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QUICK ASSESSMENT OF BRIDGE PERFORMANCE BASED ON DYNAMIC PARAMETERS ACQUIRED WITH SMARTPHONE APPLICATION

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Abstract: The Road Maintenance Regulation aims to ensure reliable and high-quality road services that prioritize community interests by meeting the functional and competitive performance of the road, as well as community participation in road maintenance in accordance with Republic of Indonesia Law No. 2 of 2022. As part of the community, when crossing the Tegineneng bridge on the Tegineneng-Sp. Tanjung Karang road section in Lampung Province and experiencing discomfort due to bridge vibrations, we participated in measuring vibrations using two smartphones. The gyroscopes in the smartphones, packaged in a g-force application, were able to record real-time vibrations in a user-friendly manner, and the output data were compatible with existing modal analysis software. The recorded acceleration data were then analyzed using the SSI algorithm to obtain dynamic parameters. The results identified that the structure had a natural frequency of 2.009Hz and a damping ratio of 7.927%. The frequency of 2.009Hz for a span of 60m is lower compared to bridges with the same span from the regression equation of dynamic tests on bridges in Indonesia, which is 2.347Hz. With this condition, it is estimated that the Tegineneng bridge has experienced minor structural damage with a damage level of 14.1% and its capacity is 28.2% lower than its empirical estimate. The damping ratio exceeding 5% is estimated due to excessive energy dissipation through cracks in concrete or defects in connections between steel frame elements. It is recommended for relevant stakeholders to conduct a detailed inspection of the bridge to ensure its integrity and to undertake necessary measures to ensure the safety of its users.

Keywords: bridge, dynamic, loading test, quick assessment, smartphone

1. INTRODUCTION

Road bridges and tunnels are among the transportation infrastructure that directly affect the lives of many people and serve a crucial social function, thus requiring security measures for road users. Security management for road bridges and tunnels is carried out by the Road Bridge and Tunnel Security Commission (KKJTJ) and the Managers. Bridge and/or Tunnel Managers can be government entities, private entities, corporations, or individuals authorized and responsible for the construction, management, and inspection of road bridges and tunnels. (Menteri Pekerjaan Umum dan Perumahan Rakyat, 2022). The purpose of bridge inspections is to ensure that the bridge conditions meet all service requirements, monitored systematically to promptly identify conditions that may lead to structural damage or collapse so that appropriate interventions or corrective actions can be taken .(Direktorat Jenderal Bina Marga, 2022; Murtosidi, Wahyudi, Soeherman, & Kurniawati, 2021).

Dynamic load testing is used to identify load capacity, integrity level, and bridge damage level, identified from dynamic parameters such as vibration frequency, damping, and vibration patterns. Frequency is a measure

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of structural stiffness and integrity. Any periodic changes in dynamic parameters correlate structural conditions with the rate of damage. Condition assessment criteria using vibration testing are applied to various types of bridges including reinforced concrete, prestressed concrete, steel frame, and composite steel girders (Direktorat Jenderal Bina Marga, 2002). The accuracy of dynamic test results compared to the static load test capacity is sufficiently accurate for assessing the reliability of the structure as long as the structure remains linearly elastic (Khoeri, Alisjahbana, Widjajakusuma, & Najid, 2023; Khoeri, Pradana, & Tasrim, 2024). Operational Modal Analysis (OMA) is a technique for identifying modal parameters based on vibration data collected when the structure is in its operational condition (Zahid, Ong, & Khoo, 2020). OMA is widely used by civil engineering communities to identify structural modal models. Finding a structural modal model is not the ultimate goal. The results of OMA can be adopted for various significant applications (Ghalishooyan & Shooshtari, 2015).

Smartphones can be used as tools for assessing dynamic vibrations caused by pedestrian loads, where the dynamics due to human footsteps are difficult to measure with traditional sensors (Ho, Mohtadi, Daud, Leonards, & Handy, 2019; Khoeri, Adeputra, & Sembada, 2024). The gyroscope in smartphones can record real-time vibrations, which are easy to use, analyze, and share, overcoming the limitations of traditional sensors (Wang, He, & Li, 2022). Experiments with vibrating tables show that smartphone-based wireless monitoring systems are sufficiently accurate in identifying structural modal parameters (Zhang, Tian, & Li, 2020). Massive and inexpensive data collected by smartphones can play a role in monitoring the health of existing transportation infrastructure (T. J. Matarazzo et al., 2022; T. Matarazzo, Vazifeh, Pakzad, Santi, & Ratti, 2017). Comparing results obtained from MEMS smartphone accelerometers with those obtained from classic piezoelectric sensors demonstrates how this cheap and common technology allows for accurate results, which is crucial for the potential future implementation of crowd-sensing systems for massive infrastructure monitoring in road networks that could be based on the VBI approach (Di Matteo, Fiandaca, & Pirrotta, 2022).

