# Detecting structural damage to bridge girders using radar interferometry and computational modelling

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## SUMMARY

The process for assessing the condition of a bridge involves continuously monitoring changes to the material properties, support conditions and system connectivity throughout its life-cycle. It is known that the structural integrity of bridges can be monitored by measuring their vibration responses. However, the relationship between frequency changes and structural damage are still not fully understood. This study presents a bridge condition assessment framework which integrates computational modelling and non-contact radar sensor techniques (*i.e.* IBIS-S) to predict changes in the natural frequencies of a bridge girder as a result of a range of parameters that govern its structural performance (*e.g.* elastomeric bearing stiffness, concrete compressive stiffness and crack propagation). Using a prestressed concrete bridge in Australia as a case study, the research outcomes suggest that vibration monitoring using IBIS-S is an efficient way for detecting the degradation of elastomeric bearing stiffness and shear crack propagation in the support areas which can significantly affect the overall structural integrity of a bridge structure. However, frequency measurements have limited capability for detecting the decrease in the material properties of a bridge girder.

KEY WORDS: bridge girder; IBIS-S; elastomeric bearing stiffness; shear crack propagation.

## 1. INTRODUCTION

With increased demand in freight transport, the structural performance of urban transport infrastructure networks has become a major concern for society globally especially for its maintenance and replacement. In Australia, articulated trucks now represent approximately 80% of freight transport [1]. Consequently, the increased volume of articulated trucks and their induced dynamic effects could accelerate the structural deterioration of bridges and so reduce their service life due to the degradation of construction materials (*e.g.* concrete creep, elastomeric bearing degradation, and crack propagation) [2-4]. As traditional visual inspection techniques may not be able to detect some types of bridge damage (*e.g.* deep cracks and holes in concrete bridge girders) in a timely and efficiently manner, the development of innovative condition inspection techniques in conjunction with computer modelling becomes necessary.

In recent decades, numerous advanced non-destructive testing (NDT) techniques have been developed with the aim of detecting the structural performance of bridge structures in an accurate and timely manner. Among these, the application of vibration techniques has been considered to be a cost-efficient way of monitoring the overall structural integrity of a bridge based on the dynamic characteristics of a structure (*e.g.* natural frequencies) [5-7]. In comparison to modal shape measurement which requires multiple locations and is prone to noise, natural frequency measurement only requires a single measurement point, and therefore the measured results are more accurate and reliable [8, 9]. Although it is well known that changes in natural frequencies are also closely correlated to changes of the overall stiffness of bridge structures [10], further research work is required to accurately identify a range of different types of structural damage for bridges.

Dynamic monitoring of structures under operational conditions using non-contact sensors has gained popularity in recent years. Testing of various civil engineering structures worldwide has demonstrated the significant advantages of NDT techniques over traditional methods [11, 12]. Newly developed non-contact radar sensors such as IBIS-S are capable of remotely monitoring static and dynamic measurements of a structure with high accuracy by detecting changes in natural frequencies of bridge structures, and therefore can detect damage to a bridge under operational conditions in a convenient and efficient way [13, 14]. While previous studies have mainly focused on comparing the measurement results of radar sensors (IBIS-S) with that of various other types of instruments (*e.g.* accelerometers), there are relatively few studies that have validated and interpreted IBIS-S results by developing computational models [15-17]. Our recent study on monitoring the dynamic behaviour of a full-scale prestressed concrete bridge using non-contact sensors (IBIS-S) under daily traffic loading showed that the natural frequency of the bridge measured by IBIS-S and the maximum vertical displacement of the bridge girders are consistent with that obtained from numerical simulation [18, 19]. However, it is still not fully understood how changes in natural frequencies are correlated to changes in a series of key parameters (*e.g.* support conditions and crack propagation near the zone of supports) that govern the overall structural performance of a bridge structure. For example, it has been shown that crack propagation on a cantilever beam could potentially decrease the natural frequency of the beam by 16% [20-22].

