*The 2020 World Congress on*
***The 2020 Structures Congress (Structures20)***
*25-28, August, 2020, GECE, Seoul, Korea*

# Vibration-based comparison of accelerometer and microtremor sensors with numerical verification by assessing a PC-bridge

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## ABSTRACT

The application of structure health monitoring systems to civil engineering structures has been attracted a lot of attention among the various research committees due to providing better understanding of structures' conditions that result in more cost-effective management of those structures. This paper focuses on a vibration-based damage detection method as a tool for determining variation in structural stiffness that results changing in modal parameter. The target structure for the evaluation is a pre-tensioned PC bridge located in the seaside that exists a large amount of alkali-silica reaction in the airborne particles of the environment which deteriorated the downstream side of the bridge. The study aims to manifest the accuracy of two vibration-based damage detection sensors (accelerometer transducer and microtremor) by evaluating the vibration characteristics (natural frequencies) of the structure. Furthermore, to identify the declination in structural serviceability of the bridge, the recorded data from the sensors that demonstrates the current health condition of the bridge is then compared with the vibration response obtained from finite element software (MIDAS Civil) which represents initial intact state of the bridge. The good agreement of results measured by both sensors leads to a decision, that any of the two sensors is capable of evaluating a structure accurately.

Keywords: Prestressed Concrete bridge; Accelerometer transducer; Microtremor sensor; Natural frequency; Midas civil

## 1. INTRODUCTION

Among the other civil infrastructures, transport infrastructure, especially bridges are of great importance to modern society (Aasim et al. 2020 and Karimi et al. 2019), and like other structures, their performance decreases gradually throughout their service life due to their exposure to various types of deterioration processes such as: traffics, environmental effects, natural disasters (storm, earthquake, flood and typhoon), accidental overloading and excessive usage (Zordan et al. 2014 and Aasim et al. 2020). Around the world, a considerable number of bridges have succeeded their estimated service life (Cruz and Salgado 2009). A survey conducted by the Ministry of Land, Infrastructure Transport and Tourism in 2015 in Japan showing the results that, about 18% of existing road bridges are more than 50 years old in 2013 and will gradually increase to 67% in 2033 (Owolabi et al. 2003; Ručevskis et al. 2009).

In the last few decades, structural health monitoring (SHM) of all infrastructures, particularly the existing bridges have received considerable attention among the civil engineering societies (Yabe et al. 2019; Kudela et al. 2018; Song et al. 2017; Liao et al. 2019; Kong et al. 2016; Peng et al. 2019; Xu et al. 2013; Zhang et al. 2018). Therefore, in order to prevent the unexpected failure of the bridge structure, a potential and periodical evaluation and maintenance is essential (Twayana and Mori 2014). A large number of studies are carried out to evaluate the integrity of structures categorizing them into two major groups; local damage detection methods and global damage detection methods (Nanda et al. 2012; Qui et al. 2016). Local damage detection methods are widely used because of their ease in implementation (Jo et al. 2018) but, the methods are subjected to some limitations such as, the limited access to all parts of the structure and are unable to provide information of the initial stage of the damage which is usually invisible that makes the application methods inappropriate in most of the times (Boukabache et al. 2012). Whereas, global damage detection methods can assess the structure as a whole and without the vicinity of damage to be known a prior. Usually, damage detection is identified based on the comparison of the dynamic modal parameters of the structure before and after damage occurrence (Eraky et al. 2015; Sharma and Kumar 2018), and most of the global damage detection methods are focused on the vibration characteristics of a structure, either finding shifts in resonant frequencies or changes in structural mode shapes while evaluating a structure because they contain embedded information about structure’s inherent properties (Peter et al. 2003). This is due to the development of new powerful systems in data acquisition and signal processing, allowing to determine accurately the dynamic system characteristics of a structure. Nevertheless, the user has to be careful because some non-controllable problems related to measurement quality and accuracy may lead to wrong interpretation of the obtained measurements. The basic idea of damage detection techniques based on vibrations is that the dynamic characteristics are functions of the physical properties of the structure, and therefore changes in the structural condition will be reflected in the vibration signature, making it possible to identify the presence of damage by tracking changes to that signature stated by (Zhou et al. 2010; Maruyama, I 2016; He and Zhu 2011; Choi et al. 2005; Ansary and Arefin 2020, Aasim et al. 2017). Among the dynamic components (natural frequency, mode shape, and damping ratio) of a structure, as a diagnostic tool of damage detection, it is easier to use the change in natural frequency to identify damage in a structure compare to others and, the measurement error is reported less than 1% (Kim et al. 2003; Tuttipongsawat et al. 2018)

This paper presents vibration-based damage identification approach utilizing experimental and numerical methods by assessing a pre-tensioned PC bridge. the objective of the study is to compare the vibration characteristics obtained from the bridge by two experimental measurement sensors to identify their accuracy. Furthermore, FE model of the bridge is created to illustrate the as-built sate and declination in bridge's serviceability, and also to confirm the experimental results.