The road maintenance arrangement aims to provide reliable and high-quality road services that prioritize the interests of the community by ensuring the functionality and competitiveness of the road performance and involving community participation in road maintenance (Presiden Republik Indonesia, 2022). Based on this, as part of the community, when crossing the Tegineneng Bridge on the Tegineneng-Sp. Tanjung Karang road section in Lampung Province (Fig. 1) and experiencing discomfort from bridge vibrations, vibration measurements were conducted using a smartphone. Acceleration vibration data recorded using an iPhone 11 smartphone, with the source of vibration being ambient traffic loads on the bridge, were then subjected to Operational Modal Analysis (OMA) to identify dynamic parameters. From the assessment of these dynamic parameters, estimates of bridge capacity and damage level will be obtained.

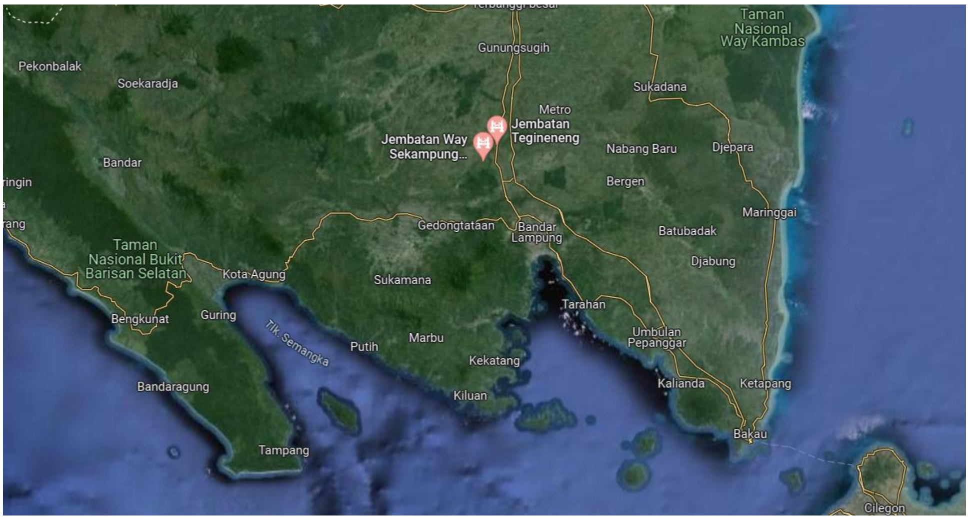

Fig. 1 The location of the Tegineneng Bridge

From this study, it is expected to obtain information on vibration data, dynamic parameters, and the assessment results of these dynamic parameters, which can be forwarded to road and bridge management authorities for further action.

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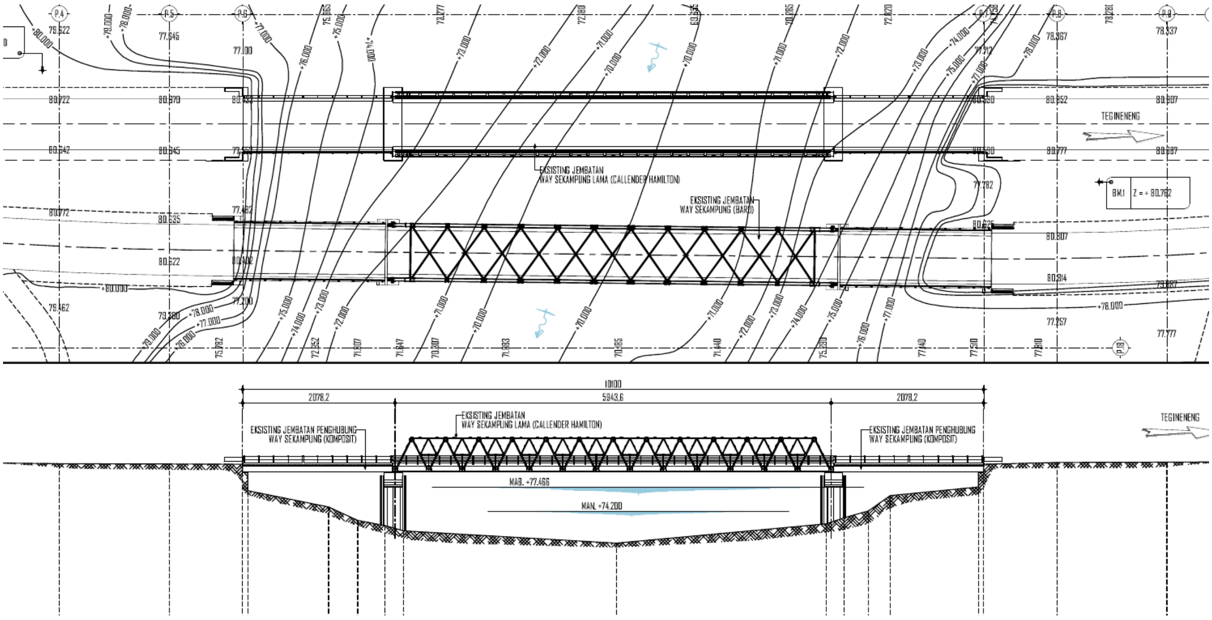

Fig. 2 Plan and longitudinal section of the bridge

2. METHOD

The bridge under study is a 60 m span girder bridge, with a total width of 10.40 m, a traffic lane width of 7 m, and a pedestrian lane width of 0.7 m (Fig. 2). In summary, the research steps conducted were: (1) Vibration data acquisition under operational loads; (2) Transformation of acceleration data into the frequency domain; (3) Identification of dynamic parameters; and (4) Assessment of dynamic parameters. The research flow is depicted in Fig. 3.