The purpose of this study is to integrate advanced interferometric radar techniques (IBIS-S) and numerical modelling to investigate changes in natural frequencies of a bridge due to the deterioration of structural performance under various conditions (*e.g.* degradation of elastomeric bearings and concrete compressive strength, and propagation of shear cracks in the support zones). The Merlynston Creek Bridge located on the M80 Ring Road in Melbourne, Australia was used in this study. This prestressed concrete bridge was initially constructed in 1996 with a length of 41 m and width of 12 m. To accommodate the increased amount of traffic and to reduce traffic congestion during peak hours, the bridge was upgraded in 2012. The bridge deck is supported by two types of bridge girders (i.e. Normal T-girder and Super T-girder). This study mainly focusses on changes in natural frequencies of the Super-T girders as a result of structural performance deterioration. For this purpose, we first developed a three dimensional

(3D) finite element model of the bridge. The model predictions were then validated by conducting field testing using IBIS-S. Finally, a series of parametric studies were carried out to investigate changes in natural frequencies of the bridge as a result of a decrease in elastomeric bearing stiffness and concrete compressive strength, as well as shear crack propagation, respectively.

## 2. METHODS

### *2.1. Finite Element modelling for concrete bridges*

A 3D FE model of the prestressed concrete Super-T girder was developed using commercial software package COMSOL 5.0 [23] to simulate changes in natural frequencies of the bridge girders as a result of their structural performance deterioration. COMSOL is a commercial finite element package which becomes increasingly popular in modelling reinforced concrete structures [24, 25]. In COMSOL, the concrete can be modelled using solid elements, while individual steel rebars may be modelled by adding a truss interface to the solid interface used for the concrete.

The geometric and material properties of the Super-T girder were based on the “As built” construction drawings provided by VicRoads, Australia (Figure 1 and Table I). As shown in Figure 1(a), the Super-T girder is supported by elastomeric bearings which are modelled as two elastic springs in this study with compressive stiffness $K_1$ and $K_2$, respectively. In addition, to investigate the effects of crack propagation on changes in natural frequencies of the Super-T girder, it is assumed that there are two shear cracks near the supports with a length of $d$ in $45^o$ as shown in Figure 1(a). Using Eigen frequency analysis, the steel bars were modelled using truss elements and the concrete girder was modelled using 6581 tetrahedral solid elements (Figure 1(c)).

### *2.2. Monitoring the dynamic behaviour of bridges using interferometric radar technique*

To validate the FE model developed in Section 2.1, a series of field tests were carried out using IBIS-S [26]. The IBIS-S instrument was located underneath the bridge as shown in Figure 2 to capture the strong reflected signals from the target girder with a configuration of 4.3m height *(h)* at mid of span of the girder and a distance resolution of 0.75m.

Dynamic response measurement using IBIS is based on two well-known radar techniques, *i.e.* the stepped-frequency continuous wave technique (SF-CW) and the interferometry technique. The SF-CW technique enables the detection of different target points along the line sight of radar measurement through transmitting short time duration ($\tau$) pulses to achieve high range resolution ($\Delta R$), which is the minimum distance between two points on the structure can be determined in term of pulse duration ($\tau = 1/B$) as follows:

$$\Delta R = \frac{c\tau}{2} \tag{1}$$

where $c$ is speed of light in free space. The frequency bandwidth $B$ of $N$ monochromatic pulses with set of frequency step $\Delta f$ emitted by radar is given by,

$$B = (N-1)\Delta f \tag{2}$$

It should be noted that the main frequencies of large civil engineering structures (*e.g.* bridges, buildings and towers) is in the range of 0-30Hz. Thus, the configuration of IBIS-S with an acquisition rate at 30 Hz is able to meet the requirements of sampling frequency of dynamic testing [27]. In addition, an unambiguous range measurement is obtained if the range of the targets is restricted to the maximum measured distance (

$R_{\max}$), *i.e.* $\Delta f$ is required to be less than 150 KHz for a 1000m unambiguous target range.

