Initial Implementation of Structural Health Monitoring System of a Railway Bridge

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Abstract. In order to determine the actual condition of the railway bridge structure in the field, predictive monitoring is needed by installing a structural health monitoring system (SHMS). In the process of applying the SHMS, a bridge design review was applied to have railway bridge characteristics. The purpose of conducting this design review is to determine the allowable threshold for deflection and vibration of the bridge. This paper will present the analysis of the steel frame structure; with a span of 51.60 meters, 4.45 meters wide, of 5.00 meters high, respectively. According to the applicable standards, the loads used following the function of the bridge on the railroad tracks are calculated. The purpose of this paper is to (1) analyze the strength of the attached profile against the working forces, especially the live load of the rail line, (2) to know the deflection that occurs, (3) to know the natural frequency that occurs, and (4) to develop expert systems. The simulation results are used as the basis for placing sensors on the bridge and as the basis for determining the threshold for the railway bridge SHMS.

1. Introduction
The maintenance of a railway infrastructure plays an important role in the operation of transportation systems and infrastructures. Such activity aims to ensure the safety of operations and the availability of railroads and related equipment for traffic control. Maintenance is one of the main costs of operating rail transport. Furthermore, the increasingly fierce competition in the traffic market demands maintenance improvements, which aim to reduce maintenance costs while maintaining safe operations. This problem is expected to be overcome by the methodology presented in this paper. The first step of the methodology consists of a cluster-based approach to equipment reliability analysis. Its purpose is to identify groups of railway items that can be given the same reliability target. The second step is to pay attention to the level of service required in the transportation system. This needs to be done by identifying the most critical items in an effort to develop a railway system reliability model. This second step system includes implementing SHMS (structural health monitoring systems) for railway infrastructures such as SHMS on railroads and railway bridges.

As widely known, SHMS is the process of assessing the health/damage condition of a civil building structure using instruments. The term SHMS is familiar to the civil construction industry and has been widely installed in tall buildings, bridges, tunnels, dams, and other important civilian buildings. The SHMS, in general, serves as an early warning to increase the security and reliability of the infrastructure system by detecting damage before it reaches a critical state and allowing an assessment of the condition of the infrastructure being observed with the SHMS facility.
The benefits of SHMS include early detection of problems or damage to the structure of a building object which can prevent fatal damage, such as the collapse of the main structure or the settlement of the foundation. In that sense, SHMS can monitor in real-time the state of the building object. The implementation of the SHMS for the BH77 railway bridge in Lampung starts with determining until obtaining adequate structural modeling through a review of the bridge design. The step of implementing the SHMS on the BH77 railway bridge with collecting the dimensions of structural bridge members because the as-built drawing of the bridge was not available. Furthermore, deflection calculations as the effect of loads and natural frequency are carried out. Once overall displacement data were obtained, IoT Ecosystem will be followed by an intelligent decision-making process. The expected output from the development of this expert system is to obtain the health condition of the bridge structure in real-time through the reading dashboard to the authorities in taking necessary actions.

2. Literature study
In 2012 Macchi et al. [1] stated that the maintenance of railroad infrastructures plays an important role in railway transportation. This aims to ensure the safe operation and availability of railroads and related equipment for traffic control. There has been an increasing demand for improved conditions of transport infrastructures in Indonesia. Bridges are important facilities of transportation infrastructures and require such monitoring. Davis and Goldberg [2] reported that there were 66,405 structurally deficient bridges in the United States in 2013. The structurally deficient bridges were more than 11 percent of all bridges. Moreover, most of them were more than 65 years old. This condition is similar to that in Europe [3], in which the majority of bridges were built in the post-war era period from 1945 to 1965. In Indonesia, many railway bridges were built more than 100 years ago. The railway bridges were built in connection with the construction of railway lines. The first rail line was built by the Staats Spoorwegen (SS) company. The railway was constructed along 115 kilometers, located between Surabaya and Pasuruan. The railway was completed and inaugurated on May 16, 1878 [4]. Subsequently, the construction of several bridges and railroads began [5][6].