## 2. BRIDGE CHARACTERISTICS

The model structure considered for the evaluation in this study is a simply supported pre-tensioned PC bridge. The bridge was constructed in 1989 across a small river near by the sea connecting two narrow streets at the north part of Okinawa prefecture, Japan. Site location and view of the bridge is shown in Fig. 1. It is a single-span, pre-tensioned PC box girder bridge of 16 m length with 12 m effective width composed with six PC box-girders. The girders are placed side by side having 16 m length, 700 mm width and 500 mm depth supported by two transverse diaphragms to form deck stiffening and resist transverse tensioning for integration, and they are introduced as G1, G2 … G6 from the upstream side to the downstream side. The bridge has curbs of 300 mm width, 40 mm height and railings at both exterior girders and curve portions' edges. Also, a curve portion is attached to both sides by the abutments for providing easy access to the traffic. Schematic diagram of the bridge is shown in Fig. 2.

**Fig. 1** Location and overall view of the target bridge

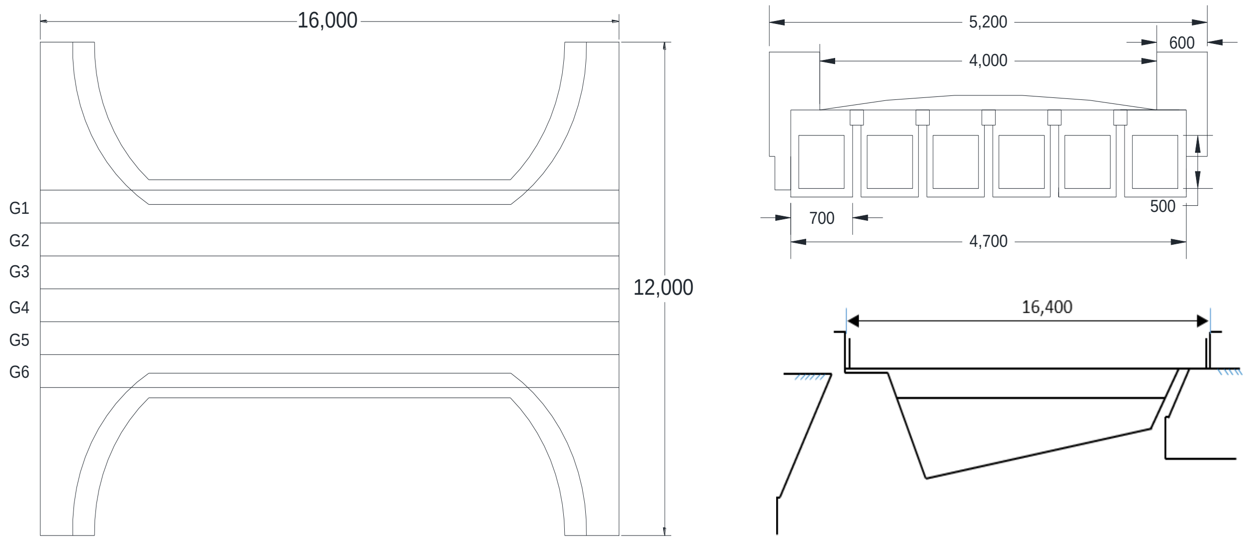



**Fig. 2** Top, cross-sectional and transversal views of the bridge

## 3. DAMAGE SCENARIOS

Structures in general deteriorate depending on its usage, types of materials, age, and the surrounding environment. The main causes of deterioration of this bridge are considered to be the immense existence of alkali-silica reaction in the airborne particle in the environment and also, lack of periodical structural inspection and maintenance. The bridge does not have any other major deficiency rather than the crack occurrence on some girders. According to visual inspection, girders (G1, G2 and G3) on the upstream side of the bridge are evaluated to be healthy members whereas, girders (G4, G5 and G6) on the downstream side contain some cracks. Based on the evaluations carried out in two years, the major cracks were in the state of incredible development by measuring width of some cracks to be 0.8 mm in December 2015 but enlarged to 4.0 mm in December 2017 which were later retrofitted (Fig. 3). In this area, similar cases happened to various structures and the results of conducting several types of tests such as: concrete compressive strength test, chloride ion concentration analysis, neutralization test, acceleration expansion test and petrological evaluation conducted on the bridge's girders showed; the cause of this type of deterioration is the exposure of the structure to an aggressive environment that contains a massive amount of ASR in the airborne particles.