$$R_{\max} = \frac{c}{2\Delta f} \tag{3}$$

By substituting Eq.(1) and Eq.(2) into Eq.(3), the maximum sampling rate ( $f_{\max}$ ) can be obtained,

$$f_{\max} = \frac{c\Delta R}{4R_{\max}^2} \tag{4}$$

In addition, the interferometry technique enables the radial displacement ( $d_r$ ) of the scatter objects of the structure illuminated by the antenna beam by equating phase the shift of the electromagnetic waves reflected by the object in various time intervals to be remotely measured. That is,

$$d_r = -\frac{\lambda}{4\pi}\Delta\theta \tag{5}$$

where $\lambda$ is the wavelength of the electromagnetic signal, and $\Delta\theta$ is the phase shift. Hence, the actual displacement of different targeted point can be easily determined by way of geometric projection.

The resonant frequency of a bridge can be obtained by extracting the data sets based on the Frequency Domain Decomposition (FDD) technique in the frequency domain. The Power Spectral Density (PSD) function matrix is decomposed into a set of auto spectral density functions using Singular Value Decomposition (SVD), with each function corresponding to an individual frequency mode [28, 29].

For a linear dynamic system, the response spectral density matrix subjected to a white-noise random excitation may be expressed as:

$$\boldsymbol{G}(f) = \boldsymbol{\Phi}\boldsymbol{G}_{qq}(f)\boldsymbol{\Phi}^H \tag{6}$$

where $\boldsymbol{\Phi}$ and $\boldsymbol{G}_{qq}(f)$ are the mode shapes matrix and the spectral matrix of the modal coordinates, respectively. The superscript $H$ represents the complex conjugate matrix transpose. The spectral matrix should be composed of diagonal terms with the auto-spectral densities while the other terms with the cross-spectral densities. Taking the SVD at each frequency, the output PSD $\boldsymbol{G}(f)$ becomes:

$$\boldsymbol{G}(f) = \boldsymbol{U}(f)\boldsymbol{\Sigma}(f)\boldsymbol{U}^H(f) \tag{7}$$

where $\boldsymbol{U}$ is a unitary matrix of the singular vector $u_{ij}$, $\boldsymbol{\Sigma}$ contains a diagonal matrix of the real positive singular scalar values in descending order. If the mode shapes are orthogonal, there will only be one term in Eq. (6). Thus, the spectral matrix can be estimated by a rank-one matrix as follows:

$$\boldsymbol{G}(f_r) \approx \sigma_1(f_r)\boldsymbol{u}_1(f_r)\boldsymbol{u}_1^H(f_r) \tag{8}$$

For this case, the first singular vector $\boldsymbol{u}_1(f_r)$ becomes an estimate of the mode shape while the first singular scalar value $\sigma_1(f)$ at each frequency represents the strength of the dominating vibration mode. Most importantly, the first singular function can be used as a modal indication function to estimate resonant frequencies. The remaining singular values may contain either noise or modes close to the dominant mode.

## 3. RESULTS AND DISCUSSION

### *3.1. Model validation*

The thermal signal-to-noise ratios (SNR) as a function of range profile of the bridge girder is shown in Figure 3(a), while the range bin-polar coordinates at test point (TP) represent the quality of the acquired signals (*e.g.* a coherent data at a fixed distance from the centre of polar graph) are shown in Figure 3(b). The natural frequencies were identified through analysing the datasets acquired by IBIS-S using the FDD technique are as shown in Figure 3(c). The results indicate that the resonant frequency and the second mode of natural frequency of the bridge girder are 9.4Hz and 15.5Hz, respectively. Most importantly, it demonstrated that FE modelling results agree remarkably well with the IBIS-S measurements (Table II).

### *3.2. Parametric study*

After validation, the model developed was implemented to investigate the interrelationship between changes in natural frequencies and the structural performance deterioration of a bridge girder through conducting a series of parametric studies. Specially, this study focused on studying the effects of the degradation of elastomeric bearings stiffness and concrete compressive strength as well as shear crack propagations in the support zones of the bridge girder on the dynamic characteristics of the bridge girders.

