HEALTH MONITORING OF HIGHWAY BRIDGES

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ABSTRACT

Structures such as bridges, buildings and infrastructure were constructed to serve the society over an expected long period of time. Today, many of them have decayed due to aging, deterioration, misuse or lack of proper maintenance. It is important to be able to identify and monitor the health status of these structures to prevent potential sudden structural failures. An index proposed for inferring the health deterioration is the spectral norm of the flexibility matrix associated with selected reference points sensitive to the service environment of the structure. This index can be evaluated from the dynamic responses detected by sensors installed at these reference points under forced vibration. A sharp increase in the index calls for further investigations for appropriate actions. In this study, a laboratory test was conducted to demonstrate the sensitivity of the proposed index with respect to variable levels of controlled damages imposed on the tested structure, followed by a real test on existing highway bridges.

1. INTRODUCTION

Highway bridges can suffer structural deterioration due to aging, misuse or lack of proper maintenance. Being able to inspect and monitor the structural health of existing bridges is crucial for avoiding sudden bridge collapses leading to losses of lives and economy. The present research focuses on developing a reliable technique to identify health deteriorations of highway bridges using the combination of simple field test and the numerical modeling power of finite element method.

In practice, any method used to determine existing health condition of bridges should be nondestructive. Ambient vibration tests have been used in many engineering applications to detect and to evaluate damages. Recently, forced vibration gains more interest (Bakht and Pinjargar, 1989). This is due to the development of new powerful systems in data acquisition and signal processing, allowing reliable and accurate determination of dynamic characteristics of the system. The basic idea of damage evaluation techniques based on vibrations can be referred to the literature (McLamore et al., 1971; Abdel-Ghaffar and Housner, 1978; Flesch and Kernbicher, 1988, Douglas and Reid, 1982, Salane and Baldwin, 1990; and Hogue et al., 1991)

Dynamic characteristics of a structure, namely natural frequencies and mode shapes, are known to be functions of its stiffness and mass distribution. Deteriorations of structure result in a reduction of its stiffness, which causes the change in its dynamics characteristics. Thus, monitoring the change in these dynamic characteristics enables us to infer to a structural deterioration.

Present status of dynamic characteristics of structures can be evaluated under either ambient or forced vibration. For bridges, dynamic excitation under ambient condition may not be able to excite the structure sufficiently. Thus, forced excitation is almost necessary (Hogue et al., 1991; Raghavendrachar and Aktan, 1992).

In the present study, forced excitation in the form of shock will be induced by an impact hammer at *referenced* locations. These locations are so selected where responses are pronounced and sensitive to the potential damages. Both input excitation and output responses are measured and processed. Though modal characteristics can theoretically be evaluated by processing the vibratory responses alone; results are not as reliable as the case when both excitation and responses are considered.

As changes in frequencies and mode shapes are not sufficiently sensitive to structural deteriorations, a more effective index is developed in this study. An index should be established in relation to the softening of the structure. This need points to the flexibility matrix that can be established from the test in association with the *referenced* sensor locations. In parallel, a base-line finite element model can be formulated to represent the bridge. This model can be continuously updated to tune its flexibility property to the corresponding *observed* value from the test.

2. MODAL FLEXIBILITY MATRIX

Structural deterioration reduces stiffness and increases flexibility. Increase in structural flexibility can serve as a good indicator of structural deterioration, and allow one to evaluate the degree of structural damage (Raghavendrachar, and Aktan, 1992). Numerically, the flexibility matrix of a bridge can be established with respect to selected degrees of freedom from the mode shapes and frequencies. For the purpose of monitoring the flexibility change, these *referenced* degrees of freedom should be selected in such a way that they can reflect dominant deformations of the structure under its service environment.

