].

As mentioned earlier, the bridge's condition rating can be determined by comparing the dynamic characteristics of the actual bridges to that of the initial. Federal Highway Administration (FHWA) of U.S. Department of Transportation proposed an approach where the bridge's condition rating is determined based on the difference between the actual frequency response to the initial frequency response of the bridge,

$$\text{Bridge Condition Rating} = Integer(9 - G) \tag{1}$$

$$G = \frac{\Delta f \times 1000}{123} \tag{2}$$

$$\Delta f = \frac{f_{initial} - f_{actual}}{f_{initial}} \tag{3}$$

The description of the bridge condition corresponds to the Bridge Condition Rating in Eq. (1) is presented in the following table I.

TABLE I
GENERAL RATING CONDITION [15]

Rating	**Description**	**Commonly Employed Feasible Action**
9	EXCELLENT CONDITION	Preventive Maintenance
8	VERY GOOD CONDITION: No problems noted.	
7	GOOD CONDITION: Some minor problems.	
6	SATISFACTORY CONDITION: Structural elements show some minor deterioration.	Preventive Maintenance and/or Repair
5	FAIR CONDITION: Primary structural elements are sound but may have some minor section loss, cracking, spalling, or scour.	
4	POOR CONDITON: Advance section loss, deterioration, spalling, or scour.	Rehabilitation or Replacement
3	SERIOUS CONDITION: Loss of section, deterioration, spalling, or scour have seriously affected primary structural component. Local failure is possible. Fatigue cracks in steel or sheer cracks in concrete may be present.	
2	CRITICAL CONDITION: Advance deterioration of primary structural element. Fatigue cracks in steel or shear cracks in concrete may be present or scour may have removed substructure support. Unless closely monitored, the bridge may have to be closed until corrective action is taken.	
1	IMMINENT FAILURE CONDITION: Major deterioration of section loss present in critical structure component or obvious vertical or horizontal movement affecting structure stability. Bridge is closed to traffic but corrective action may put back in light service.	
0	FAILED CONDITION: Out of service, beyond corrective action.	

The load rating, or the maximum load that the bridge is capable to withstand, is determined using the stiffness and the displacement of the bridge under the load. The displacement response is obtained using the integration method, as shown in the following equation,

$$x(t) = \iint_{t_1}^{t_2} a(t)\, dt \tag{4}$$

which can be calculated using the numerical method as proposed by [17].

As the dominant frequency of the bridge's response f is identified using the FFT approach, the stiffness of the bridge structure k can be determined using the following formula [18],

$$f = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \tag{5}$$

With the assumption that the response's first mode (the dominant frequency of the bridge's response) as the most critical, the bending stiffness associated with this mode may be determined using Eq. (5).

Subsequently, using Hooke's law for deformation for static load,

$$\delta = \frac{P}{k} \tag{6}$$

the relationship between the load and the displacement is established.

As the bridge has a maximum allowable displacement δ_{max} specified codes, hence the maximum allowable load P_{max} is calculated as follow,

$$P_{max} = k \cdot \delta_{max} \tag{7}$$

It should be noted that the present problem is a dynamic problem instead of static. Therefore, it is necessary to introduce an impact factor for dynamic effect, $DLFA$ or the Dynamic Load Factor of Acceleration. The $DLFA$ is essentially the ratio between the dynamic and static deflections which expressed in term of acceleration (see [14] and [15]),

$$DLFA = \frac{a_{fast}(t)}{a_{slow}(t)} \geq 1.33 \tag{8}$$

Using Eq. (8), the correspondent maximum allowable static load P_{static} for the bridge is,

$$P_{static} = \frac{P_{max}}{DLFA} \tag{9}$$

III. Result and Discussion

A. Laboratory Test

It is clear from the relationship that the bridge's condition rating and subsequently its load capacity can be determined by measuring the bridge's dynamic response under excitation loads. The excitation loads are the traffic passing over the bridge. WSNs, as mentioned in earlier, has the capability to measure the acceleration of the bridge's response with respect of time during the excitation loads.

In the present research, a simulator is used to study the bridge characteristics. A scaled model of steel truss bridge was developed. As the excitation load, a scaled model of truck was used. The scaled model of the bridge and the truck are shown in Fig. 1 and Fig. 2. To measure the bridge dynamic response, four accelerometers were installed at certain locations of the bridge (see Fig. 3).