In Indonesia, the loading conditions of railway bridges have changed in recent decades due to increased freight volumes [7]. Besides, many of those railway bridges have been structurally deficient due to gradual deterioration with time. Rehabilitation and extension of the lives of these structures raise important maintenance and safety issues. Practically, bridge maintenance has been performed utilizing visual inspection methods, which are highly variable and lack resolution. It can only detect damage when it is visible. In addition, structurally deficient bridges may be left undiscovered. Several railway bridges have collapsed due to a lack of structural capacity information and routine maintenance. Chupani and Phromsorn [8] suggested that a bridge health monitoring technique is necessary rather than visual inspection alone, and it may not be adequate.

Performance evaluation of existing railway bridges is usually by load testing method. The method covers retrofitting or strengthening old bridges, bridges that are in service already, and new railway bridges for post-construction maintenance. Duvnjak et al. [9] applied proof and diagnostic load testing when monitored and diagnostic a damaged railway bridge. Proof load testing is very useful for the evaluation of bridges when information related to the capacity of the bridge is insufficient. However, most existing railway bridges past their design life and require have much heavier loads during the design period. For this condition, it is suggested that assessment and prediction of the current conditions and safety of the remaining life on older railway bridges are necessary as a result of increased loads on locomotives [10]. Therefore, Mirza et al. [11] evaluated the effect of wheel loading in the rail component system between railheads and sleepers interaction.

In special conditions, there are often crossings with slopes greater than the determining ramps. These special conditions are referred to as steep ramps with a length of ramps that must meet the applicable provisions [12]. Various methods are engineered to make the rail slope within a safe threshold by constructing a bridge to overcome gradients. Railway bridges are bridges specially designed to be crossed by trains. Planning these bridges from the railway tracks, free space of the bridge until the load received by the bridge is adjusted to the trains that cross the bridge.
Axle loads used as a basis for planning must be following the classification of the path, and the largest load operated [13]. Bridge inspection systems and monitoring procedures have to be in line with the bridge management system. Improved bridge inspection addressing a structurally deficient bridge has substantial cost and practical implications. Various countries [14] have developed bridge inspection measurements integrated with the bridge management systems. The development of the bridge monitoring systems in Japan has been highly influenced by geographic and socioeconomic conditions [15]. Japan, geographically, is prone to natural disasters. Therefore, civil infrastructure monitoring has to be performed regularly. Damage detection techniques were developed and implemented so that the service life of these structures can be monitored beyond the design basis service life [16]. The process of damage detection techniques for civil engineering infrastructures is referred to as Structural Health Monitoring [17]. Malekjafarian et al. (2015) performed indirect bridge monitoring utilizing an instrumented vehicle [18]. The system is called the “drive-by bridge health monitoring.” The car was instrumented with sensors, consisting of the most common accelerometers, and fitted on its axles. Li et al. [19] conducted an extensive study regarding vertical vehicle-track interaction at pivotal points on railway bridge approaches and lateral misalignment issues associated with bridges located in sharp curves.

The dynamic interaction between wheels and rails is increasing due to the accelerated speed of the train and the additional heavy axle loads, especially in the vertical direction [20]. Therefore, there is a need to improve and inspect existing railway bridges to meet the service requirement. The purpose of this study is to (1) analyze the strength of the attached profile against the working forces, especially the live load of the rail line, (2) to know the deflection that occurs, (3) to know the natural frequency that occurs, and (4) to develop expert systems.

3. Research methodology

3.1. Study activities
The study of this program was to evaluate the existing steel railway bridge structure. The railway truss bridge is a Warren truss configuration with a vertical height of 5.00 m, a single span of 51.6 m, and a width of 4.45 m. In order to have a comprehensive load-carrying capacity, loading combination which acts to the railway bridge structure were numerically simulated. Three-dimensional (3D) detailed models of the railway bridge were established. Finite element analysis was applied for the analytical calculation of the railway bridge in this study. The finite element analysis was performed by means of SAP2000® software Ver. 6.1 [21]. As mentioned earlier, due to lack of documentation, existing dimensions should be directly measured at the bridge location. Numerical simulation was then performed to understand the bridge characteristics, especially related to its deflection, stress distribution, and natural frequency. The flow of the study diagram and the effect of increased loading and loading standards on this railway bridge can be seen in figure 1.