The flexibility matrix associated with referenced degrees of freedom can be established for an existing bridge as a result of impact test. Based on the schematic test set-up in Figure 1, the response signals from the accelerometers and the impact hammer can be recorded each time. The time domain equations of motion can then be transformed into the frequency domain by the Fast Fourier Transform (FFT) resulting in a Frequency Response Function (FRF). Then, the modal flexibility matrix associated with the referenced degrees of freedom can be established from the following equation.

$$[F] = [\Phi]\left[{}^{1}\!/_{\omega^2}\right][\Phi]^T \tag{1}$$

where [F] is the modal flexibility matrix; [Φ] the mass-normalized modal vectors; and $[1/\omega^2]$ the diagonal matrix of ascending natural frequencies. As flexibility matrix reflects global structural deterioration, its norm will be a good overall indication of its flexibility condition, i.e.

$$FMN = \sqrt{\lambda_{\max}(F^T F)} \tag{2}$$

where F is the flexibility matrix; FMN is the flexibility-matrix norm; and $\lambda_{max}(F^TF)$ is the largest eigenvalue of F^TF matrix.

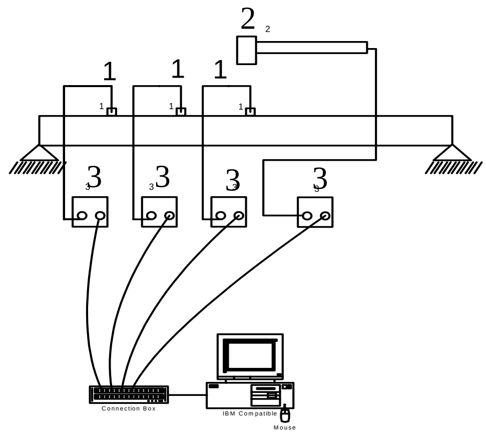

Figure 1: Schematic impact test setup: (1) accelerometers, (2) impact hammer and (3) signal conditioning.

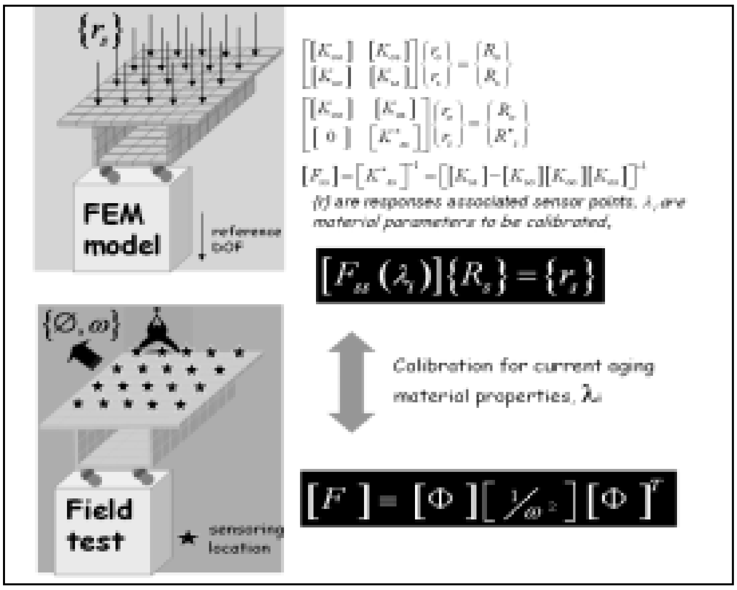

Figure 2: Calibration of the finite elementmModel

3. CALIBRATION OF FINITE-ELEMENT MODEL

At the same time, standard finite element model must be established to represent the existing bridge based on its present in-service condition. Information could be obtained from as-built drawings and in-situ measurements. Initially, standard material parameters, λ_i, can be assumed. The variation of these parameters after its usage shall be calibrated by tuning the flexibility matrix of the FE model to that obtained from the test. It is important that both matrices are associated with the same referenced degrees of freedom. As shown in Figure 2, the flexibility matrix, $[F_{ss}]$ of the FE model is obtained by inverting the reduced stiffness matrix $[K^*_{ss}]$ associated with the referenced degrees of freedom $\{r_s\}$, after condensing it from the full stiffness matrix.