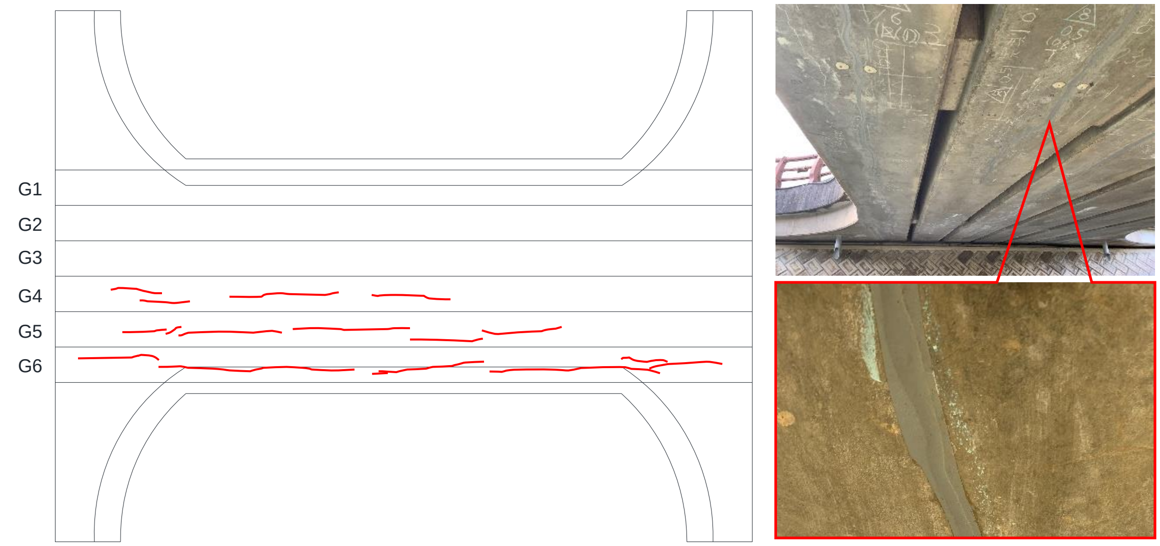



**Fig. 3** Measured cracks positions and patterns on the girders

## 4. STRUCTURAL DETERIORATION AND DAMAGE DETECTION METHOD

Structures begin to deteriorate once they are built and opened for the service load, therefore, maintaining safe and reliable structures for daily use is essential to all (Peter et al. 2003). Neglecting timely, regularly and the standard process of assessment can cause their structural failure that leads to calamitous consequences which could not only cause high expenditure, but the loss of human lives as well (Ručevskis et al. 2009; Karimi et al. 2019). Hence, as long as the structures are in service, they have regular costly inspections all over the world in both developing and developed countries based on their economic situation (Pour-Zhaz et al. 2011). Therefore, a wide variety of structural applications have been in practice for decades or even more than hundred years. Vibration-based damage detection method is one of the widely adopted technique among the other structural health monitoring applications that non-destructively evaluate a structure by investigating its dynamic behavior (natural frequency, mode shape and damping ratio) (Aasim et al. 2020). The method even shows great potential for on-line damage assessment of various type of structures including civil engineering structures (Fan and Qiao 2011). An extensive study has conducted stating that decades ago, literatures provided that, damage in a structure can be detected using changes in vibration characteristics and the result obtained from them was quite reliable and consistent (Deobling et al. 1998). The delay in bringing these diagnostic parameters in practice was the presence of some confounding factors which could not be easily analyzed.

In this study, vibration-based damage detection method is adopted to evaluate the structural health condition of the bridge with the purpose of validating the accuracy of two measuring sensors (Accelerometer transducer and microtremor).

## 5. EXPERIMENTAL PROGRAM

Vibration-based testing is performed on the bridge by using dynamic testing equipment including a mass of 30kg, accelerometers, microtremors and data acquisition system. The instrumentation setup is shown in Fig. 4. all the measuring sensors are carefully inspected and collaborated to ensure that they work effectively as intended. The main objective of this test is to compare the results of two measuring sensors and their validity as well as to check the current state of the bridge.