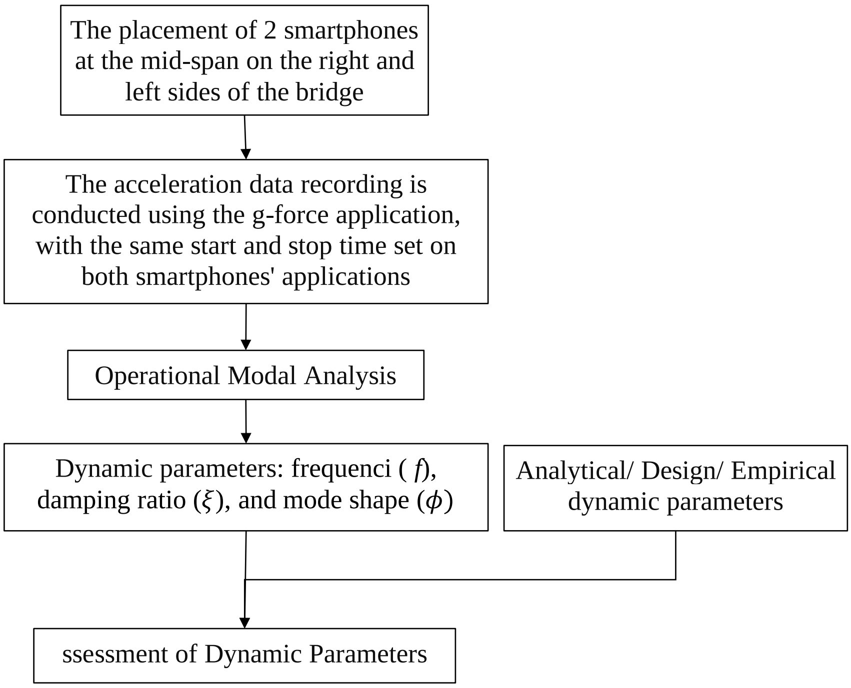

Fig. 3 Research Workflow

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2.1 Vibration data acquisition under operational loads

The vibration measurement is conducted using the ambient load of people walking on the structure. Vibration data is recorded using the accelerometer on an iPhone 11 with the g-force application. The sensor placement location is as shown in Fig. 4.

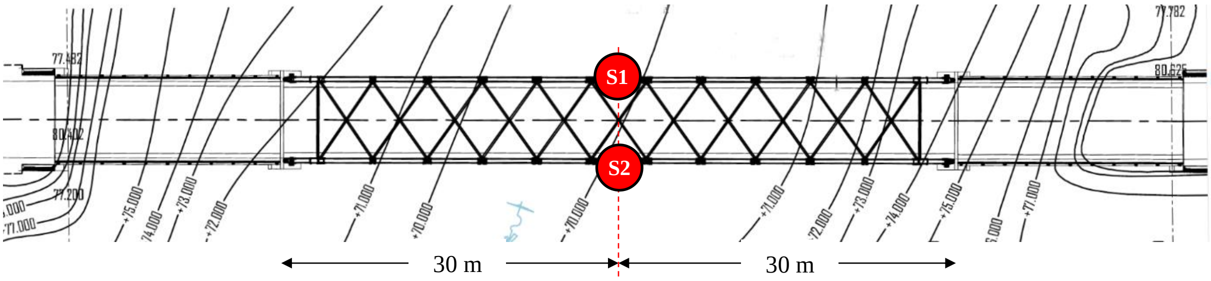
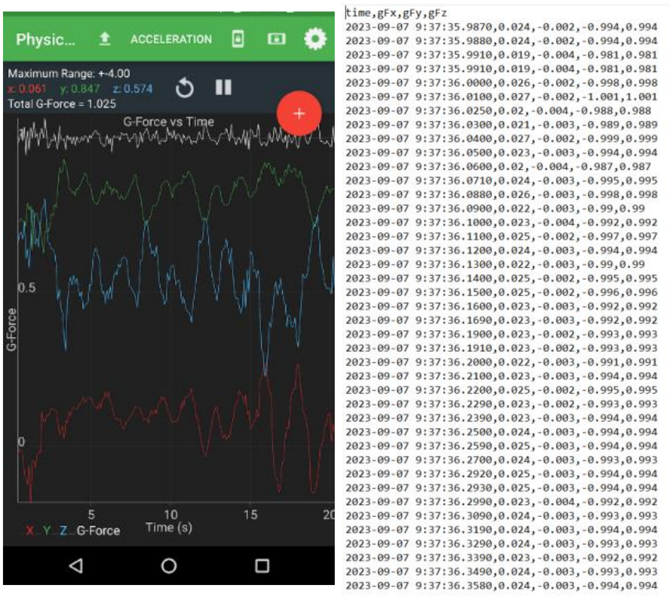


Fig. 4. The placement of smartphones

The data collection with ambient load is part of the Operational Modal Analysis (OMA). OMA is a method used to test structures under their operational conditions. It can be applied to various purposes such as Finite Element (FE) model validation and updating, Structural Health Monitoring (SHM), damage detection, load estimation, and condition monitoring (Zahid et al., 2020).