*3.2.1. Degradation of concrete compressive strength.* In this study, the natural frequencies were theoretically predicted assuming that the concrete compressive strength degradation of the bridge girder is reduced by 80%, 64% and 50%, respectively. The simulation results presented in Figure 4 showed that degradation of the concrete compressive strength of the bridge girder would generally lead to a decrease in the natural frequencies of the girder. However, the impact of concrete compressive strength degradation on natural frequencies is apparently not significant. For example, 20% decrease of concrete compressive strength only reduces the natural frequency of the girder around 2%.

*3.2.2. Degradation of elastomeric bearings.* The deterioration of the mechanical stiffness of elastomeric bearings could be modelled by either decreasing both $K_1$ and $K_2$ or only decreasing one of them. It can be seen from Figure 5 that elastomeric bearings stiffness degradation is significantly correlated to the natural frequency of the girder. For example, changes in natural frequencies decrease by 45% when the stiffness of both elastomeric bearings stiffness are decreased by 20% simultaneously. Further, it showed that decreasing either $K_1$ or $K_2$ also has a significant impact on the natural frequencies of the girder. These results indicate that monitoring natural frequencies is an effective way of detecting changes in the mechanical stiffness of elastomeric bearings.

*3.2.3. Propagation of shear cracks in support zones of bridge girders.* Recent studies have revealed that natural frequencies are generally insensitive to bending crack propagation [30]. However, the propagation of shear cracks which commonly occur near the supports of a bridge girder which are subjected to relatively larger shear forces may have a significant impact on the natural frequencies of the girder, and so are worthy of further investigation [31]. Figure 6 shows the natural frequency of the bridge girder as a function of the geometry of a shear crack (*i.e.* $d/H$ from 0-0.6). It can be seen that shear crack propagation generally has a significant impact on changes of natural frequencies of a bridge girder due to the damage of the girder supports. Most importantly, the rate of decrease is significantly higher as the ratio of $d/H$ increases from 0 to 0.2. This outcome indicates that the measurement of the dynamic characteristics of a bridge using IBIS-S is an effective way of monitoring the propagation of shear cracks in the support areas.

## 4. CONCLUSIONS

In this study, we investigated the relationship between different types of structural damage on a bridge girder and its impact on the natural frequencies of the girder by developing computational models in conjunction with IBIS-S testing. The major findings were:

- The bridge condition assessment framework proposed in this study can both effectively and efficiently monitor the overall structural integrity of a bridge structure.
- The stiffness of elastomeric bearings is one of the most important parameters that govern the natural frequency of a girder. The degradation rate of elastomeric bearing stiffness leads to the significant decrease in the structural performance of bridge girders.
- Changes in the natural frequencies of a bridge girder are also very sensitive to shear crack propagation in the support zone of the girder, especially when the ratio of *d/H* increases from 0 to 0.2.
- The degradation of the compressive strength of the concrete of a bridge girder has little impact on the natural frequencies of the girder.

## ACKNOWLEGMENT

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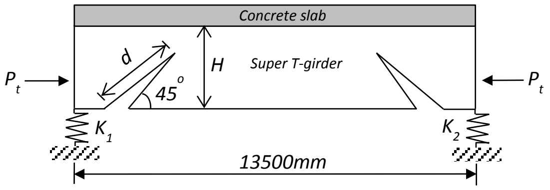
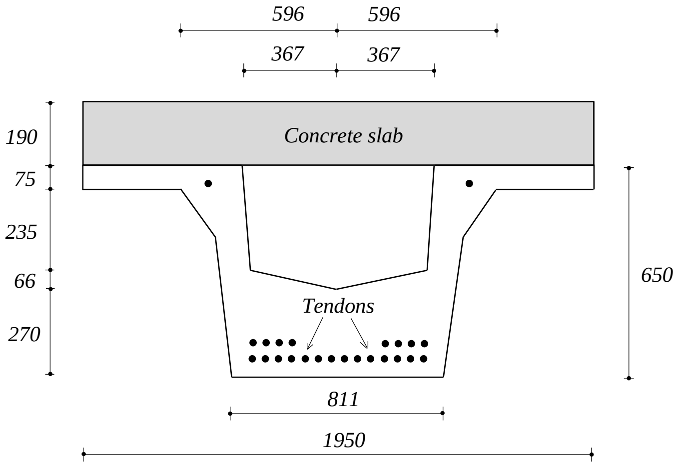
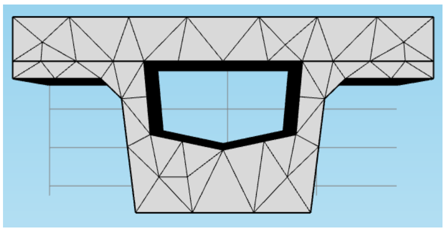