4. LABORATORY IMPACT TESTS

4.1 Undamaged beam test

A simple steel beam of channel section was selected in the experiment to confirm the correlation between theoretical and experimental results. The setup detail and the locations of the accelerometers are presented in Figure 3.

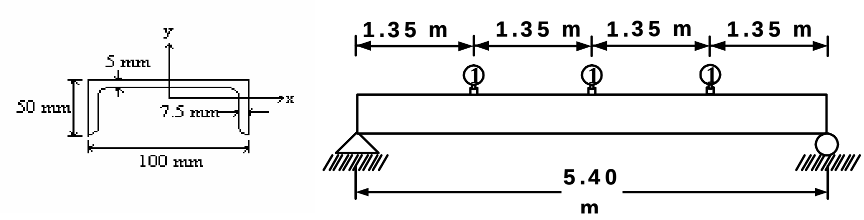

Figure 3: Laboratory setup of simply-supported steel beam, with mass density = 9.72 kg/m, $I_x = 26.0*10^{-8}$ m^4, and $E = 2.04*10^{11}$ N/m^2.

Table 1 lists frequencies of the first 7 modes obtained from the test in comparison with the analytical results. The corresponding FRF is presented in Figure 4.

Table 1: Natural frequencies: theory vs impact test

Mode	Theory (Hz)	From Test (Hz)
1	4.0	4.0
2	15.9	15.9
3	35.6	35.7
4	65.3	65.3
5	98.8	98.6
6	142.0	141.0
7	191.5	191.0

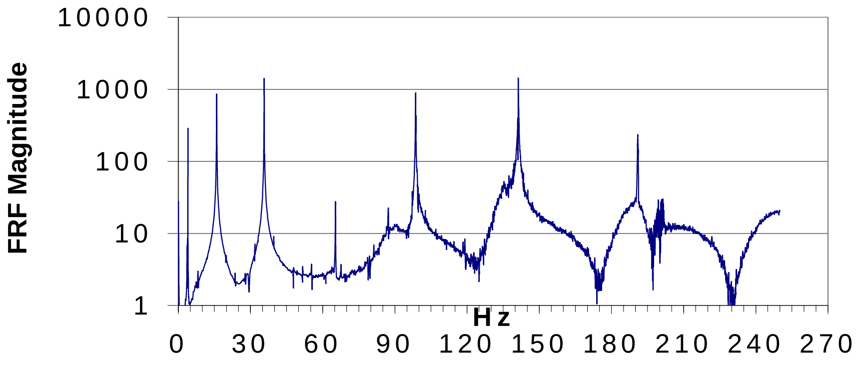

Figure 4: Frequency-response function of steel beam under impact test

The modal flexibility matrix based on modal frequencies and mass-normalized mode shapes is evaluated using Equation (1), and compared very well with the corresponding theoretical result in the following:

$$
\begin{aligned}
[F]_{theory} &= \begin{bmatrix} 0.3479 & 0.4252 & 0.2706 \\ 0.4252 & 0.6185 & 0.4252 \\ 0.2706 & 0.4252 & 0.3479 \end{bmatrix} \times 10^{-4}; \quad FMN = \left\| F_{theory} \right\|_2 = 1.220 \times 10^{-4} \\
[F]_{modal} &= \begin{bmatrix} 0.3542 & 0.4264 & 0.2718 \\ 0.4264 & 0.6190 & 0.4160 \\ 0.2718 & 0.4160 & 0.3422 \end{bmatrix} \times 10^{-4}; \quad FMN = \left\| F_{modal} \right\|_2 = 1.207 \times 10^{-4}
\end{aligned} \tag{3}
$$

4.2 Impact Test on Steel Beam with Controlled Defects

A series of similar impact tests are conducted to evaluate the mode shapes and frequencies of the same C-shaped steel beam, but with some prescribed defects. This test simulates different degrees of deterioration by introducing cuts in the bottom flanges at the beam mid-span.

