The dynamic test of simple span precast prestressed concrete bridge with elastomeric bearing support

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Abstract. The dynamic test of an elevated freeway bridge in Surabaya has been conducted. Eccentric mass shaker succeeded to apply an excitement to the bridge and hence the dynamic parameters such as the mode shape, the natural frequency and the damping ratio were obtained. The two main mode shapes from the test were the first vertical mode and the first longitudinal mode. The average damping ratio attained is within the range of damping ratio of prestresses concrete where the average is 2.12% whereas the range is between 2-3%. The test results are closely represented by a 3D FE model using SAP2000 without modelling the whole foundation. The deviation of the natural frequency compared to the test results is 8.50%. The elastomeric bearing effectively reduces the acceleration from upper to the bottom structure by 54.62% and 60.22% obtained from two measurements.

1. Introduction
Located on the ring of fire, the occurrence of an earthquake in Indonesia is considered high. Hence civil structures in Indonesia like bridges and buildings have been subjected to repeated earthquakes for years. As a dynamic load, earthquakes can cause damage to infrastructure. The structural health monitoring system should be conducted regularly as a part of building maintenance. Dynamic loading test is one method that has been done to assess the health performance of a building. There are three types of dynamic tests; ambient vibration test, forced vibration test, and free vibration test [1]. For an economic reason, FEM modelling has been used to obtain the dynamic characteristics of large structures. An effort has been done to get an accurate identification with development of experimental tools to make health assessment of existing structures is more economics and the damage can be easily detected. Eccentric mass shaker (EMS) is one of the innovative tool that can generate excitement for a large building, which is commonly called forced-vibration tests (FVTs).

In the last few decades, dynamic tests have been used to obtain the dynamic parameters of structures [2]. The parameters are natural frequency, mode shape, and damping ratio [3]. The natural frequency can be used as an indicator for detecting structural damage by examining the decrease in natural frequency [4]. The decrease as 5% or more indicates that the damage is occurring [5]. Research [4-8] has been reported the use of FVTs and experimental modal analysis to detect damage to existing structures. Selawu and Williams [5] conducted a forced-vibration test on RC bridge. It was a 6 spans bridges with a total length of 104m. The test was meant to study the change of natural frequency before and after repairing the deck. The dynamic load was applied by hydraulic actuators. The study found the decrement of natural frequency as 3% after repairing. It was concluded that 5% was the maximum decrement to indicate that the building is in good health, up to that value, the damage is occurring. Kevin C. Womack et al [4] conducted FVT on 9-spans bridge with a total length of 188.76 m by using EMS. The force applied was equal to 89 KN. The natural frequency and damping ratio of the bridge were 1.79 Hz and 3.47%, respectively. Conte et al in 2008 [6] used forced vibration test based on controlled traffic loads and vehicle-induced impact loads to determine the natural frequency and damping ratio of an
Alfred Zampa Memorial Bridge in San Francisco. In 2016, Hogan et al [7] used a dynamic shaker to determine the natural frequency and mode shapes of a precast concrete bridge in Auckland, New Zealand. 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%.

In Indonesia, a field test usually employs vehicles to apply dynamic excitement to a large bridge, and this method is expensive. None of the dynamic tests have been reported utilising eccentric mass shaker. As a part of bridge health monitoring; FVTs with EMS has been conducted on an elevated highway bridge which is located on the Krian-Legundi-Bunder-Manyar (KLBM), Surabaya-East Java. It is a prestressed precast concrete bridge with elastomeric bearing support. Figure 1 shows the EMS that used in the field test.