(a) Super T-girder modelling



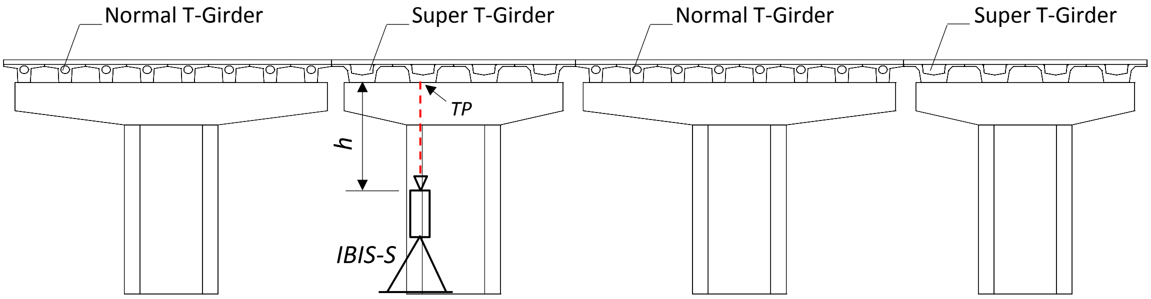
(b) Cross section details



(c) Tetrahedral solid elements of Super-T girder

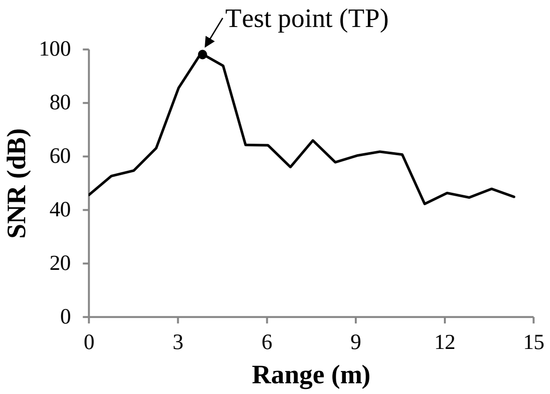
Figure 1. Schematic diagram of super T-girder for FE modelling

(a) View of Merlynston Creek Bridge during the in-field test using non-contact sensors IBIS-S