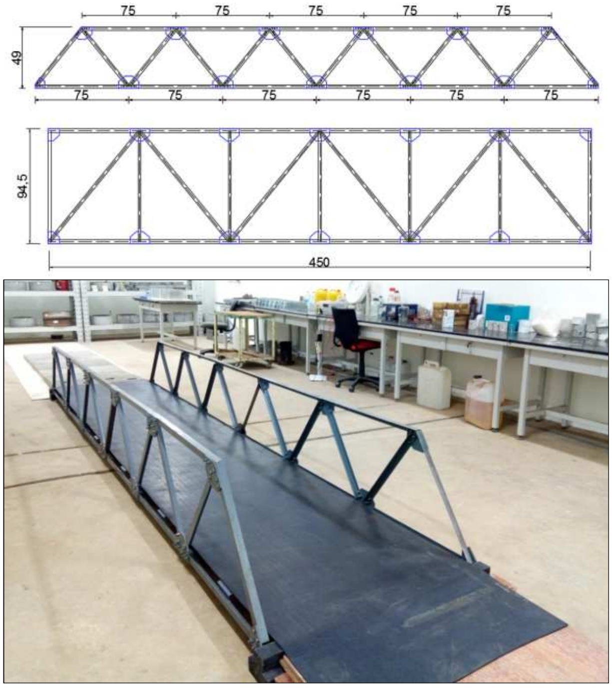

Fig. 1 Scaled bridge model for simulation

Fig. 2 Miniature truck to simulate the traffic load

Fig. 3 Accelerometer sensors and their positions on the bridge model

The weight and the speed of the miniature truck passing through the bridge model are varied to obtain the effect of both parameters to the dynamic response of the bridge model. The weights being considered were empty (7.68 kg), half-full (10.66 kg), and full load (13.62 kg); whereas the speed was low (0.85 m/s) and high (1.95 m/s).

Firstly, the scaled model of bridge was used to verify the computer model. The weight and the sizes of the structural elements can be easily measured. However, the rigidity of the connections needs to be verified by comparing the results from the test using the scaled bridge model and the results from the computer model simulations.

To do so, the rigidity of the connections in the computer model are varied and the bridge response frequency and the maximum acceleration occurred of the computer model are compared to that of the scaled bridge. It was found that the connections in the computer model had to be modelled as semi-rigid with the coefficient of 0.77. The models were then used to establish the relationship between the parameters and the bridge dynamic response.

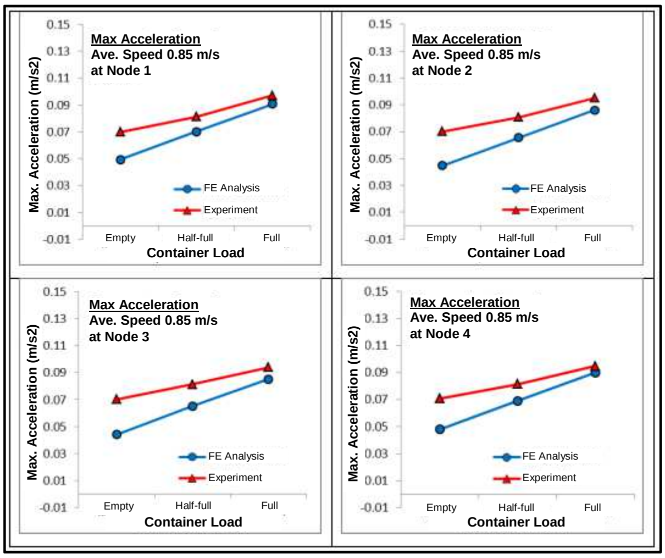

Fig. 4 Relationship between maximum acceleration of the bridge response and the truck load for low speed

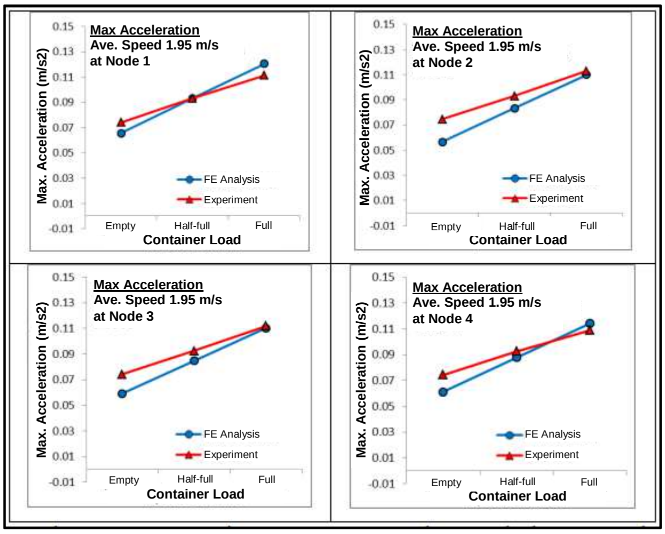

Fig. 5 Relationship between maximum acceleration of bridge response and the truck load for high speed