For relevant comparison, SB01 is designated to the original beam and SB11, SB21 and SB31 denote the same beam with cuts of 10 mm, 20 mm and 30 mm respectively. It was found that the alterations of mode shapes and frequencies due to adding the defects are found to be rather insignificant.

However, the change of flexibility matrix norm (FMN) is found to be more pronounced as in Figure 5. This confirms that FMN is sufficiently sensitive to the defect built into the structure and serves the present purpose.

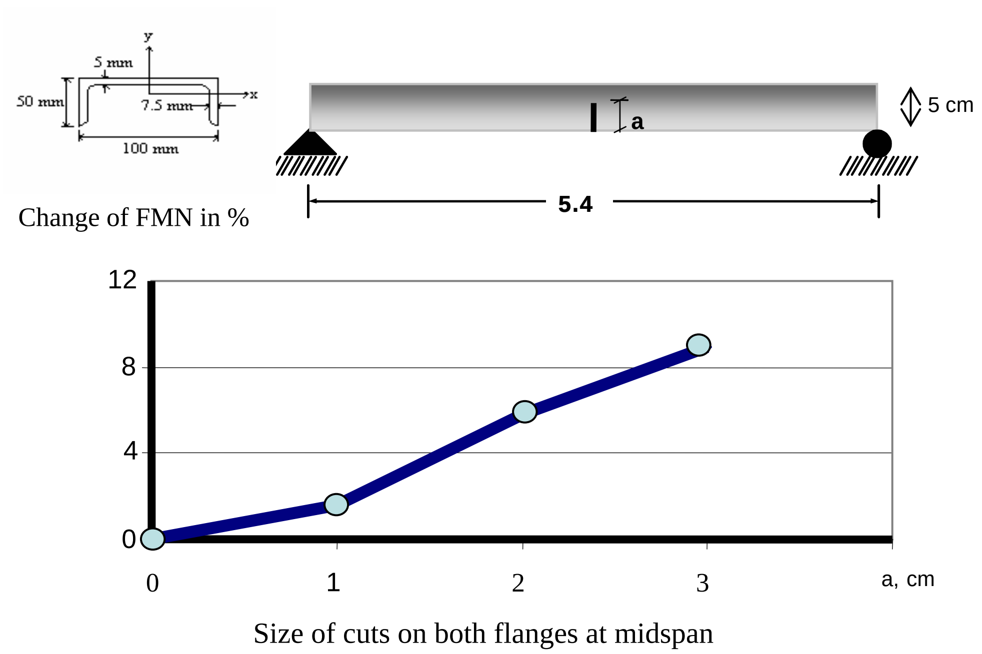

Figure 5: Effect of defects on FMN in steel beam

4.3 Impact Tests on Reinforced Concrete Beam with Controlled Defects

Similar tests were conducted on reinforced concrete beam with various 10-mm deep cuts on the bottom zone of the beam as shown in Fig. 6. As in the previous case, only small changes in mode shapes and frequencies could be observed in the comparison due to the cuts. However, the flexibility matrix associated with the three sensor points can be evaluated for each of the four cases. In Fig. 6, it can be seen that FMN increases with the amount of defects prescribed in the reinforced concrete beam.