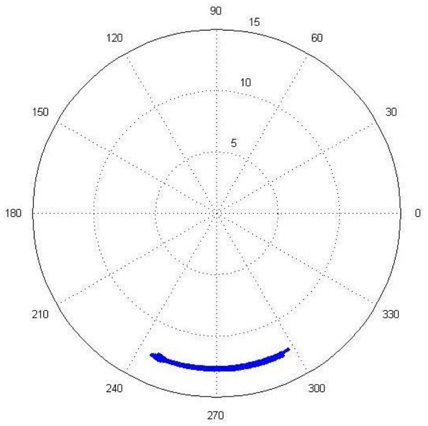


(b) Configuration of IBIS-S

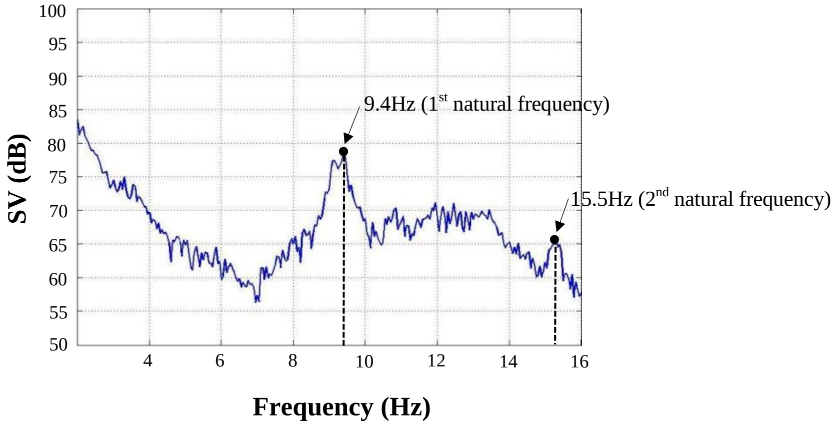
Figure 2. Dynamic monitoring of Merlynston Creek Bridge using non-contact sensors IBIS-S



(a) Thermal signal-to-noise ratio (SNR) as a function of range profile of the bridge



(b) The range bin-polar coordinates at test point (TP) representing the quality of the acquired signals



(c) Natural frequencies generated from experimental datasets

Figure 3. Results generated from IBIS-S measurements

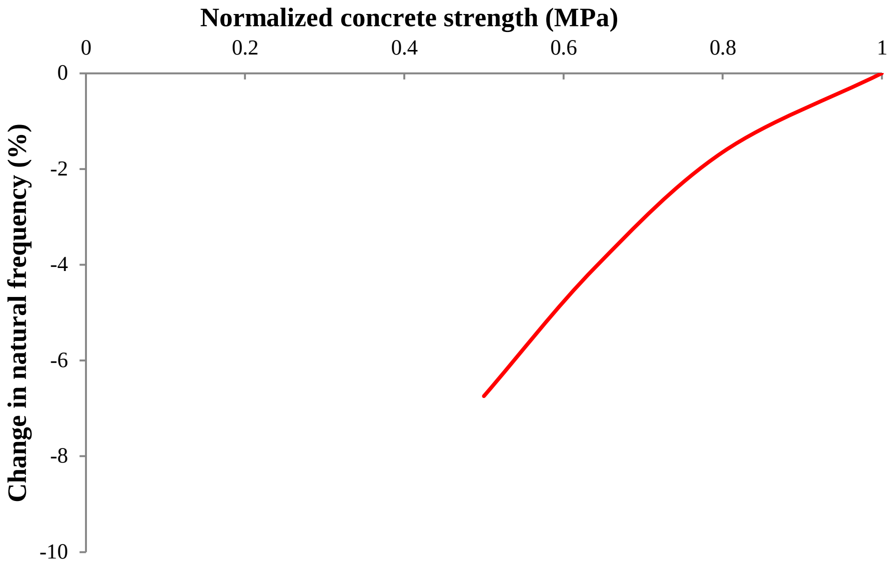


Figure 4. Changes in natural frequencies due to concrete compressive strength degradation. Concrete compressive strength is normalized to its initial value (*i.e.* 50MPa) while the reference value of natural frequency is 9.37Hz.