The data recording process is conducted over a duration of 60 seconds, with data being trimmed from the first 15 seconds and the last 15 seconds, meaning the analyzed data spans a duration of 30 seconds. The obtained data consists of acceleration data in the z, y, and z directions, as well as the resultant acceleration in g (gravity), with a data interval of 0.01 seconds, or a sampling frequency of 100 Hz. A screenshot of the application and an example of the recorded data in *.csv format are provided in Fig. 5.




```
time,gFx,gFy,gFz
2023-09-07 9:37:35.9870,0.024,-0.002,-0.994,0.994
2023-09-07 9:37:35.9880,0.024,-0.002,-0.994,0.994
2023-09-07 9:37:35.9910,0.019,-0.004,-0.981,0.981
2023-09-07 9:37:35.9910,0.019,-0.004,-0.981,0.981
2023-09-07 9:37:36.0000,0.026,-0.002,-0.998,0.998
2023-09-07 9:37:36.0100,0.027,-0.002,-1.001,1.001
2023-09-07 9:37:36.0250,0.02,-0.004,-0.988,0.988
2023-09-07 9:37:36.0300,0.021,-0.003,-0.989,0.989
2023-09-07 9:37:36.0400,0.027,-0.002,-0.999,0.999
2023-09-07 9:37:36.0500,0.023,-0.003,-0.994,0.994
2023-09-07 9:37:36.0600,0.02,-0.004,-0.987,0.987
2023-09-07 9:37:36.0710,0.024,-0.003,-0.995,0.995
2023-09-07 9:37:36.0880,0.026,-0.003,-0.998,0.998
2023-09-07 9:37:36.0900,0.022,-0.003,-0.99,0.99
2023-09-07 9:37:36.1000,0.023,-0.004,-0.992,0.992
2023-09-07 9:37:36.1100,0.025,-0.002,-0.997,0.997
2023-09-07 9:37:36.1200,0.024,-0.003,-0.994,0.994
2023-09-07 9:37:36.1300,0.022,-0.003,-0.99,0.99
2023-09-07 9:37:36.1400,0.025,-0.002,-0.995,0.995
2023-09-07 9:37:36.1500,0.025,-0.002,-0.996,0.996
2023-09-07 9:37:36.1600,0.023,-0.003,-0.992,0.992
2023-09-07 9:37:36.1690,0.023,-0.003,-0.992,0.992
2023-09-07 9:37:36.1900,0.023,-0.002,-0.993,0.993
2023-09-07 9:37:36.1910,0.023,-0.002,-0.993,0.993
2023-09-07 9:37:36.2000,0.022,-0.003,-0.991,0.991
2023-09-07 9:37:36.2100,0.023,-0.003,-0.994,0.994
2023-09-07 9:37:36.2200,0.025,-0.002,-0.995,0.995
2023-09-07 9:37:36.2290,0.023,-0.002,-0.993,0.993
2023-09-07 9:37:36.2390,0.023,-0.003,-0.994,0.994
2023-09-07 9:37:36.2500,0.024,-0.003,-0.994,0.994
2023-09-07 9:37:36.2590,0.025,-0.003,-0.994,0.994
2023-09-07 9:37:36.2700,0.024,-0.003,-0.993,0.993
2023-09-07 9:37:36.2920,0.025,-0.003,-0.994,0.994
2023-09-07 9:37:36.2930,0.025,-0.003,-0.994,0.994
2023-09-07 9:37:36.2990,0.023,-0.004,-0.992,0.992
2023-09-07 9:37:36.3090,0.024,-0.003,-0.993,0.993
2023-09-07 9:37:36.3190,0.024,-0.003,-0.994,0.994
2023-09-07 9:37:36.3290,0.024,-0.003,-0.993,0.993
2023-09-07 9:37:36.3390,0.023,-0.003,-0.992,0.992
2023-09-07 9:37:36.3490,0.024,-0.003,-0.993,0.993
2023-09-07 9:37:36.3580,0.024,-0.003,-0.994,0.994
```

Fig. 5. G-force on iPhone 11 and acceleration recording results in *.csv format

2.2 Identification of dynamic parameters in Operational Modal Analysis

The identified dynamic parameters include natural frequency, damping ratio, and vibration patterns in the x, y, and z directions. The dynamic data processing is conducted using the Stochastic Subspace Identification technique. For statistical data analysis as an indicator of the quality of the discovered mode shapes, the Modal

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Assurance Criterion (MAC) is utilized. The algorithm flow for Operational Modal Analysis using the SSI method is depicted in the Fig. 6.