In Figs. 4 and 5, it was clearly shown that the maximum acceleration of the bridge response increases as the truck load increases, for low speed as well as high speed. The relationship of the load rating, or the maximum load the bridge can withstand, with the truck load is also established from the models, as shown in Fig. 6. The load rating less than 1.0 means the truck load exceeded the maximum allowable load of the bridge. There is no significant change in the bridge condition rating, as the bridge structure did not have any deterioration.

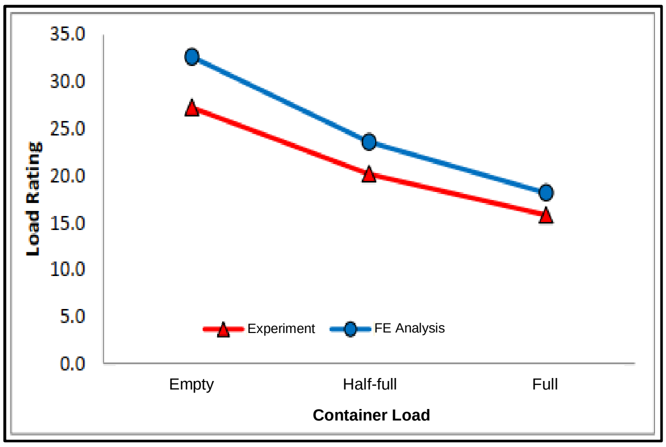

Fig. 6 Relationship between bridge load rating and the truck load

Present research also studied the effect of damage to the bridge dynamic response. For this purpose, structural damage was simulated in several structural elements in the model. There are 2 scenarios considered here. In the first scenario, the damage was simulated in the mid-part of the bridge model, whereas in the second one, the damage was in the end-part (see Figs. 7 and 8).

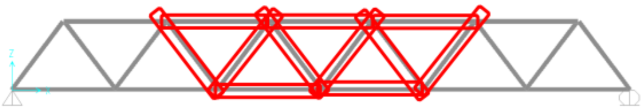

Fig. 7 Simulated damage in the mid-part of the model

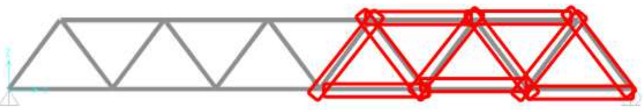

Fig. 8 Simulated damage in the end-part of the model

There are 3 levels of damage considered in the study: $0.95EA$, $0.90EA$, and $0.80EA$. The parameter EA is the axial stiffness of the truss members of the bridge model.

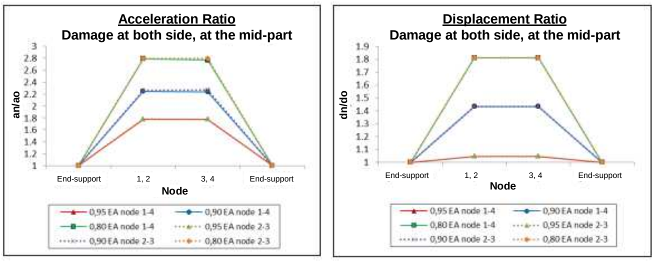

Fig. 9 Bridge response for various level of damage in the mid-part of the bridge model

It can be seen in Fig. 9, that the maximum acceleration and the displacement of the bridge increase significantly when damage is introduced to the bridge structure. For damaged elements with axial stiffness reduced to $0.95EA$, the maximum acceleration increases up to 1.8 times the initial, whereas when it was reduced to $0.80EA$, it can reach up to 2.8 times. The same trend is also observed in the bridge displacement, although the increase is not as much as the maximum acceleration. Since the damage was introduced in the mid-part of the bridge model, the bridge overall response was symmetrical.