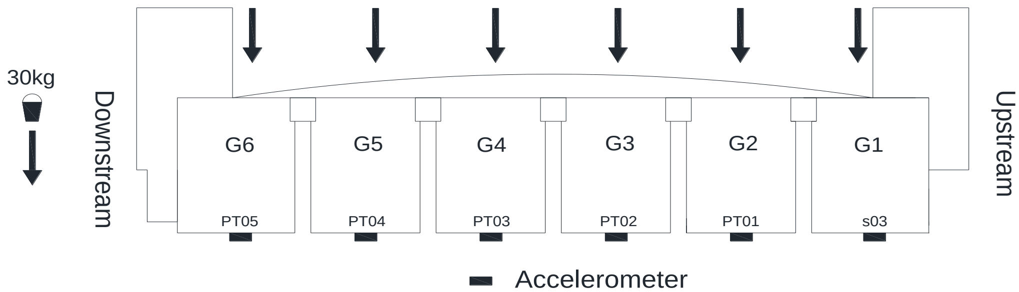



**Fig. 4** Layout of data acquisition system using accelerometers

### *5.1 Accelerometer*

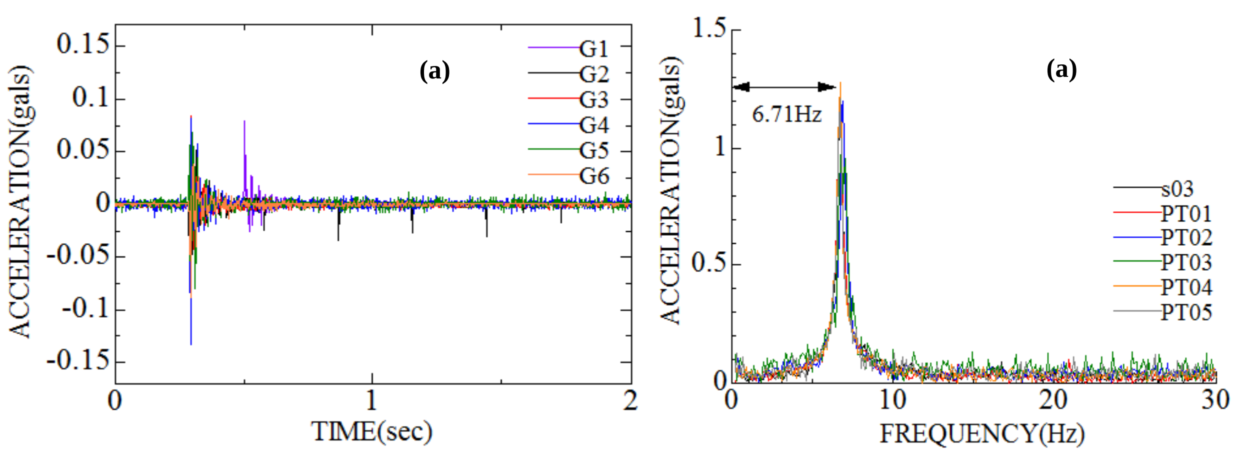
In this test, an impact load is induced to generate vibration waves by dropping 30kg sandbag from 70 cm height on the points where the portable type of accelerometers are attached to the girders for acquiring the vibration response of the bridge. The reason of using specific type load is to reduce the reflection influence of the weight and to uniformly transmit the shock wave due to free fall of the mass. During free vibration, the response of the bridge is measured through triaxial acceleration transducers (hereinafter referred to as a sensor) with nominal sensitivity range (± 2000gal), the trigger level and sampling interval of the sensors is set for data recording to be 20 gals in 2 milli-seconds, accordingly. The sensors are set on the girders, two horizontal components are oriented along the longitudinal and transverse directions, and vertical component is upward positive. For the bridges vertical vibrations are generally dominant rather than horizontal ones that correspond to the fundamental natural frequency. The sensors (s03, PT01, PT02, PT03, PT04 and PT05) are attached to the center of each girder (G1, G2, G3, G4, G5, and G6) as shown in Fig. 5. The vibration is caused by an impact at three locations (mid-span of the bridge, G2 girder and G5 girder) by dropping the mass to vibrate the bridge in various locations.

(a) (b)

**Fig. 5** (a) dropping load illustration (b) positions of accelerometers on the bridge's girders

*5.1.1 Accelerometer Result*

From the accelerometers' result, it appears that the vibration response of the bridge is governed by vertical bending mode coupled with torsional mode in the frequency range of 6-17 Hz. In the first test when the load is exited at the mid-span, the sensors could only capture the natural frequency of the bending mode, while in two other tests, where the impact is induced on G2 and G5, the sensors could measure the value of torsional mode along the bending mode of the bridge. It is observed that, position of the load application may cause variation in amplitude in bending mode but does not affect the frequency itself. Whereas, capturing the torsional mode is the result of changing the impact position. The typical acceleration response and frequency spectrum of the tested bridge are shown in Fig. 6.



