Vibration Amplitude - Dependent Natural Frequency and Damping Ratio of Repaired Pier Model

Reem Alsehnawi, Akinori Nakajima, Ryuji Takeshima, Hafez Al Sadeq

VIBRATION AMPLITUDE - DEPENDENT NATURAL FREQUENCY AND DAMPING RATIO OF REPAIRED PIER MODEL

Reem Al Sehnawi [1], Akinori Nakajima [1], Ryuji Takeshima[2], Hafez Al Sadeq[3]

[1] *Graduate School of Engineering, Utsunomiya University, Japan*
[2] *IHI Infrastructure Systems Co., Ltd., Japan*
[3] *Department of Structural Engineering, Faculty of Civil Engineering, Damascus University, Syria*

reemsalman_seh@hotmail.com

ABSTRACT

The present work aims to investigate the dependency of dynamic characteristics such as the natural frequency and the damping ratio of pier model on the vibration amplitude under a series of different vibration levels. Several free vibration tests with a wide range of amplitudes were, therefore, carried out under excitation with relatively small amplitude levels. The pier model was subjected to a progressive damage by conducting a shaking table test to study the influence of different damage scenarios on its dynamic characteristics. After the damage occurs at the plastic hinge zone of the pier model, free vibration tests with different amplitude excitation were carried out to derive the dynamic characteristics of the damaged pier model. Furthermore, after the damage of the pier model was repaired by carbon fiber sheets (CFS) jacketing, free vibration test was carried out again, to derive the dynamic characteristics of the repaired pier model. Generally, this study indicates that overall natural frequency and damping ratio are very sensitive to vibration amplitude level. Particularly, whenever the acceleration amplitude increases, damping ratio significantly increases while natural frequency slightly decreases. Also, the repairing method by CFS proved to be effective in restoring performance characteristics of damaged pier.

KEYWORDS : *Dynamic characteristics, Amplitude dependency, RC Pier model, Shaking table test, Free vibration test.*

INTRODUCTION

Dynamic analysis of structures is becoming an increasingly important part of the seismic design process. However, dynamic characteristics such as damping ratio and natural frequency of bridge structures that can be affected by nonlinearity, and changes of their mass and stiffness, they also have a significant effect on their dynamic behaviour. In addition, since the actual dynamic characteristics of a completed bridge are generally different from the design values, it is important to confirm the dynamic characteristics of a bridge by measuring its vibration. Therefore, so far, vibration measurements have been carried out to various bridge structures [4, 8, 10, 12]. Among these, in order to confirm the dynamic characteristics, large equipment such as vibration generating apparatus have been introduced. Although, the dynamic behaviour of a large level of vibration can be verified by this method, in some cases, vibration measurement of existing bridges is avoided from the viewpoint of cost and effort requirements of large equipment.

In recent years, numbers of vibration measurement methods without the need of vibration devices were founded [8]. The main purpose of this study is to investigate the dependency of the dynamic characteristics on the vibration amplitude in inelastic stage of RC pier models by applying free vibration test. Therefore, to reach the inelastic stage, the pier model was excited to failure using JMA Kushiro record of 1994 Kushiro earthquake with peak ground acceleration (PGA) of 0.7g. Meanwhile, the excitations were repeated to clarify dynamic characteristics of RC pier model that is subjected to moderate and severe earthquake motions by increasing the seismic excitation intensity of Kushiro record gradually. During the application of seismic excitation, a free vibration test was performed after each excitation to investigate the changes of dynamic characteristics during damage progress. Furthermore, the performance of the damaged pier was restored by wrapping the damaged region by carbon fiber sheets CFS after injecting the wide cracks by resin epoxy. Free vibration test was, thereafter, applied to the repaired pier to check the effectiveness of the damage repair on the dynamic characteristics. After all, the results of the dynamic characteristics changes of the pier model depending on the excitation amplitude were compared.