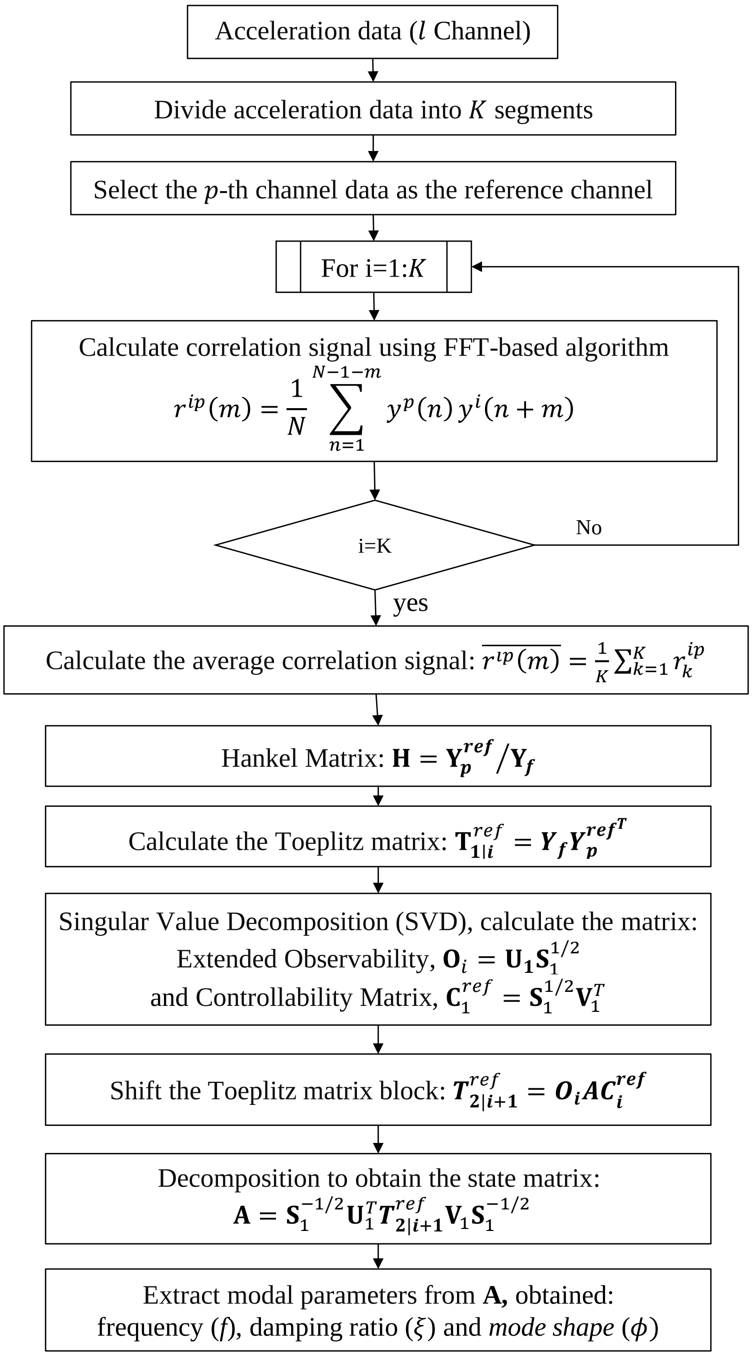

Fig. 6 The algorithm flow for Operational Modal Analysis using the SSI method

2.3 Penilaian Parameter dinamik

The parameters for dynamic assessment are as follows (Direktorat Jenderal Bina Marga, 2002):

1. First natural frequency or measured fundamental, f_{actual} which comes from free vibration.
2. Flexural rigidity, EI_{actual}
3. Critical Damping, ζ_{actual}

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A reduction in the observed natural frequency compared to the expected natural frequency value indicates a decline in the structural integrity. The structural reaction is intricately linked to the state of structural damage. The values indicating the extent of structural damage are as follows (Direktorat Jenderal Bina Marga, 2002):

$$D_{realtive} = \frac{(f_{theoretical} - f_{actual})}{f_{theoretical}} \times 100\% \quad (1)$$

Where:
$D_{realtive}$ = relative structure damage value
f_{actual} = actual natural frequency [Hz]
$f_{theoretical}$ = theoretical natural frequency [Hz]

The capacity decrease value may be approximated by using the below equation (Direktorat Jenderal Bina Marga, 2002):

$$D_{capacity} = \frac{(EI_{theoretical} - EI_{actual})}{EI_{theoretial}} \times 100\% \quad (2)$$

Where:
$D_{capacity}$ = capacity loss value
$EI_{theoretial}$ = theoretical bending stiffness [kN.m^2]
EI_{actual} = actual bending stiffness [kN.m^2]
$E_{dinamic}$ obtained by the following formula(Wilayah, n.d.):

Next, the interpretation of conditions is based on the reference provided in the following Table 1:

Table 1 Penilaian Kondisi Bangunan Atas (Direktorat Jenderal Bina Marga, 2002)

Condition Value	Damage Type	Relative Damage Value	Capacity Decrease Value
Excelent	Intact	0%-5%	0%-10%
Goood	Slight damage (non-structural)	6%-10%	11%-20%
Doubtfull	Slight damage (structural)	11%-17%	21%-34%
Not good	Severe damage (structural)	18%-20%	35%-40%

Note: The values in Table 1 apply to similar upper structure materials. For composite upper structure assessments, remaining cross-sections should be considered, and objective assessments are aided by visual inspections.