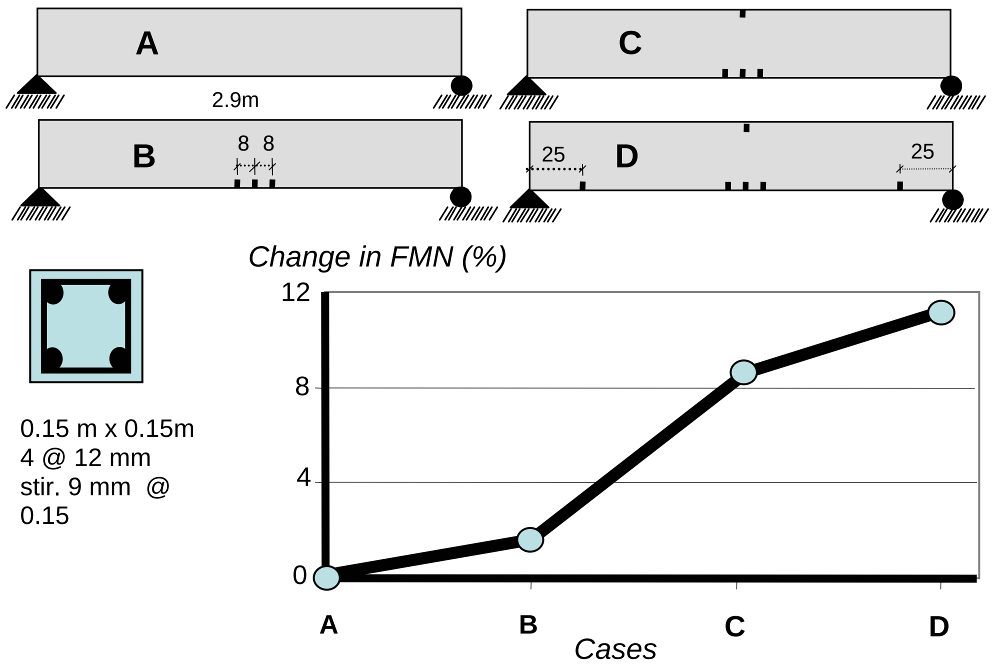

Figure 6: Effect of defects on FMN in reinforced concrete beam

5. IMPACT TESTS ON EXISING BRIDGES

The tests are performed on two existing bridges as the mean for acquiring mode shapes and natural frequencies. Subsequently the flexibility matrix of these bridges can be evaluated in association with the referenced locations where sensors are installed. It is proposed that the norm of this flexibility matrix (FMN) shall be monitored regularly each year. Aging of a bridge over a period of time will be reflected by the gradual increase of FMN. Rapid deterioration of the bridge structure will be warned by its very sharp increase, signifying the need for a close attention to retrofit the bridge.

5.1 Bridge 1: Slab Girder Bridge.

The selected bridge, shown in Fig. 7, was constructed in 1999 as a part of national highway No.33 over a canal in Nakhon-Nayok Province, Thailand. It consists of three simple 10-meter spans of slab girders. Impact test provides an extremely portable and versatile method. Striking the test bridge with impact hammer will impart a measured force, and induce vibratory responses at seismic accelerometers installed at selected referenced points, as shown in Figure 8. Defining referenced locations of accelerometers are important. Results from eigenvalue analysis of the finite element model can serves as a guide.

