Forced vibration test of pedestrian steel bridge using eccentric mass shaker

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Abstract. The dynamic test has been performed on Jembatan Teksas, Universitas Indonesia. The purpose of the test was to obtain the dynamic parameters, which are the natural frequencies, the mode shapes, and the damping ratio. The test was conducted by applied forced excitation using an eccentric mass shaker. The dynamic responses were recorded using accelerometers and vibrometer during forced vibration state and a free vibration state. A comparison study was conducted through the 3D finite element analysis using SAP2000. The test could obtain five mode shapes of the bridge and the damping ratio. Close results were found between FE analysis and the test result. The average damping ratio obtained was 1.72% which was within the range of welding steel structures according to reference. Compared to the test conducted in 2011 and 2013, the bridge is in good condition which is indicated by its natural frequency where the current test decrease less than 2%.

1. Introduction

Bridge health monitoring system is a part of structural maintenance to meet the needs for providing safer transportation. The monitoring is conducted by applying a dynamic load on bridges and analyzing the response. A dynamic test is usually performed by applying excitation to the structure directly. Periodic monitoring will result an early detection if damage has been indicated. The results will help the owner to identify the structural conditions and take immediate repairing. The dynamic response of an elastic structure is determined based on the natural frequencies, damping and mode shape vibration [1]. There are three types of dynamic tests; ambient vibration, forced vibration, and free vibration test [2]. Modal analysis can be used to determine the dynamic parameters [3].

Several research [4-8] explored the use of forced vibration test (FVT) and experimental modal analysis to detect damage to existing civil structures. Salawu and Williams [4] conducted a forced vibration test on RC bridge with a total length of 104m which consist of 6 spans. The test was conducted before and after repairing the deck. The hydraulic actuator was used to apply the dynamic load. The natural frequency of that bridge decrease as 3% after repairing was conducted. The study concluded that the decrement exceeding 5% indicates that the damage occurred. Hogan et al [7], performed a dynamic test on a precast RC bridge in Auckland. Eccentric mass shaker was used to generate dynamic load on transversal and longitudinal direction meanwhile the vertical excitemenit was generated by an electrodynamic shaker. The natural frequency and the mode shape were obtained. Setareh dan Gan [8] reported a dynamic test on steel bridge in Virginia, USA by using an electrodynamic shaker. The results were compared to a FE analysis, and the difference was about 6%. The dynamic response which was natural frequency, mode shape and damping ratio was attained.

Eccentric mass shaker is rarely used for dynamic test of bridges in Indonesia. The dynamic load is applied traditionally by using vehicles and this is expensive. The use of eccentric mass shaker as an alternative of force vibration test for bridge health monitoring was introduced. The test was conducted on a pedestrian bridge, Jembatan Teksas, in Universitas Indonesia. It is a steel-truss footbridge with a...
total span of 84 meters which was opened for public in 2007. As a part of bridge health monitoring system in the university; dynamic tests had been performed twice, in 2011 [9] and 2013 [10]. The first test applied impulse excitation using an impulse hammer and the last test was conducted by human excitations. EMS was employed on the third test conducted in 2020. The excitation is a sinusoidal load.

2. Research Methodology

The dynamic test was conducted by applying sinusoidal force using an ANCO MK-139-10 eccentric mass shaker. Prior to the test, the FE analysis using SAP2000 was performed to get the general dynamic response of the bridge and as guide for the dynamic test. Figure 1 shows the bridge and the FE model. The shaker was placed in the middle of the bridge as shown in figure 2. Excitation was applied in two directions, horizontal and vertical to get both modes. The accelerometer and laser vibrometer were used to measure the response of the structure. Four sensors were attached along the length of the bridge, at the edge (sensor #1), 1/4L (sensor #2), 1/2L (sensor #3), and at 3/4L (sensor #4). The placement was based on the FE results to ensure that the sensor can capture the particular mode shape. The vibrometer was located on quarter span (1/4L) and in the middle (1/2L) of the bridge. Natural frequency, mode shape, and damping ratio were obtained by performing a free and forced vibration test. Furthermore, the results were compared to dynamic response attained from FE analysis.