3. RESULT AND DISCUSSION

Acceleration data measurement was conducted while the bridge was in operation. Photo of traffic conditions during vibration data recording using smartphones, as depicted in Fig. 7.

Fig. 7 Documentation photo of traffic conditions during data recording using smartphones

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The acceleration data recorded from smartphone-1 (S1) and smartphone-2 (S2), with the start and end times cross-checked for the x, y, and z directions, are provided sequentially in the Fig. 8 and Fig. 9.

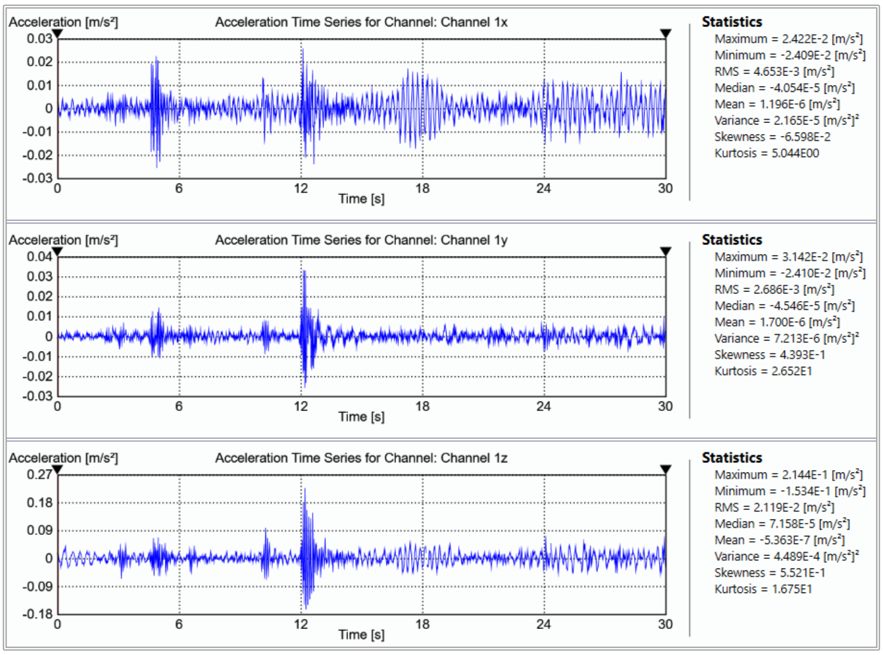

Fig. 8 Acceleration data in the x, y, and z directions from S1

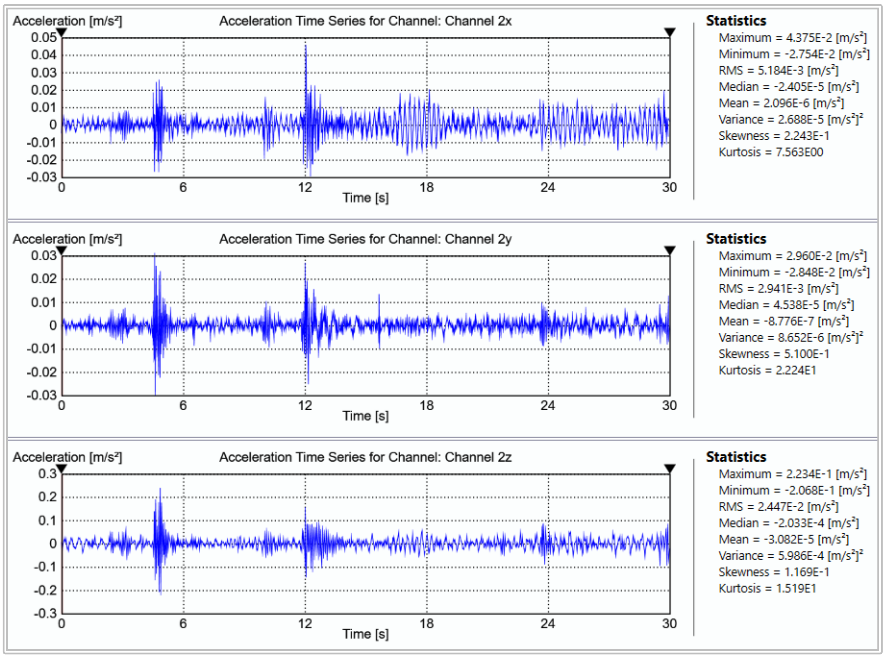

Fig. 9 Acceleration data in the x, y, and z directions from S2

Next, the acceleration data in the time domain is transformed into the frequency domain using FFT, as described in Fig. 6. This yields the dynamic parameters: natural frequency (Fig. 10), damping ratio (Fig. 10), and mode shape (Fig. 13).