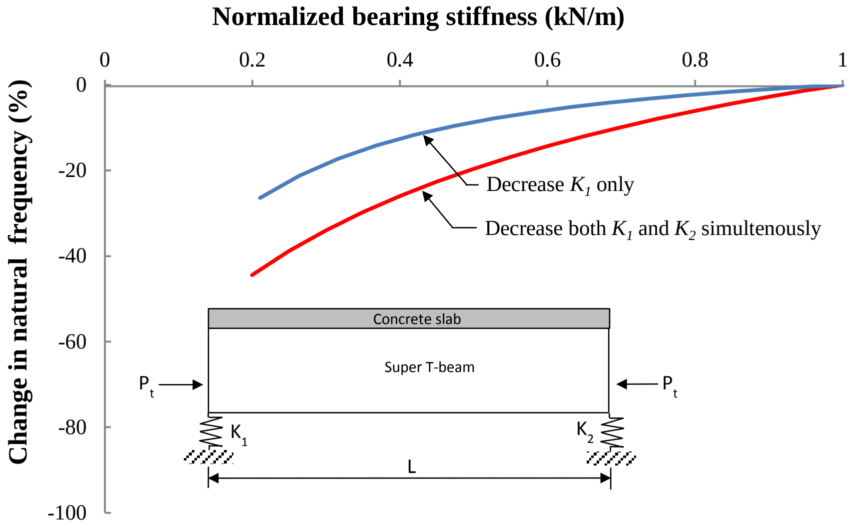


Figure 5. Changes in natural frequencies due to degradation of elastomeric bearings stiffness. Elastomeric bearings stiffness is normalized to its initial value (*i.e.* 168× $10^3$ kN/m) while the reference value of natural frequency is 9.37Hz.

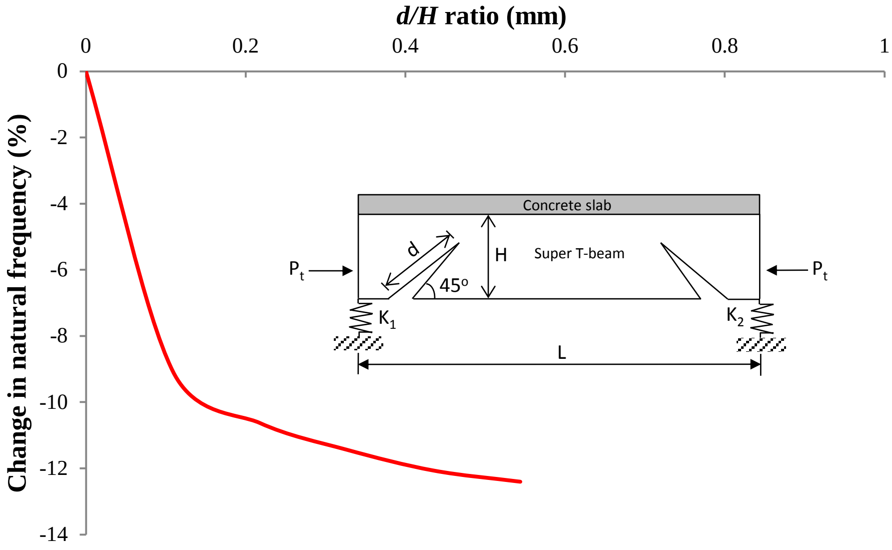


Figure 6. Changes in natural frequencies due to shear cracks propagations. The reference value of natural frequency is 9.37Hz.

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Table I.  Parameters used in this study

| Parameter | Value |
|---|---|
| Mass density of concrete (kg/cm$^3$) | 2400 |
| Poisson's ratio of concrete | 0.2 |
| Concrete compressive strength $f_c'$ of girder (MPa) | 50 |
| Concrete compressive strength $f_c'$ of bridge deck (MPa) | 40 |
| Modulus elasticity of bridge girder (MPa) | $34.8 \times 10^4$ |
| Modulus elasticity of bridge deck (MPa) | $32.8 \times 10^4$ |
| Mass density of rebar (kg/cm$^3$) | 7850 |
| Poisson's ratio of rebar | 0.3 |
| Young's modulus of steel bar (MPa) | $2 \times 10^6$ |
| Cross section area of steel bar (mm$^2$) | 14 × 113.04 |
| Mass density of prestressing steel (kg/cm$^3$) | 7850 |
| Poisson's ratio of prestressing steel | 0.33 |
| Young's modulus of prestressing steel (MPa) | $2 \times 10^6$ |
| Cross section area of prestressing steel (mm$^2$) | 22 × 98.6 |
| Prestressing force $P_t$ (kN) | 187 |
| Elastic spring stiffness $K_1$ and $K_2$ (N/m) | $168\times 10^6$ |

Table II. Comparing natural frequencies from FE predictions with that from IBIS-S measurements

| Method | Natural frequency (Hz) | |
|---|---|---|
| | First mode | Second mode |
| IBIS-S measurements | 9.4 | 15.5 |
| FE prediction | 9.37 | 15.74 |

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