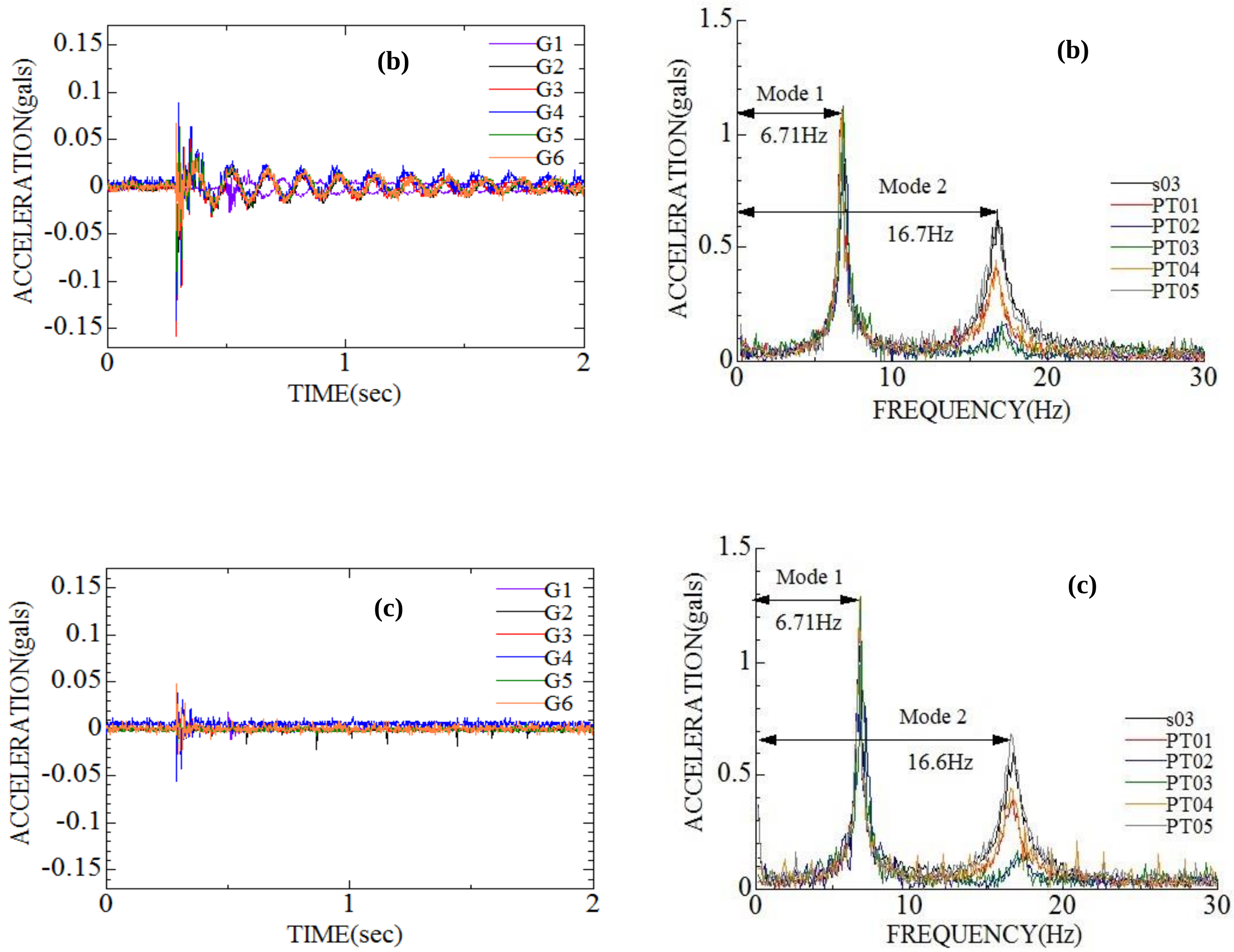



**Fig. 6** Measured acceleration and frequency responses of the bridge (a) time-history and natural frequency result of load dropped on the center of the bridge (b) time-history and natural frequency result of load dropped on G2 (c) time-history and natural frequency result of load dropped on G5.

### *5.2 Microtremor*

Microtremor is one the of the widely used measurement sensor in the field of structural health monitoring that can detect seismograph with high magnification by measuring ground vibrations with displacement amplitude and velocity amplitude (Rezaei Choobbasti 2017). Surface of the Earth is always in motion at seismic frequencies, even without earthquakes stated by (Okada and Suto 2003). Both, these constant vibrations of the ground surface and the sensor are called microtremor(s). Here, microtremor measurement sensors are permanently installed to the two outside girders (G1 and G6) of the bridge for recording the vibration response for long-term structural health monitoring. Figure 7 shows data collection of microtremor. The sensors are oriented to record the vibration data in a sampling interval of 10 mls in every continuous period of 45 seconds. The advantage of this type evaluation is that, these sensors are independent. The data can be recorded in the absence of an evaluator and without imposing the external load that results in avoiding traffic interference. Nevertheless, the professionals recommend measuring the data to be more than one time for confirming the result, because the surrounding noise and other environmental influential factors sometimes disturb the stationarity of the sensors required for data.