3.2. Loading combination of the railway bridge
Before carrying out a numerical analysis of the loading combination, it is necessary to test the numerical model with a simpler problem. The initial step is to equalize all the truss geometries of the railway bridge to obtain a completely symmetrical and uniform bridge. Furthermore, the symmetrically distributed load is applied, for example, the combined magnitude of the dead load and the live load evenly. This is to check whether the resulting deflection and stresses are symmetrical, and the magnitude should be smaller than the applicable standard [22].
Existing bridge elements shall exhibit reliable load-carrying capacities. It should, therefore, be verified and determined by using applicable standards with appropriate safety factors. All main provisions for loading actions on the railway bridge should be considered.

Characteristic values of the bridge loading conditions should be according to Indonesian National Standard [22] and following the transportation minister regulation number PM 60 of 2012 [23] regarding railway line technical requirements. In many cases, EN 1991:2-2003 [24] regarding Technical Requirements of Railway Lines and Actions on Structures and Traffic Loads on Bridges should be considered. The reliability of the existing bridge structural members and their cross-sections should also be verified, and the load-carrying capacity should be determined by means applicable standard [25][26].

In order to have a comprehensive load-carrying capacity, a loading combination based on the code was applied to the railway bridge structure. Load factors implemented for this numerical simulation follow SNI 1725-2016 [22] and are presented in table 1. Table 1 represents the applied loading combination and becomes the input for numerical simulation modeling of the railway bridge. Strong mean that loading combination takes into account the forces caused on the bridge under normal state without taking into account the wind load. In this boundary state, all the normal forces that occur are multiplied by the appropriate load factor. Roman numerals, I through V, indicate the loading type acting on the bridge. Extreme conditions are loading combination that considers the combination of live loads reduced by loads due to ship collision, vehicle collisions, flooding, or other hydraulic loads, except for cases of loading due to vehicle collisions. Loading cases due to flooding should not be combined with loads due to vehicle collisions and ship collisions.

Serviceability load is loading related to bridge operation with all loads having a nominal value and taking into account the wind load speed of 90 km/hour to 126 km/hour. This combination is also used to control deflection in steel culverts, tunnel lining plates, thermoplastic pipes, control the crack width of reinforced concrete structures, and tensile stress analysis in segmental concrete cross-sections. This loading combination should also be used for the investigation of slope stability [22].

Figure 1. Flowchart of the study.
Meanwhile, fatigue load is a combination of fatigue and fracture loads in relation to fatigue life due to the induction of loads that have unlimited time. The results of the numbers listed in this table represent the load factors used as input for numerical simulation modeling of the railway bridge [27]. Three-dimensional (3D) detailed models of the railway bridge were established, and the models were shown in figure 2.