1 EXPERIMENTAL MODEL CONFIGURATION AND PROPERTIES

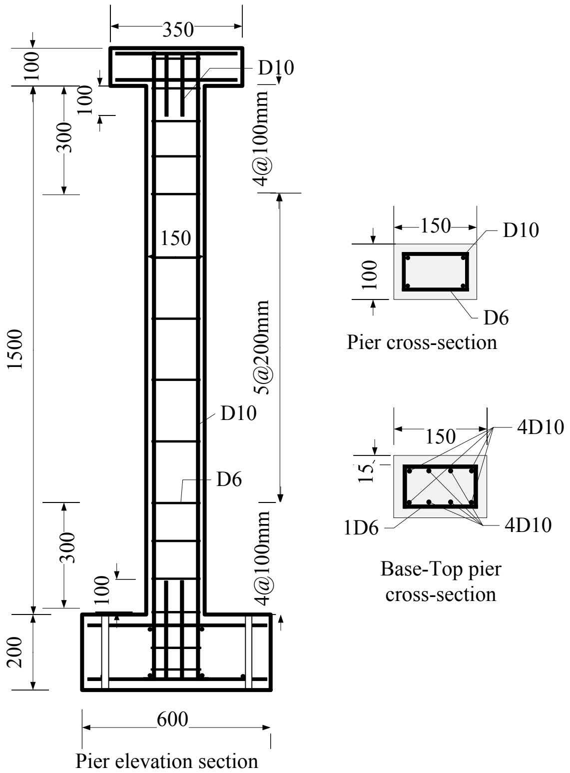


Figure 1: Configuration of RC pier model

In order to clarify the dependency of the dynamic characteristics on the vibration amplitude, a specimen of pier model is used with limiting in size due to the capacity of the shaking table to maintain the proper vibration amplitude in the whole test procedures. The specimen's geometries and reinforcement details are illustrated in Figure 1. As illustrated in this figure, the experimental model is a cantilever pier which consists of single column, cap and footing. The longitudinal reinforcement is continuous to the bottom of the footing, to provide adequate moment resistance at the base of the pier, and the connection between the pier and the cap is also effectively continuous. In addition, 4 additional reinforcement bars were added at the pier-footing and at the pier-cap connections with length of 100mm from the connection cross-section to avoid cracks in the connection surface. The recommendations and requirements in designing the specimen were specified by JSCE Standard Specifications for Concrete Structures [2]. Moreover, a concrete block was used to simulate a bridge superstructure. Yield strength and young modulus of used longitudinal reinforcing bars are, respectively, 401N/mm^2 and 210kN/mm^2. The compressive and tensile strengths of concrete were, respectively, 31.8N/mm^2 and 2.3N/mm^2, and the young modulus of concrete was 29.1kN/mm^2.

Furthermore, to minimize the effect of radiation damping that simulate the effect of soil-structure interaction and energy dissipation, as shown in Figure.1, the pier footing and two steel I-girders are fixed by 6 bolts of 20mm in diameter to resist the longitudinal, transverse and rotational movement of the specimen. In addition, the additional weight was fixed to the pier cap through 4 bolts of 20mm in diameter.

2 FREE VIBRATION TEST

The free vibration was excited by hummer impact at the top of the RC pier model with additional weight. The horizontal acceleration responses were recorded by an accelerometer that was placed at the top of the concrete block in the transverse direction of the pier model.
In this research, the identified natural frequency of free vibration response of pier model was extracted using Fast Fourier Transform (FFT) [1, 11]. One example of the acceleration response records of free vibration is shown in Figure 2(a), whereas its Fourier spectrum and the relationship of logarithmic acceleration versus number of cycles for the peak of each cycle in the waveform are, respectively, shown Figure 2(b) and 2(c). Herein, the band-pass filter was employed with band width of 5% above and below the natural frequency to identify the damping ratio from the filtered free decay function by fitting exponential functions to the relative maxima of these free decays [7] as illustrated in Figure 2(c). In this figure, the blue and the pink lines, respectively, correspond to the positive and the negative exponential function of the filtered free decay function.