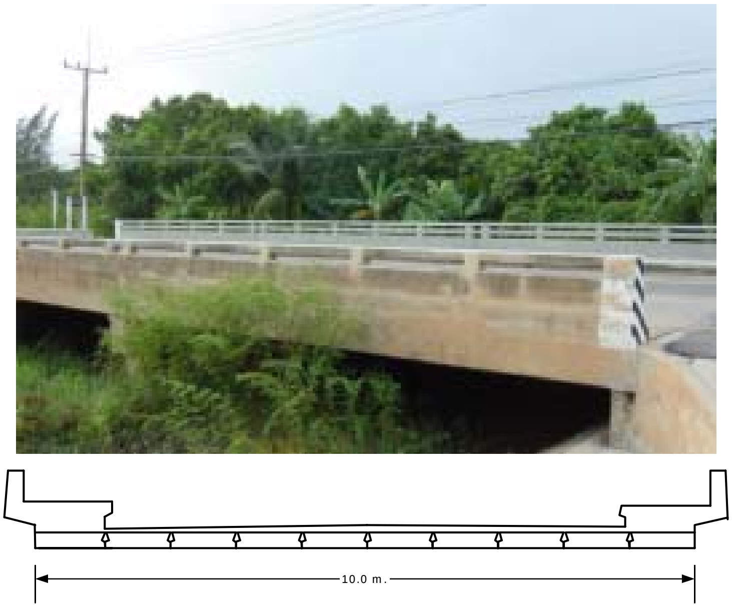

Figure 7: The first bridge under impact test

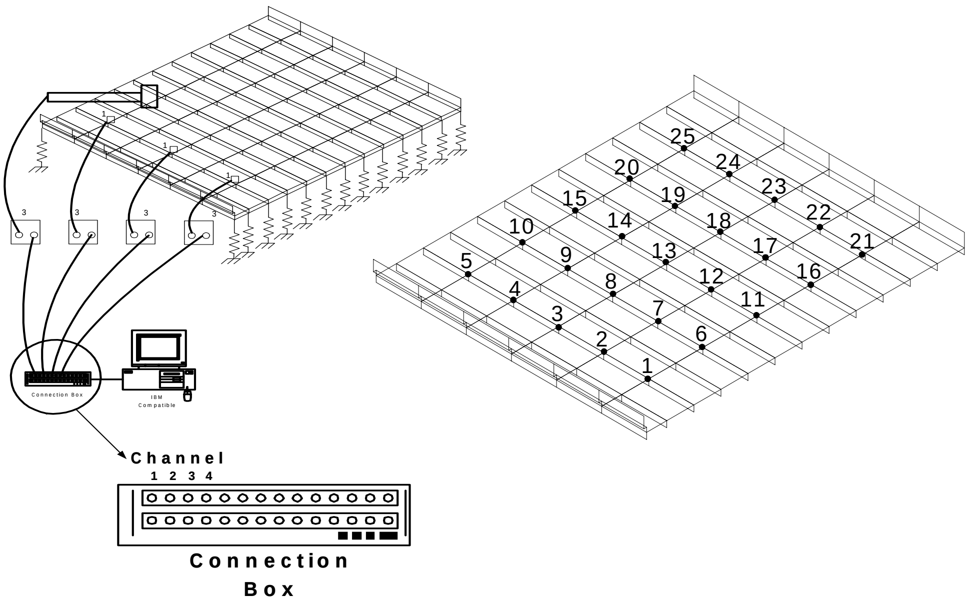

Figure 8: Field equipment setup and selected locations for sensors

A typical responses in frequency domain is illustrated in Figure 9 in the form of Frequency Response Functions (FRF), by which one can estimate the mode shapes and frequencies. Figure 10 shows the first and the second mode shapes of the bridge. With these test results, the finite element model can be calibrated by obtaining the current state of the material parameters. Finally, the flexibility matrix can be established from the modes shapes and frequencies. Based on the first two modes, the norm of the flexibility matrix, FMN, is evaluated as 6.39E-8 m/N.

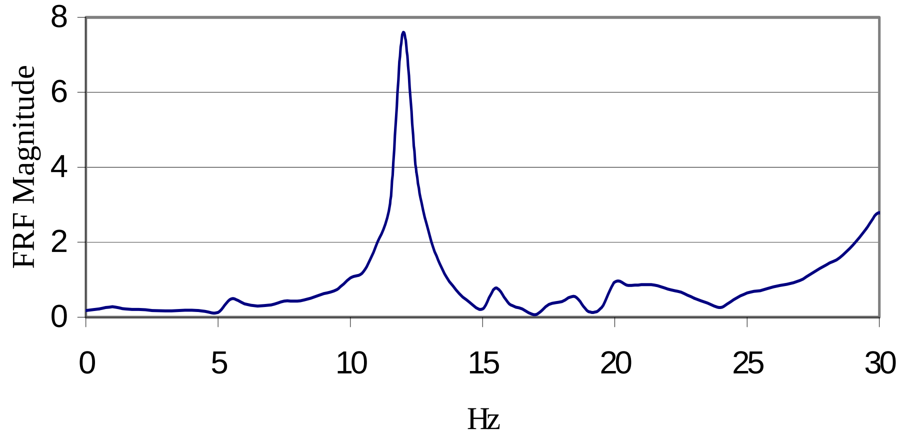

Figure 9: A typical FRF obtained by impact test for Bridge 1.