![Figure 1. The bridge and the 3D Model](image)

Three-dimensional FE modelled as shown in figure 1 was generated by SAP2000. The steel truss has yield stress as 380 MPa, and the floor was made of K225 concrete with fc’ equals to 18.7 MPa. Two different connections type were modelled, pinned and rigid connections and the results were compared to the experiment results to seek the closest assumption. The mass sources include in the model were the steel deck, the roof, and the handrails.

![Figure 2. Eccentric mass shaker installed on Jembatan Teksas Universitas Indonesia](image)
The responses obtained from both the accelerometer and the vibrometer were in time-domain which were transformed into frequency-domain by the Fast Fourier Transformation (FFT) method [11] by using SIGVIEW software. The natural frequency of the structure was obtained based on the peak value of the Frequency Response Function (FRF) where the first peak value is the natural frequency. Half-power bandwidth method was used to determine the damping ratio of the structure [1]. The mode shape can be obtained by plotting each accelerometer reading amplitude, which has the same frequency. The direction of the amplitude can be obtained by checking the imaginary part [11].

3. Results and Discussion

3.1 The Mode Shapes dan The Natural Frequency

Table 1 presents the first six modes as a result of the FE analysis based on two different connection types of truss element. The mode shapes are shown in Figure 3 – 6. Assuming the connection as a rigid joint improve the stiffness of the bridge which results in higher frequency. The difference is not significant in the vertical mode where the difference is only about 1-2%. A significant effect was detected on first torsion mode; where the natural frequency of rigid connection is 20% higher than pinned connection. However, the natural frequency of the rigid connection model has closer results to the experiment than the pinned connection. If data from free vibration is used as a reference, on average, the difference of rigid connection is about 11% whereas pin connection is 13%. Opposite result was found if forced vibration was used as a baseline. The natural frequency of pin connection is closer to the experiment with the difference of 11% whereas the rigid connection was 14%.

Table 1. The Mode shapes and the natural frequencies obtained from structural modelling

| Mode Shapes     | Pin Connection | Rigid Connection | Free Vibration |
|-----------------|----------------|------------------|----------------|
| Transverse 1<sup>st</sup> Mode | 1.798          | 1.976            | 1.829          |
| Vertical 1<sup>st</sup> Mode   | 1.997          | 2.026            | 2.413          |
| Torsion 1<sup>st</sup> Mode   | 2.743          | 3.294            | NA             |
| Transverse 2<sup>nd</sup> Mode | 4.109          | 4.588            | 3.685          |
| Vertical 2<sup>nd</sup> Mode   | 4.600          | 4.700            | 5.503          |
| Torsion 2<sup>nd</sup> Mode   | 5.982          | 6.345            | 6.085          |

Figure 3. The first and the second transverse mode shapes; (a) FE analysis; (b) dynamic test
Figure 4. The first and the second vertical mode shapes; (a) FE analysis  (b) dynamic test

Figure 5. The first torsional mode shapes based on the FE analysis;  (a) side view; (b) top view

Figure 6. The second torsional mode shapes based on the FE analysis;  (a) side view; (b) top view

Figure 7. Torsion second mode shape obtained from the dynamic test. (a) side view; (b) top view
Table 2 list the comparison of natural frequency attained from the free and forced vibration test. As presented, the results are almost similar to the deviation is around 0.1% to 2.9%. However, the test could not capture the first torsion mode. This is due to the placement of the accelerometers that were located in the longitudinal centerline of the bridge. Since the first mode is pure torsion, hence it could not detect the mode. Meanwhile, the second torsional mode has a transversal movement, therefore it can be acquired by the accelerometer. The movements are shown in Figure 5(b) and Figure 6(b). It seems that the accelerometer should be located at the edge of the bridge width near the handrail to catch the first mode. The measurement from accelerometer was compared to vibrometer and presented in Table 3. Both sensors have similar results where the difference was less than 2%.

| Mode               | Frequency (Hz) | Forced Vibration | Free Vibration | Deviation | Average |
|--------------------|----------------|------------------|----------------|-----------|---------|
| Transverse 1st Mode| 1.827          | 1.829            | 0.1%           | 1.828     |
| Vertical 1st Mode  | 2.409          | 2.413            | 0.2%           | 2.411     |
| Torsion 1st Mode   | NA             | NA               | -              | -         |
| Transverse 2nd Mode| 3.578          | 3.685            | 2.9%           | 3.632     |
| Vertical 2nd Mode  | 5.450          | 5.503            | 1%             | 5.477     |
| Torsion 2nd Mode   | 6.093          | 6.085            | 0.1%           | 6.089     |