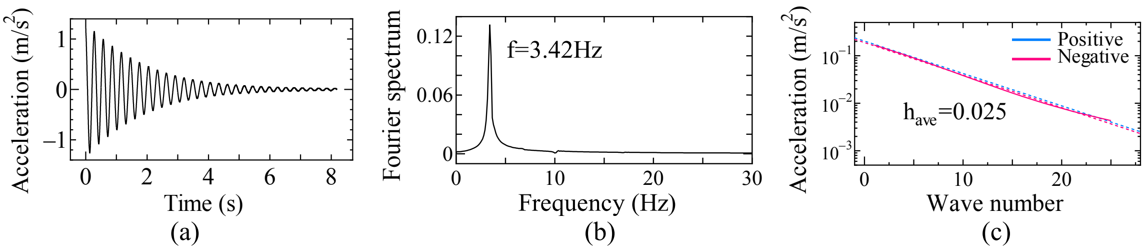


Figure 2 : (a) Acceleration time-history response, (b) Fourier spectrum, (c) Acceleration vs wave numbers

3 SHAKING TABLE EXCITATIONS

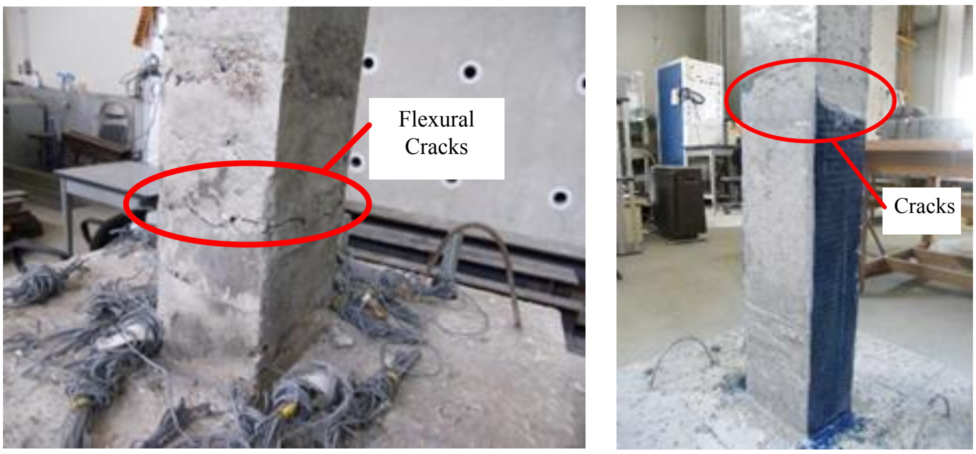
After conducting free vibration test on the original pier model, it is subjected to progressive damage to study the influence of different damage scenarios on its dynamic characteristics, and to investigate the variations of the natural frequency and the damping ratio of the pier model after the damage has occurred at the plastic hinge zone at the pier base. To represent moderate and severe earthquake motions, the specimen is excited in the transverse direction by a scaled ground motion of Kushiro earthquake using JMA Kushiro record of 1994 Kushiro earthquake with peak ground acceleration (PGA) of 0.7g. The shaking table excitation is conducted with a wide range of seismic excitation intensity of 15, 20, 25, 30%, and then the intensity is increased by 10% until reaching 160% of the peak intensity. Meanwhile, after each seismic excitation, a free vibration test is conducted to evaluate the natural frequency and the damping ratio. Finally, to check the effectiveness of the damage repair with regard to the dynamic characteristics of the specimen, free vibration test was reconducted for the repaired pier model.