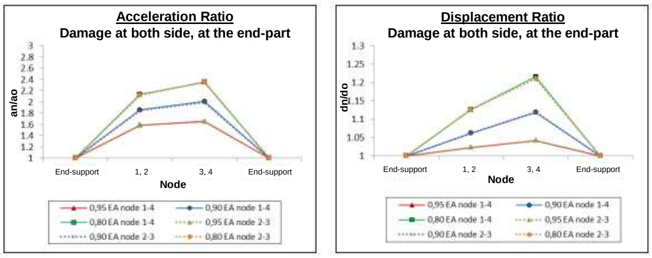

Fig. 10 Bridge response for various level of damage in the end-part of the bridge model

The second scenario, where the damage was introduced at one of the end-part of the bridge model, shows similar tendency with that of first scenario. As the level of damage increase, the maximum acceleration and the displacement increase (see Fig. 10). However, for the scenario where the damage was introduced at one of the end-part of the bridge model, the increase is slightly less than that of the first scenario. For the second scenario, the increase ranges from 1.6 to 2.4 times compares to 1.8 to 2.8 times in the first one. Furthermore, the pattern of the bridge overall response is not symmetrical. The end of the bridge where the damage was introducing has larger response than the other end.

From this parametric study, the load rating of the bridge, or the capability of the bridge to carry load, is reduced significantly when there is damage in the bridge structural elements. From Fig. 11, it was shown that if the mid-part of the bridge had deteriorated with level of damage equivalent to the reduction of the axial stiffness of the structural element of 20%, the bridge load rating reduced up to 25%. This is regardless of the condition of the other part of the bridge.

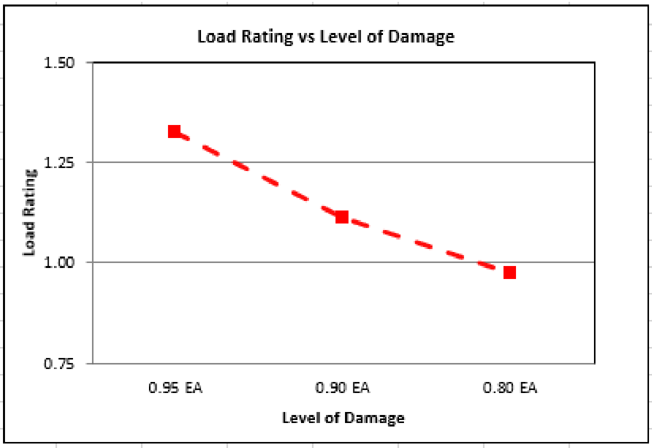

Fig. 11 Load rating vs the level of damage at the mid-part of the bridge

However, the load rating for the bridge with damage elements, can be slightly improved by reducing the traffic load on the bridge (see Fig. 12). This means for bridges with deteriorations, they can still be operated during the maintenance as long as the traffic load is limited.

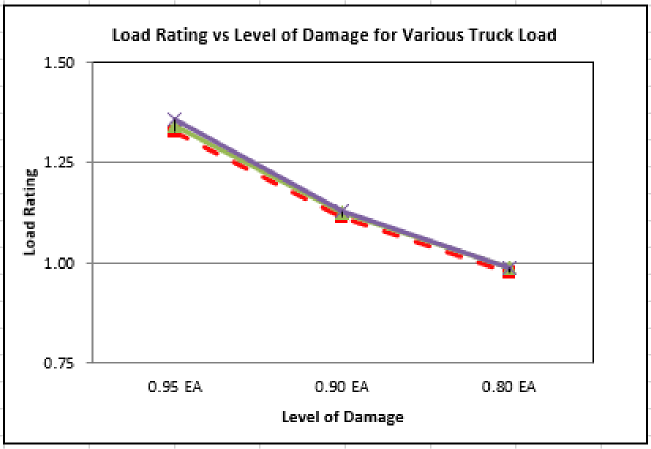

Fig. 12 Load rating vs level of damage at the mid-part of the bridge for various truck load

IV. CONCLUSIONS

From the present research, there are several conclusions that can be made: Wireless Sensor Networks (WSN) can be used to measure bridge dynamic response under traffic load. The acceleration measured by the WSN can be used to determine the bridge frequency response and the maximum displacement. The difference between the frequency response of the actual and the initial can be used to determine the bridge condition rating. The bridge frequency response can also be used to determine the overall stiffness of the bridge, which in turn can be used to determine the maximum load the bridge can withstand, or the load rating. The bridge dynamic response is in direct proportion with the traffic load. The acceleration and the displacement of the bridge increases as the traffic load increases. The bridge condition and load ratings is in inverse proportion with the traffic load and the level of damage of the bridge. Damage in the bridge can significantly reduces the bridge load rating. The load rating of the bridge with deterioration can be slightly improved by reducing the traffic load.

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