2. Research Methodology
KLBM bridge is an elevated highway bridge which was constructed by high strength concrete PC-I girder with a depth of 230cm. The girder sits on a 4m-width pier head through the elastomeric bearing pad. Figure 2 and figure 3 show a side view and the cross-section of the bridge. The test set-up is described in figure 4. Eccentric mass shaker ANCO MK-139-10 was used to excite the bridge with sinusoidal load. It can apply forces in horizontal and vertical direction with the maximum forces up to 100kN. EMS was placed in the middle of the bridge which was the centre rigidity of the bridge. Meanwhile, the accelerometer was located on the bridge pillar (sensor AC1) and in the middle of the bridge span (sensor AC4). The placement is based on the FE analysis where the maximum responds occur. To determine the transmissibility of the elastomeric, two accelerometers, AC3 and AC2, were put on the top and at the bottom of the elastomeric bearing pad, respectively. The accelerometer can capture structural response in all directions, longitudinal (X), transversal (Y) and vertical (Z) meanwhile the vibrometer which was located at the bottom of the deck only measured the longitudinal direction of the bridge according to the laser shooting. The test was conducted twice, to measure the response of pillar PaH and at pillar PaI. Figure 3 is the arrangement of tools of pillar PaH.

The responses captured by the accelerometer and vibrometer were the acceleration in time-domain which then were converted into a frequency domain based on the Fast Fourier Transformation (FFT) [9] by SIGVIEW software. The natural frequency of the structure was obtained by looking at the peak frequency of the Frequency Response Function (FRF). Figure 8 shows one example of response recorded by the vibrometer in the time domain, and the right side is the result of FFT in the frequency domain. The first peak value that appears on the FRF is the natural frequency of the first mode. Meanwhile, the damping ratio can be determined based on the half-power bandwidth method if the data in a frequency domain or logarithmic decrement method if it is a time domain [2].

Figure 1. Eccentric Mass Shaker, ANCO MK-139-10
Before the test, the FE was conducted using SAP2000. Different 3D models were created as shown in figure 5, a complete model included the foundation of 42m-depth and without the foundation by assuming fix restrain at the bottom. The objective is to seek which one has the closest results to the test
by comparing the dynamic parameters. The PC I-girder, pier head and pillar were modelled as a frame element. Link element was employed to model the bearing pad. The pile and pile cap were modelled as frame and shell element, respectively. The concrete strength was 30 MPa except for the I-girder which was 70 MPa. The mass source includes asphalt, barrier, and parapet. Results from FE analysis was used to locate the transducer in accordance with mode shape obtained from the analysis.

![3D KLBM bridge with and without foundation](image)

**Figure 5.** 3D KLBM bridge (a) with foundation (b) without foundation

### 3. Results and Discussion

#### 3.1. Mode shape and Natural Frequency

Figure 6 – 7 show mode shape of the bridge at a different model, with and without foundation. As can be seen, similar mode shape was detected but a different value of natural frequency. The frequency that mentioned hereafter is the average data from accelerometer and vibrometer as result of FFT. Figure 8 shows an example of data recorded from vibrometer in a time domain and the result after converting to the frequency domain. Table 1 shows a comparison of the frequency obtained from two models. Assuming fixed restraint at the bottom without modelling the foundation result in a stiffer structure and hence the frequency is higher than those with the full model. Both FE models have a lower frequency than test results. However, fix restrain give the closest results with a deviation of 8.5% whereas the deviation of the full model is 22.89%. It can be explained that the forces generated by EMS was not sufficient to make the foundation to shake and therefore modelling the bridge without the foundation has closer result to the test.

![Mode shape of the bridge](image)

**Figure 6.** (a) The first vertical mode and (b) the first longitudinal mode of the model with the foundation

![Mode shape of the bridge without foundation](image)

**Figure 7.** (a) The first vertical mode and (b) the first longitudinal mode of the model without the foundation
Figure 8. Response in the time domain (a) and Frequency Domain (b) recorded by Vibrometer

Table 1. Comparison of Natural Frequency between the FE Analysis and test result

| Mode Shape              | Dynamic Test | The FE Analysis | Deviation |
|-------------------------|--------------|-----------------|-----------|
|                         | with foundation | without foundation | with foundation | without foundation |
| The 1st Vertical Mode   | 2.1740        | 1.7942          | 21.17%    | 13.03%    |
| The 1st Longitudinal Mode | 8.0618      | 6.4695          | 24.61%    | 3.97%     |
| **Average**             |              | **22.89%**      | **8.50%** |           |

As mentioned earlier, the dynamic test was conducted twice. First, all sensors are located on the PaH pillar and then all were moved to the next pillar (PaI). Table 2 shows the natural frequency obtained from two measurements. As presented, the results from both measurement are very close. This is because the structure is symmetry and the test results are valid since it can represent the real condition.