4 REPAIR PROCEDURES AND MATERIALS

During shaking table test, horizontal flexural cracks developed at the bottom of the pier model within 150mm from the face of the footing. At later stages of exciting intensities, the cracks extended into the neutral axis of the pier cross-section, in addition horizontal flexural cracks were developed into a distance of about 300mm from the pier base. Meanwhile, the concrete cover didn't spall off and no significant diagonal shear cracks were found. Thus, it is apparent that the failure mode of the specimen should be identified as flexural failure [4]. The wide cracks were repaired, as shown in Figure 3(a), by resin epoxy injection, and then the plastic hinge zone were wrapped by carbon fiber sheets (CFS) as denoted in Figure 3(b). The design concept of CFS jacketing refers to the one proposed by Seible [9]. The repair procedures can be summarized as follows; after the surface of the cracked concrete was cleaned, the wide cracks were injected by resin epoxy as illustrated in Figure 3(a). Thereafter, CFS were wrapped around the cross-section of the pier model as shown in Figure 3(b). An epoxy was applied on the surface of CFS sheets during wrapping the sheets around the pier cross-section. The impregnated sheets were tightly wrapped around the pier to ensure that there were no entrapped air pockets or fabric distortions. CFS Jacketing were wrapped with fiber orientation in the transverse direction to prevent the shear failure in addition to the longitudinal direction of its fiber orientation for preventing the flexure-shear failure [6]. In this research, the used CFS are 0.111mm of thickness, and have an ultimate strength and modulus of elasticity of 3400N/mm^2 and 245000N/mm^2, respectively. Consequently, the plastic hinge zone were wrapped by three layers with repairing length of 500mm of CFS with an overlap length of 100mm, two layers with fiber orientation in the longitudinal direction to restore the flexural ductility, and one layer in transverse direction of the fiber orientation for restoring the shear strength.

(a) Resin epoxy injecting (b) CFS jacket

Figure 3: Repairing method of damaged pier by resin epoxy injection and CFS jacketing



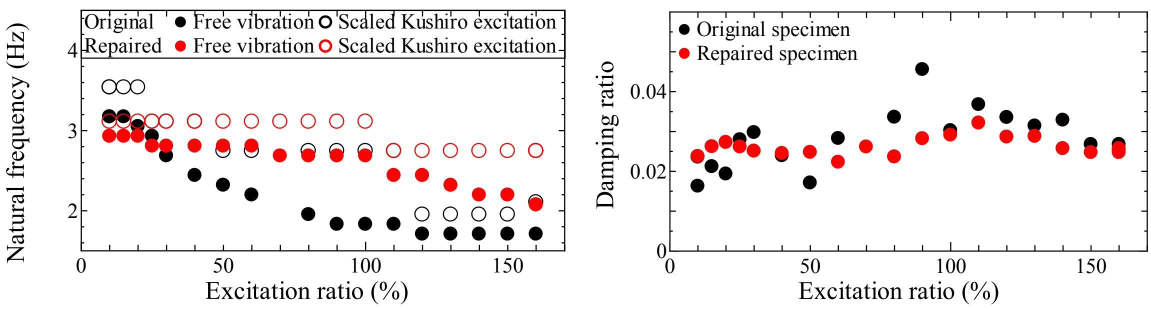
(a) Cracks in original specimen (b) Cracks in repaired specimen

Figure 4: Cracks in plastic hinge zone of original pier model and at top of CFS of repaired pier model

5 RESPONSE ON SHAKING TABLE TEST

In order to elucidate the damage effect on the dynamic characteristics, the original and repaired specimen was tested to failure by applying shaking table test. The seismic behaviour of the repaired specimen was also evaluated and compared to the seismic behaviour of the original specimen. Cracks in original specimen is depicted in Figure 4(a). It was observed that the cracks size increased by increasing the excitation amplitude gradually until the cracks width exceeded about 2.0mm around the pier perimeter. Hairline vertical cracks were also observed at the plastic hinge zone within 300mm from the bottom of the pier cross-section, whereas, the concrete cover didn't spall off. On the other hand, the concrete flexural cracks of the repaired specimen, as shown in Figure 4(b), were observed within a distance of about 150mm from the top of CFS jacketing. Meanwhile, no cracks appeared on the surface of CFS jacketing. Thus, the repaired specimen performed well under the seismic excitations since the repairing technique delay the concrete damage in the repaired region. Fourier spectrum of the acceleration time-history responses under shaking table test was derived by applying FFT analysis.