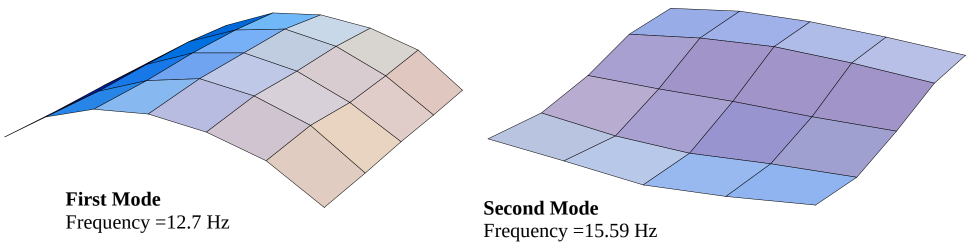

Figure 10: The first and second mode shapes of Bridge No. 1

5.2 Bridge 2: Prestressed Concrete I-girder Bridge.

This bridge was constructed in 1978 as a part of National Route No.2256 crossing the Pasak River in Lopburi Province, Thailand. The bridge is a prestressed concrete I-girder type, with three 30-meter spans. Figure 11 shows the photograph and structural configuration of the bridge.

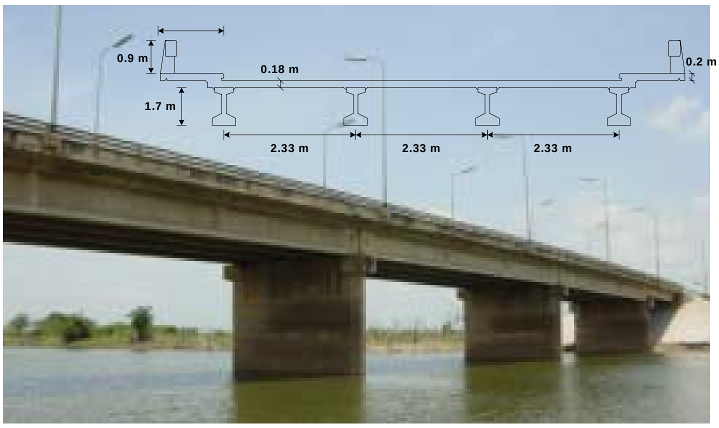

Figure 11: Prestressed I-girder bridge

Similar to the first bridge, the same impact test procedure was conducted for Bridge 2. A typical result of the frequency-response function is illustrated in Figure 12. The natural frequencies of this bridge are found to be 4.5 Hz and 9 Hz, corresponding to the mode shapes shown in Figure 13. Based on the first two modes, the norm of the flexibility matrix, FMN, can be evaluated as 5.602E-8 m/N.