**Fig. 7** Data acquisition from microtremor sensors

### *1.2.1 Microtremor Result*

Vibration response of microtremor sensors is obtained from two out-side girders: G1, is a healthy girder and G6 that consists cracks based on the inspection conducted visually. Figure 8 shows natural frequencies acquired on the measuring point of G1 by recording the data three times (1st, 2nd, and 3rd) to confirm the environmental disruption and to validate the accuracy of microtremor. Next, the vibration response is obtained from the sensor installed on G6 and the data is obtained three times as well as seen in Fig. 9. Even though, the vibration data is recorded at a certain time to avoid most of environmental factors that can possibly influence the data. Yet, a minor variation is observed in the natural frequencies of sensors in two measuring locations. (Cawley and Adams 1979) stated that natural frequency is independent in terms of location, it can be obtained at any point of the structure and shall give the same result. In this case, the difference in natural frequencies is most probably the effects of environmental noise and it so small the extant of negligible level.

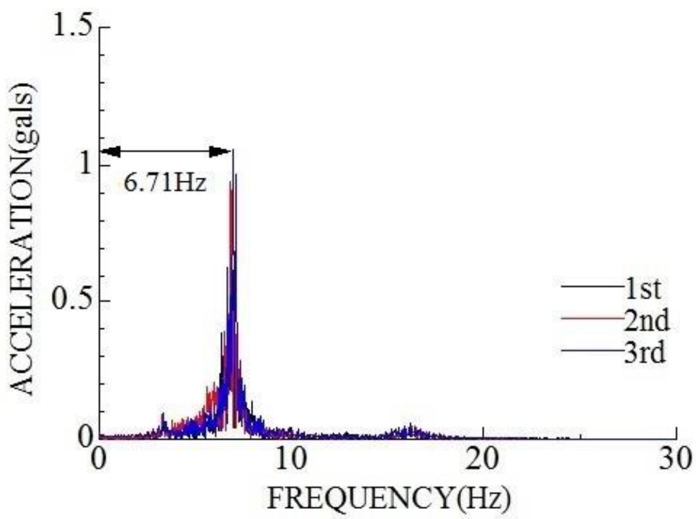



**Fig. 8** Vibration response acquired form G1 girder

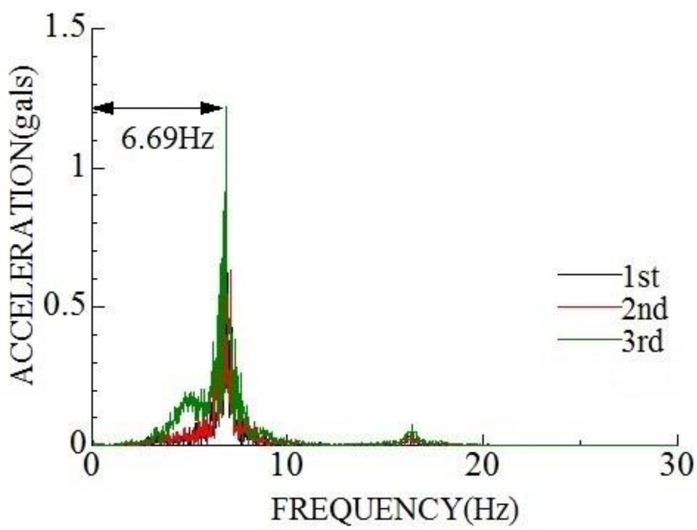



**Fig. 9** Vibration response obtained from G6 girder

## 6. NUMERICAL VERIFICATION

### *6.1 Finite Element Model*

A finite element model of the bridge is developed using commercial finite element analysis software (Midas Civil) which has been usually adopted for bridge design and analysis. FE model of the bridge deck is created using modal analysis for the purpose of generating the vibration response of the model to compare it with the experimental measured dynamic results of the bridge. The structural parameters of the bridge are assigned based on the road bridge specification and explanation (Japan road association 1978). The bridge deck is considered as simply supported beam element constraining both ends for transverse and vertical displacements and also for torsional rotation but allow it for longitudinal displacement. Material properties are assigned to be; Young's Modulus (E) = 3.3 MPa, weight density (ρ) = 2.498 t/m$^3$ and Poisson ratio (v) = 0.166667 whereas, the effects of pre-stressing force are considered to be zero. Figure 10 shows the plotted model of the bridge.