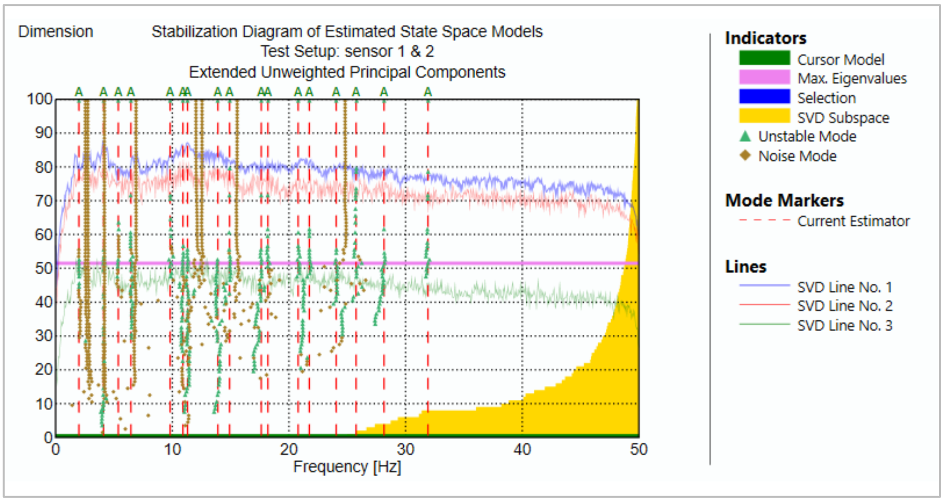

Fig. 10 Stabilization diagram of estimated state space models, test setup S1 and S2

Empirically, several previous studies have established a relationship between frequency and bridge span, which can serve as an initial reference in bridge planning or during dynamic bridge testing. This relationship is represented by equations (3) to (6), and graphically depicted in Fig. 11.

$$f_0 = 87.227L^{-0.883} \text{ (Direktorat Jenderal Bina Marga, 2014)} \quad (3)$$

$$f_0 = 90.6L^{-0.923} \text{ (Cantieni, 1983)} \quad (4)$$

$$f_0 = 82L^{-0.9} \text{ (Paultre, Chaallal, \& Proulx, 1992)} \quad (5)$$

$$f_0 = 23.58L^{-0.592} \text{ untuk 20m} < L < \text{100 m (British Standards Institution, 2003)} \quad (6)$$

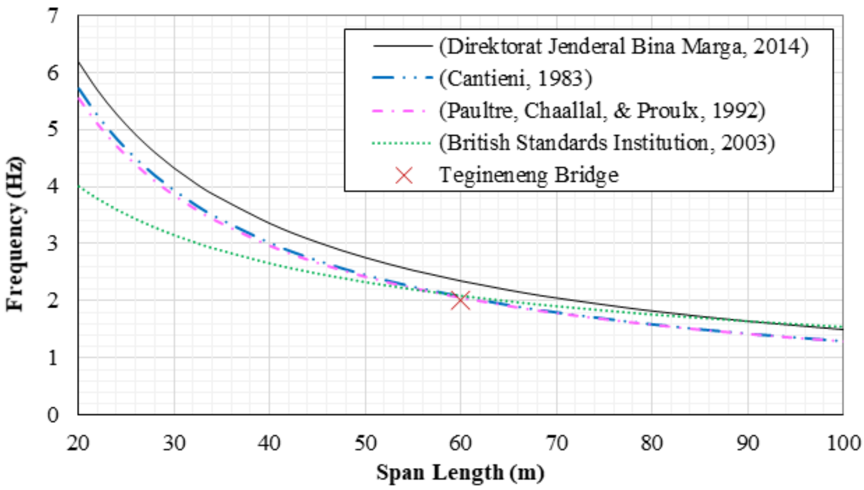

Fig. 11. Comparison between actual frequency and previous research results

Since the design data is unknown, empirical frequency data for the same span on bridges in Indonesia is used. For a span of 60m, the empirical frequency is 2.347Hz. This means that the actual frequency observed is lower than the empirical frequency. With this reference, the relative structural damage level can be estimated using equation (1):

$$D_{relative} = \frac{(f_{theoretical} - f_{actual})}{f_{theoretical}} \times 100\% = \frac{(2.347 - 2.009)}{2.347} \times 100\% = 14.41\%$$

The difference between the actual and theoretical frequencies of 10-20% is equivalent to a difference in flexural stiffness of 20-40%. With this correlation, the decrease in bridge structural capacity can be estimated from equation (2) as:

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$$D_{capacity} = \frac{(EI_{theoretical} - EI_{actual})}{EI_{theoretial}} \times 100\% \approx 2 \times D_{relative} = 2 \times 14.41\% = 28.82\%$$

Natural frequency vs damping ratio of mode-1 system and confidence interval as provided in Fig. 12.