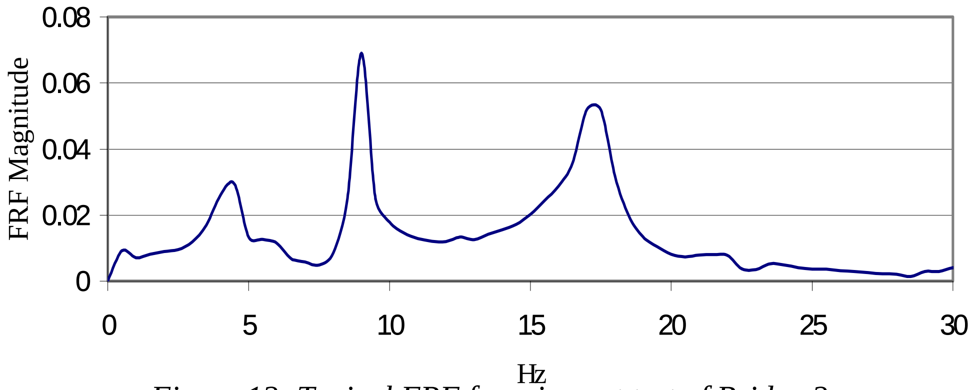

Figure 12: Typical FRF from impact test of Bridge 2

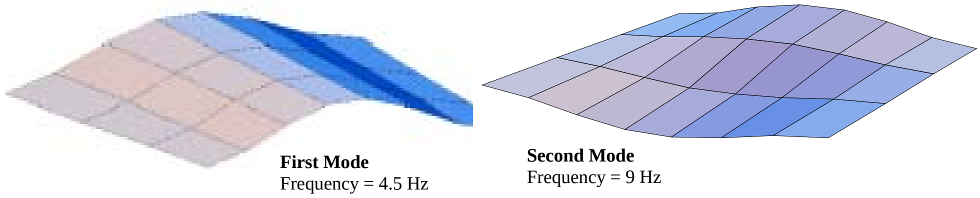

Figure 13: The first and the second mode shapes of Bridge 2

6 CONCLUSIONS

The impact hammer test is a simple, practical, and reliable nondestructive method for determining the key structural characteristics of bridges. At any decaying state of an existing bridge, its vibratory responses in terms of fundamental mode shapes and frequencies can be evaluated by this test. However, the minor alteration of mode shapes and frequencies as a direct effect of structural deterioration may not be sufficient to infer the health condition of the structure. On the other hand, in conjunction with the modern finite element modeling, fundamental mode shapes and frequencies can be used to establish the present status of the structural flexibility with respect to key referenced points, where sensors are installed to measure the vibratory responses in the test. The spectral norm of the flexibility matrix (FMN) can then be used as an index of the structural health deterioration, as FMN is sufficiently sensitive to the weakening of the structure, caused by deteriorations.

This research recommends that the present impact test be implemented as a routine maintenance for key existing bridges of the Department of Highway in Thailand. This regular monitoring of bridges will provide an advanced warning for any sharp decay of global flexibility, which is directly related to the weakening of the bridges.

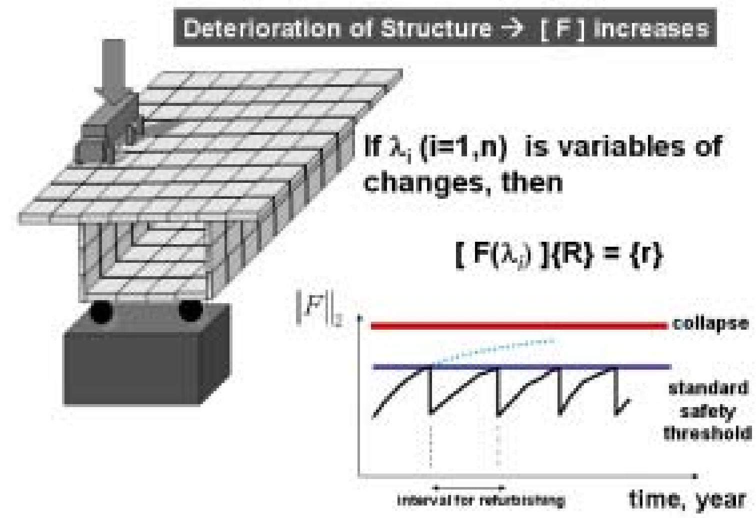

Figure 14: Recommended maintenance program of a bridge

In practice, a monitoring program can be set in such a way that when FMN increases beyond a standard safety threshold, a major investigation and retrofitting will be conducted to strengthen the bridge, and thus restore the safety margin of the bridge. The maintenance program as illustrated in Figure 14 will ensure that the bridge will not fall into a state beyond repair and becomes unsafe to the public.

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