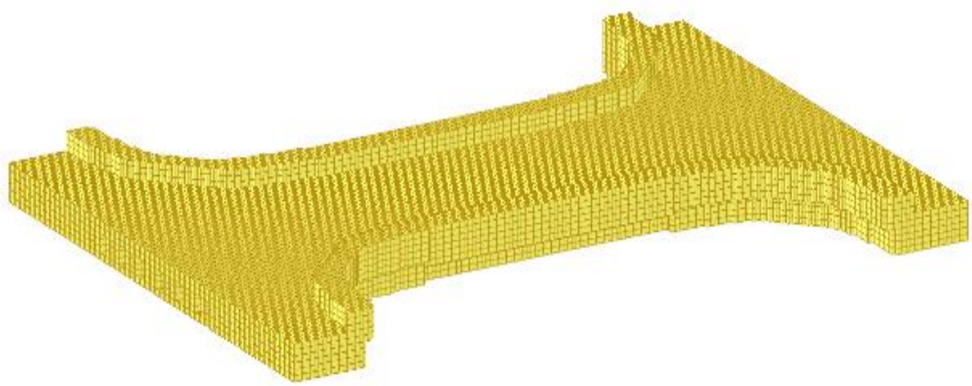


**Fig. 10** Numerical model of the bridge deck

*6.1.1 Numerical Result*

In the numerical analysis, the first four mode shapes, associated with natural frequencies obtain from eigenvalue analysis that illustrate intact (pre-damage) state of the bridge are presented in Fig. 11. The fundamental mode is the vertical bending mode of the deck with the impact vibration on the center that corresponds to the natural frequency of 7.61 Hz. Table 1 shows that all the four modes are involved in the deck vibration and most included coupled vertical bending and torsional modes of the bridge deck. It should be recalled that damage increases flexibility of a structure, unlike decreases natural frequency stated by (Sridhar and Prasad 2019). Therefore, FE model represents the as-built sate of the structure by showing higher values of numerically plotted natural frequencies than those experimental obtained through accelerometers and microtremors.

**Table 2** Numerical natural frequencies

| **Mode** | Experimental (Hz) | Numerical (Hz) | Frequency difference (%) |
|---|---|---|---|
| #1 | 6.71 | 7.61 | 11.82 |
| #2 | 16.7 | 18.81 | 11.21 |
| #3 | - | 28.05 | - |
| #4 | - | 38.28 | - |