Table 2. Mode shape and natural frequency obtained from the test

| Mode Shape              | Frequency (Hz) |
|-------------------------|----------------|
|                         | Measurement on the PaH pillar | Measurement on the PaI pillar | Average |
| The 1st Vertical Mode   | 2.1683          | 2.1797          | 2.1740 |
| The 1st Longitudinal Mode | 8.0422      | 8.0815          | 8.0618 |

3.2. Damping Ratio

There are two methods to determine the damping ratio, using the half-power bandwidth method and logarithmic decrement method. The results from the two methods are slightly different. The average damping ratio from two measurements using the logarithmic and the half-power bandwidth is 2.32% and 1.92%, respectively. The values are within the range of damping ratio of prestressed concrete suggested in reference [10], which is 2 to 3%.

Table 3. The Damping ratio obtained from the test result

| Mode Shape            | Damping Ratio |
|-----------------------|---------------|
|                       | Measurement on the PaH pillar | Measurement on the PaI pillar | Average |
| The 1st Vertical      | 2.35%          | 3.36%          | 2.86%   |
| The 1st Longitudinal Mode | 1.02%      | 0.94%          | 0.98%   |
3.3. Transmissibility of the Elastomeric Bearing Pad

Elastomeric bearing pads accommodate horizontal rotation and provide lateral shear movement. It is the most economical solution used in the construction of large span bridges and buildings [11]. As described earlier, two accelerometers (AC2, AC3) were purposely located next to bearing pad as shown in figure 9 to measure transmissibility of the bearing pad. Another accelerometers, AC4 and AC1, were located on the deck and the pillar, respectively. The graphs which present the acceleration amplitude in time domain from AC2 and AC3 from two measurements are shown on figure 10 and 11 and the summary is presented in Table 4. The sequence of accelerometer sensor listed in this table is according to its level on the bridge, AC4 is the highest on the top (deck) and AC1 is the lowest at the bottom (pillar) for easiness view the reduction of the amplitude. The elastomeric bearing can reduce the acceleration amplitude from the upper to the lower structure of the bridge. The reduction from AC3 to AC2 on PaI is about 54.62% whereas on PaH is 60.22%.

![Figure 9. Accelerometer 2 and 3](image1)

![Figure 10. The comparison of acceleration vs time of AC2 (black) and AC3 (red) from measurement at Pilar PaH](image2)

![Figure 11. The comparison of acceleration vs time of AC2 (black) and AC3 (red) from measurement at Pilar PaI](image3)
Table 4. Accelerometer response on the PaH pillar

| Sensor               | Amplitude of the Acceleration (m/s²) |
|----------------------|--------------------------------------|
|                      | Measurement at Pillar Pal | Measurement at Pillar PaH |
| Accelerometer 4 (AC4)| 1.39E-04                        | 2.36E-04 |
| Accelerometer 3 (AC3)| 1.31E-04                        | 2.24E-04 |
| Accelerometer 2 (AC2)| 0.59E-04                        | 0.89E-04 |
| Accelerometer 1 (AC1)| 0.23E-04                        | 0.25E-04 |

4. Conclusion
The forced-vibration test using eccentric mass shaker succeed in identifying the first vertical mode and the first longitudinal mode of KLBM bridge which is an elevated freeway precast-prestressed bridge. Two natural frequency of two main mode shape was 2.17 Hz for the first vertical mode and 8.06 Hz for the first longitudinal mode. The frequency obtained from the test results is slightly higher than the FE model. It indicates that the real structure is stiffer than FE model. The average damping ratio is within the range of damping ratio of prestresses concrete. The range is between 2-3% and the ratio obtain is 2.12%. The test results are closely represented by 3D FE model without modelling the whole foundation. The deviation of the natural frequency compared to the test results is 8.50%. The elastomeric bearing effectively reduces the acceleration from upper to bottom structure up to 57.42%.

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