**Table 1. Loading Combination Acting on the Railway Bridge [22][27].**

| No | Load limits | DL | MA | LL | IL | LaF | LF | PL | BL | WR | WL | QX | QY |
|----|-------------|----|----|----|----|-----|----|----|----|----|----|----|----|
| 1  | Strong I    | 1.1| 2.0| 1.8| 1.0| 1.0 | 1.0| 1.8| 0  | 0  | 0  | 0  | 0  |
| 2  | Strong II   | 1.1| 2.0| 1.4| 1.0| 1.0 | 1.0| 1.4| 0  | 0  | 0  | 0  | 0  |
| 3  | Strong III R| 1.1| 2.0| 0.0| 1.0| 1.0 | 1.0| 0.0| 1.4| 0  | 0  | 0  | 0  |
| 4  | Strong III L| 1.1| 2.0| 0.0| 1.0| 1.0 | 1.0| 0.0| 0  | 1.4| 0  | 0  | 0  |
| 5  | Strong IV   | 1.1| 2.0| 0.0| 1.0| 1.0 | 1.0| 0.0| 0  | 0  | 0  | 0  | 0  |
| 6  | Strong V R  | 1.1| 2.0| 0.0| 1.0| 1.0 | 1.0| 0.0| 0  | 0  | 0  | 0  | 0  |
| 7  | Strong V L  | 1.1| 2.0| 0.0| 1.0| 1.0 | 1.0| 0.0| 0  | 0  | 0  | 0  | 0  |
| 8  | Extreme I X | 1.1| 2.0| 0.3| 1.0| 1.0 | 1.0| 0.3| 0  | 0  | 1.0| 0.3| 0  |
| 9  | Extreme I Y | 1.1| 2.0| 0.3| 1.0| 1.0 | 1.0| 0.3| 0  | 0  | 0  | 0  | 1.0|
| 10 | Extreme II  | 1.1| 2.0| 0.5| 1.0| 1.0 | 1.0| 0.5| 0  | 0  | 0  | 0  | 0  |
| 11 | Serviceability I R | 1.0| 1.0| 1.0| 1.0| 1.0 | 1.0| 1.0| 0.3| 0  | 0  | 0  | 0  |
| 12 | Serviceability I L | 1.0| 1.0| 1.3| 1.0| 1.0 | 1.0| 1.0| 0  | 0.3| 0  | 0  | 0  |
| 13 | Serviceability II | 1.0| 1.0| 0.8| 1.0| 1.0 | 1.0| 1.3| 0  | 0  | 0  | 0  | 0  |
| 14 | Serviceability III | 1.0| 1.0| 0.0| 1.0| 1.0 | 1.0| 0.8| 0  | 0  | 0  | 0  | 0  |
| 15 | Serviceability IV R | 1.0| 1.0| 0.0| 1.0| 1.0 | 1.0| 0.0| 0.7| 0  | 0  | 0  | 0  |
| 16 | Serviceability IV L | 1.0| 1.0| 0.75| 1.0| 1.0 | 1.0| 0.0| 0  | 0.7| 0  | 0  | 0  |

DL = dead load  MA = additional dead load  LL = live load  IL = impact load  LaF = lateral force  LF = longitudinal force  PL = structural load  BL = braking load  WR = right wind load  WL = left wind load  QX = seismic force X  QY = seismic force Y

**Figure 2.** 3D Configuration model of railway bridge loading combinations.

The material property used for numerical simulations was taken as steel with quality material grade BJ55 with a modulus of elasticity of 200,000 MPa and yield stress of 410 MPa. However, justification was applied regarding diagnostic investigation and inspection in the field since the as-built drawing was not available. In table 1, the dead load (DL) is the mass of the rails and sleepers installed, which was 0.938 kN/m².
The forces (PL) were loads acting on the bridge structure during the construction process, including all the forces that occur due to changes in the segmental statics of the construction, and were taken as 3.00 kN/m'. The impact load (IL) applied to the structure was a running load of 50 kN/m'. The live load was taken to be 90 kN for one axle. The braking load (BL) designed on the structure was 22.5 kN in the direction of the X-axis or longitudinal direction. A seismic load was also considered during numerical simulation. Seismic loads applied to the railway bridge structure were related to the bridge location. Acceleration of soil parameters of $S_s = 0.571$, and $S_l = 0.236$ was considered in the design. The numbers are based on the spectral response of the peak ground acceleration. The amplification is determined based on the soil classification in the seismic design criteria for a structure at ground level.

3.3. Proposed transfer data sensor

An expert system is a system that tries to adapt human knowledge into computers. Computers are attempted to solve problems as usually executed by experts. A good expert system is designed to solve a particular problem by imitating the work of experts. Likewise, for the implementation of SHMS on the BH77 railway bridge, an expert system will be developed through the use of big data. This concept is associated with Artificial Intelligence (AI) and the Internet of Things (IoT).