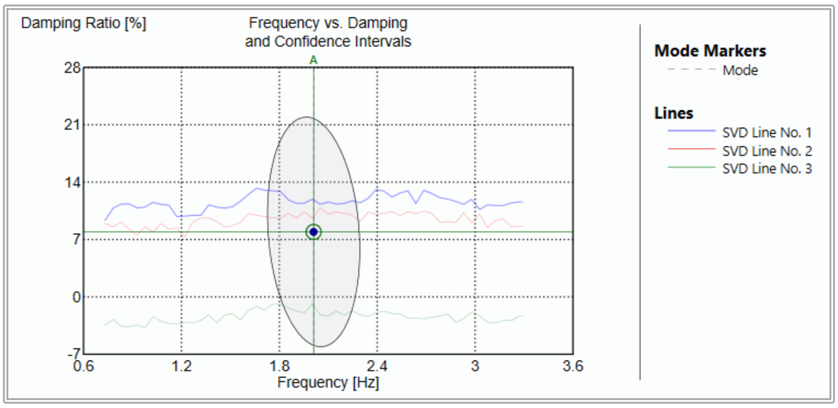

Fig. 12 Frequency vs damping and confidence intervals

With a damping ratio greater than 7.927% (Fig. 12), which is above 5%, it indicates significant energy dissipation, typically in concrete structures through cracks. However, since the bridge under study is a truss bridge, the significant energy dissipation is likely caused by issues in the connections between the steel frame elements.

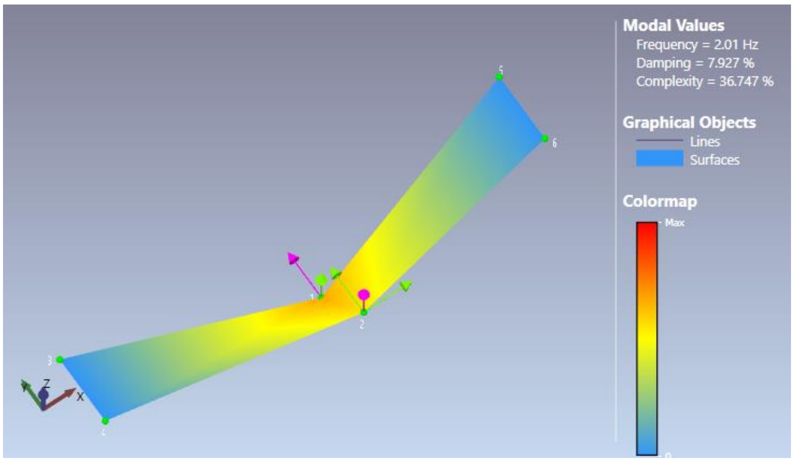

Fig. 13. Mode shape, natural frequency and damping ratio

Table 2 Shape detail

DOFs	Direction	Magnitude	Phase [Degree]	Real	Imag
1	X	0.114	-67.151	0.044	-0.105
1	Y	0.476	-159.672	-0.822	-0.304
1	Z	0.86	163.016	-0.727	0.222
2	X	0.068	-42.883	0.05	-0.046
2	Y	0.579	-137.984	-0.43	-0.388
2	Z	1	0	1	0

The other dynamic parameter obtained is the mode shape. The detailed mode shape shown in Fig. 13 is rounded as in Table 2. The structural response when subjected to loads will first appear in the most dominant mode shape, which is mode shape-1. With mode shape-1, the static deflection of the structural system when responding to static loads can be approximated. Generally, the identified mode shapes indicate that the bridge structure is in

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abnormal condition, where the ideal dominant mode shape should be vertical, symmetric, but the observed mode shape is asymmetrical. However, it is still dominated by vertical deflection (Fig. 13), indicating that the damage, although classified as structural, is still in the mild category. This category aligns with the description provided in Table 1, where a bridge with a relative damage level of 14.41% is categorized as experiencing slight structural damage.

4. CONCLUSION

The gyroscope in the smartphone, packaged within the g-force application, is capable of recording real-time vibrations and is highly user-friendly. Moreover, its output data in *.csv format is compatible for analysis with existing modal analysis software. By utilizing two iPhone 11 smartphones with the g-force application installed, data can be recorded simultaneously. From the recorded data, using the SSI algorithm, dynamic parameters such as natural frequency, damping ratio, and mode shape are obtained. Based on the testing and OMA results, the Tegineneng Bridge has a natural frequency of 2.009Hz and a damping ratio of 7.927%. The frequency of 2.009Hz for a span of 60m is lower compared to bridges of the same span in Indonesia, which have a frequency of 2.347Hz according to the dynamic bridge regression equation. With this condition, it is estimated that the Tegineneng Bridge has experienced slight structural damage with a damage level of 14.1%, and its capacity is 28.2% lower than its empirical estimate. The damping ratio exceeding 5% indicates excessive energy dissipation, likely through cracks in the concrete or defects in the connections between the steel frame elements.

With these findings, it is recommended to conduct a detailed inspection of the bridge to ensure its integrity and to undertake necessary measures to guarantee the safety and security of its users.

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