Table 3. Comparison of natural frequency measured by accelerometer and vibrometer

| Mode               | Frequency (Hz) | Accelerometer | Vibrometer | Deviation |
|--------------------|----------------|---------------|------------|-----------|
| Transverse 1st Mode| 1.828          | 1.827         | 0%         |
| Vertical 1st Mode  | 2.411          | 2.367         | 2%         |
| Torsion 1st Mode   | NA             | NA            | -          |
| Transverse 2nd Mode| 3.632          | 3.568         | 2%         |
| Vertical 2nd Mode  | 5.477          | 5.514         | 1%         |
| Torsion 2nd Mode   | 6.089          | 6.038         | 1%         |

3.2. The Damping Ratio
The damping ratio determined by the half-power bandwidth method presented in Table 4. The ratio varies from 1.3% to 2.0%, with the average ratio of 1.72%. The value is within the range of the damping ratio suggested by Newmark and Hall [12], where the welded steel structure has the ratio of 2 to 3%.

| Mode               | Damping Ratio |
|--------------------|---------------|
| Transverse 1st Mode| 2.0%          |
| Vertical 1st Mode  | 1.9%          |
| Transverse 2nd Mode| 1.4%          |
| Vertical 2nd Mode  | 2.0%          |
| Torsion 2nd Mode   | 1.3%          |
3.3. The Comparison to the Previous Test
As mentioned earlier, the bridge has been tested twice, in 2011 and 2013. Excitation was applied by a hammer in 2011 and human in 2013 as shown in Figure 8. The natural frequency of three dynamic tests is compared and presented in Table 5. As presented, except torsion, the frequency does not change much within seven years where the difference is relatively small, 0.4% – 2%. Refer to reference [4], the data indicate that the bridge is in “healthy condition”. Unfortunately, the frequency of the second mode of torsion decrease by 20% compared to the year of 2013. This value exceeds the maximum allowance decrement suggested by Salawu and Williams, which is limited to 5% [4]. However, based on physical examination in the field, there was no damage observed on the bridge. The result of 2013 related to second torsional mode is unacceptable since the gap with other mode shapes is too large. Moreover, test on 2013 relied only from one sensor and accelerometer, whereas the 2020 test consists of four sensors, accelerometers and vibrometer. Therefore, in the next few years, the dynamic test should ensure to capture the natural frequency of the second mode of torsion to verify the decrement. Based on 2020 test, it can be concluded that the bridge is in good condition without any damage.

![Figure 8. Dynamic Test of Jembatan Teksas (a) 2011; (b) 2013](image)

| Mode            | Frequency (Hz) | Test in 2011 | Test in 2013 | Test in 2020 | Deviation |
|-----------------|----------------|--------------|--------------|--------------|-----------|
| Transverse 1st Mode | 1.818          | NA           | 1.831        |              | 1%        |
| Vertical 1st Mode   | 2.457          | 2.441        | 2.410        |              | 2%        |
| Torsion 1st Mode    | 3.69           | 2.930        | NA           |              | -         |
| Transverse 2nd Mode | NA             | NA           | 3.661        |              | -         |
| Vertical 2nd Mode   | 5.55           | 5.493        | 5.530        |              | 0.4%      |
| Torsion 2nd Mode    | NA             | 7.570        | 6.051        |              | 20%       |

4. Conclusion
The forced vibration test conducted on Jembatan Teksas Universitas Indonesia could identify three important dynamic parameters, which are the first five modes, the natural frequency and also the damping ratio of the bridge. However, it is important to put the sensors on an appropriate location to capture the desired mode shape. Preliminary study with the FE analysis is suggested to guide the field-test.
The test found the similar natural frequency measured from accelerometer, vibrometer and the FE analysis. The FE results are close to the experiment when truss connection is assumed as pin rather than rigid, with a deviation of 11%. The change of natural frequency of the bridge within seven years is less than 5% which indicate that there is no damage and the bridge is in a good condition.

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