In general, the developed expert system includes four main things. (a) Managers use the user interface to enter instructions and information from the system. The input methods used by managers include menus, commands, natural language, expert system output using two forms of explanation: explanation of questions and description of problem solutions. Via the user interface, the conditions of the BH77 railway bridge can easily be monitored using sensors. (b) Knowledge Base consists of facts that describe the problem domain and presentation techniques that use facts according to logic. Rules are details in an unchanging situation. True and false conditions, where the action will be taken if the conditions are true. (c) The engine interface is part of an expert system that forms reasoning using the knowledge base contents in a certain order. (d) The development engine is used to build rule sets with an approach to programming languages and the expert systems section for the system development process.

Bridge - SHMS covers the components of the data retrieval process via a sensor system with parameters of deflection, stress on bridges, and vibration. Via the Bus System, the results of sensor monitoring are processed and sent directly to the Data Acquisition Module (DAQ) in the bridge location area. The results of DAQ data collection are sent and stored through the Gateway into Cloud Storage. The infrastructure control center can utilize the actual data on Cloud Storage to monitor bridge conditions online in a dashboard. Based on the data set on the cloud storage and the set of views of bridge experts in the near future, a bridge health prediction system can be developed.

4. Results and discussion

4.1. Structural characteristics maximum capacity

Indonesian National Standard [22], SNI 1725-2016 on loads of bridges requires that loads act on the bridge must not be greater than the bridge’s capacity. Therefore, the bridge's capacity ratio and the applied load shall not be greater than 1. Figure 4 shows the capacity ratio on the BH77 railway bridge.
Based on the numerical simulation results, the bridge capacity of each structural member was visualized using color degradation from grey, blue, green, yellow, to red. The grey color represents the capacity of the bridge is much greater than the capacity of the bridge as the loads pass over the bridge, and it is categorized as very safe. The blue color indicates that the bridge is still in the very safe category, and the green color is the safe category. The yellow color is in the warning category, while the orange color is in the very critical category, whereas the red color indicates that the bridge will collapse.

4.2. Maximum bridge deflection

Indonesian transportation minister regulation number PM 60 of 2012 regarding Technical Requirements for Railway Tracks [23] requires that the maximum deflection limit for the frame is L/1000 or equal to 51.6 mm, in which L is span length. Figure 5 shows load – maximum deflection characteristics of the BH 77 railway bridge. It can be seen from figure 5 that the maximum deflection is 93.551 mm, and it is greater than the required maximum deflection. This implies the structure fails to meet the criteria for maximum deflection in either the frame or the girder components. In summary, the existing deflection control criteria are not sufficient to address serviceability concerns. Exception of the girder 116, the deflection values of all bridges were significantly less than those mentioned earlier. However, this maximum deflection occurs at the strong load combination I, in which the calculated loading combination during operation never happens. Meanwhile, the calculated operation that occurs is a combination of 1 DL plus 1 LL simultaneously. This combination of loading results in a maximum deflection of 41,925 mm, which is smaller than the combination of strong loading I, and this is still acceptable.

4.3. Maximum stresses and natural frequency

SNI 1729-2015: Indonesia National Standard on Specifications for structural steel buildings requires that maximum allowable stress is 0.66 \( f_y \). In the design process, the yield stress of the steel is taken to be 410 MPa. Therefore, the maximum stress that occurred in any part of the bridge should not exceed 270.6 MPa. The maximum stress that occurs in the numerical modeling is 100.4 MPa. Therefore, it can be stated that the bridge structure is safe in terms of stress because it is significantly smaller than the allowable stress. The distribution of maximum stress works on the BH77 railway bridge can be seen in figure 6. Furthermore, it can be observed that the minimum and maximum frequency equal 23.28L^{0.592} Hz, and 94.76L^{0.748} Hz [24], respectively, where L represents the span length of the railway bridge. This boundary results in a natural frequency of about 2.283 Hz – 4.961 Hz. The analyzed frequency is the frequency at the first time the bending occurs in the structure with mass participation must be greater than 90%.