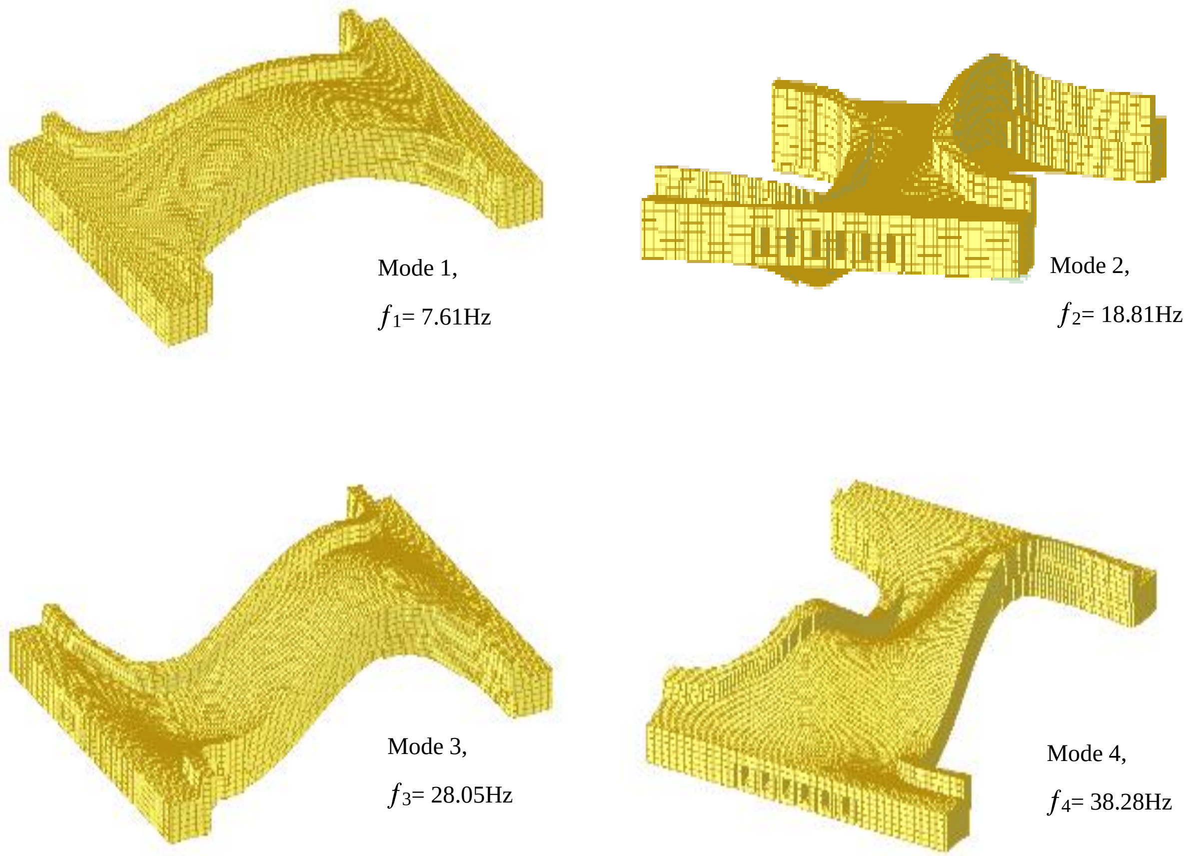



**Fig. 11** Plotted mode shapes and their corresponding natural frequency of eigenvalue analysis of the bridge

## 7. DISCUSSION

Based on the results obtained through experimental method using measured natural frequencies extracted from accelerometer transducers and microtremors. It was found that the frequencies acquired from the evaluation of accelerometers were identical by showing 6.71 Hz in all three tests. Whereas, the response recorded from two microtremors reasonably matched as well, with a minor difference of less than 0.3% in natural frequencies, and the change was considerably small to the extent of negligible level. This minor variation in microtremors data was most likely the environmental interference in the form of noise that influenced the data at the time of data acquisition.

Overall, the experimental results obtained using both measuring sensors from the bridge illustrated quite good agreement as shown in Fig. 12. Furthermore, there is another important information of mode shapes that was obtained from Eigenvalue analysis using finite element analysis in this work, that is usually used for assessing a structure. The information is the deflection pattern which is associated with each natural frequency. The interested modes of this study were the first and second modes that associated with first and second natural frequencies of the experimental response. The numerical results showed higher values of natural frequencies of corresponding mode shapes than those captured by the sensors as expected, that confirmed the accuracy of accelerometers and microtremors. Moreover, numerical results were adopted to illustrate the as-built sate of the bridge and declination in its serviceability.

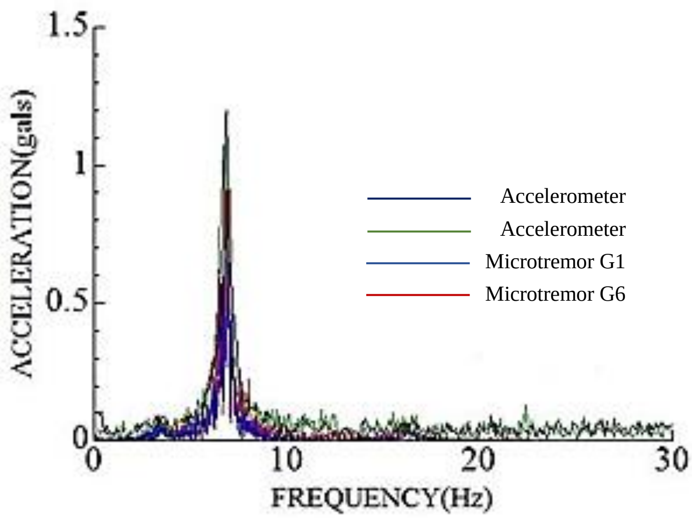



**Fig. 12** Comparison of the accelerometers' and microtremors' results

## 8. CONCLUSION

In this study, an experimental research; including accelerometer transducer test, microtremor test and finite element model using Midas Civil software were carried out to verify the validity of two sensors (accelerometer and microtremor) by evaluating a pre-tensioned PC box-girder bridge. The primary aim was to compare natural frequencies of accelerometers obtained from the evaluation to the natural frequencies measured by microtremors to confirm the accuracy of both measurements. In fact, the acquired results of both sensors were quite reliable showing error less than 0.3%.

Also, modal analysis was performed in order to obtained first few modes and their corresponding natural frequencies using eigenvalue analysis to present the as-built state of the bridge. furthermore, numerical result was used as a reference data to illustrate declination in bridge's serviceability by comparing it with experimental data that shows the current state of the bridge. Since, the girders of the downstream side of the bridge contain some cracks that could lead to decrease the natural frequency of the structure by 11.2% that is an increase in structure's flexibility which represents decline in bridge's serviceability.

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