After reviewing the simulation output results, it can be seen from figure 6 that the first bending occurs in mode 4 with the natural frequency and mass participation of 4.162 Hz and 93.639%, respectively. In summary, the identified dynamic characteristics showed typical values for the type of railway bridge structure.
4.4. Components of structural railway bridge monitoring system

The expert system adopted for application on this BH77 railway bridge SHMS is the Brickwork Expert [28] cluster system, an Expert System for civil building design structure and is commonly called BERT. BERT is used to examine a building design, furthermore provides some recommendations for improvement. The input can be in the form of images or other formats as outlined on the reading dashboard. If a bridge construction, for example, wants to be monitored in terms of bridge vibration, then a vibration sensor will be used, which will be connected to the transfer instrument. Furthermore, the data transferred through the transfer instrument will enter the data interface and document control. Therefore, through the expert system installed in the Control Center, analysis can be carried out automatically, the results of which will appear on the reading dashboard for use by stakeholders or policymakers in taking actions and policies on the results of these readings. This expert system is adjusted for engineering transportation purposes [29]. Figure 7 shows an illustration of the data sensors installed at the railway bridge. The plan for the location of the sensor installed on the bridge is as recommended by Fiantika [30]. The accelerometer sensor is used to measure vibrations on the bridge. Measurement of vibration on the bridge will be useful to reduce the risk of further damage to the bridge due to vibration and frequency is too high. In this bridge, the accelerometer sensor is also used as an alternative to measuring deflection on the bridge. Based on the analysis using SAP2000, the largest deflection is in the middle of the bridge span with a position just below the girder above which there is a rail. Therefore, the accelerometer sensor is placed in the middle of the span to measure the deflection and vibration of the bridge, especially the BH 77 bridge model is a double symmetrical bridge, meaning that it is symmetrical between the x and y axes.

5. Concluding Remarks

From the results of the review of the BH77 railway bridge design and numerical analysis, the facts are obtained and are presented as follows:

This paper has described various aspects of the initial effort to build an SHMS for a railway bridge. As an initial phase, the BH77 railway bridge was used as a case study of SHMS development. The numerical model shows that the critical boundary conditions are determined by deflection, while the natural stresses and frequencies are within safe limits. Maximum deflection occurs at frame 116 (girder). Other than frame 116, the deflection is still very far from the maximum deflection. In terms of service load, a deflection that occurs is still in a safe condition, provided bracing frames are dimensionally upgraded. These results can be used to provide an initial picture of the readings for deflection and strain measuring equipment that will soon be installed in the field.

The maximum stress that occurs is 100.4 MPa. Therefore, this structure can be stated that the bridge structure is still safe under stress control because it is smaller than the allowable stress. The maximum natural frequency allowed is a minimum of \(23.28L^{-0.592}\) Hz and a maximum of \(94.76L^{-0.748}\) Hz or about 2.283 Hz – 4.961 Hz. The frequency to be reviewed is the frequency of the first bending of the structure, and the mass participation must be greater than 90%.
The numerical analysis results show that the first bending occurs in mode 4 with the frequency and mass participation of 4.162 Hz and 93.639%, respectively. The results of this frequency value are also used as the basis for selecting the type of sensor to be installed on the bridge. From the analysis of the bridge capacity, maximum deflection, maximum stresses, and maximum frequencies, the type of sensor installed in the field can be determined and the location of its installation. This can be used for sampling against the installed sensor. Bridge-mounted sensors include accelerometers, strain gauges, and displacement leveling. Sensor sampling is carried out every second when a train is passing and every 15-20 minutes when no train is passing. Data from sensor sampling are collected by the acquisition instrument data and sent to the data processing center via instrument transfer, which is then used by the adopted expert system, which can be read in the reading dashboard of the bridge structure.

6. References

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