To clarify the dominant frequency declination of specimen, the relationships of the natural frequency of free vibration test after each seismic excitation and the dominant frequency of the original and repaired specimen, respectively, versus seismic excitation intensity of specimen are presented in Figure 5(a), in which the solid and open black circles, respectively, correspond to the natural and dominant frequencies of the original specimen, while the solid and open red circles correspond to the natural frequency and dominant frequency of the repaired specimen. It is observed that the dominant frequency derived from seismic excitation is not equal to the natural frequency derived from free vibration because of the effects of the input excitation frequency characteristics on the output response. These figures, also, confirm that the natural and dominant frequencies decreased with the increase of seismic excitation intensity in all cases. This was due to the presence of cracks in the pier model which caused deterioration in plastic hinge zone. Furthermore, the changes of the damping ratio that was derived from free vibration test after each seismic excitation with seismic excitation intensities are shown in Figure 5(b). In this figure, the black and red solid circles correspond to the dependency of damping ratio on the seismic excitation ratio of scaled Kushiro record of the original and repaired specimen, respectively. Regardless of excitation amplitude of free vibration test which didn't affect on the scattering of damping ratio, it is obvious in the figure that the damping ratio shows large scattering with respect to damage progress. This indicates that the existed cracks in the pier models caused dissipation of excitation energy through the defects and the friction between the cracks surface. However, Figure 5(b) shows that as the seismic excitation increases, the damage increases and then the damping ratio slightly increases with large scattering [3].



(a) Natural frequency vs seismic excitation ratio (b) Damping ratio vs seismic excitation ratio

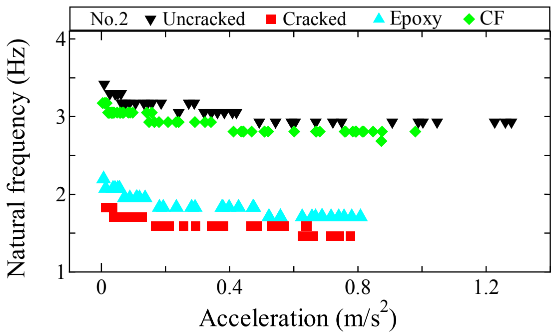
Figure 5: Seismic excitation intensity of scaled Kushiro earthquake versus dynamic characteristics

6 RESPONSE ON FREE VIBRATION TEST

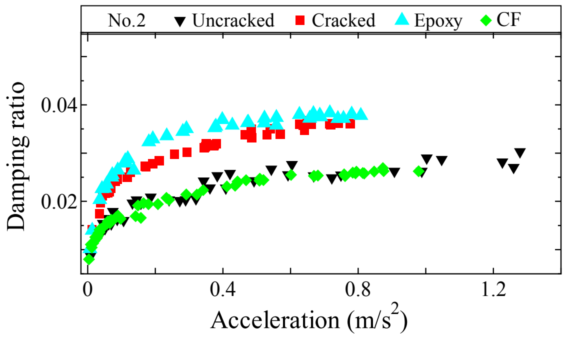
In order to investigate the changes of natural frequency and damping ratio under a series of different vibration levels, free vibration tests were conducted on the original specimen before applying shaking table test; i.e., in elastic stage of the pier model, and then after the damage occurred in the plastic hinge zone of specimen; i.e., in the inelastic stage of the pier model, that occurred after conducting shaking table test. Finally, a free vibration test was applied to the repaired specimens.

Figure 6(a) and 6(b) show, respectively, the relationship between the maximum acceleration amplitude of each excitation versus the natural frequency and damping ratio of each identified vibration level of the original, damaged and repaired specimen. In those figures, the black down pointing triangles correspond to the dependency of the natural frequency and damping ratio on the acceleration amplitude of the original specimen. While the red squares correspond to this dependency of the cracked specimen. The cyan up pointing triangles correspond to the results of the specimen after its repairing by resin epoxy injection, whereas, the green rhombuses correspond, to the results of the repaired specimen by applying CFS jacketing. It is obvious from those figures that in all cases, a similar tendency of natural frequency and damping ratio on the excitation amplitude is observed in the elastic and inelastic stage of the pier model. In Figure 6(a), it is observed that as the maximum acceleration amplitude increases, the natural frequency tends to decrease, while, in Figure 6(b), the damping ratio tends to increase significantly with the increasing of the maximum acceleration amplitude. Furthermore, Figure 6(a) and 6(b) show the changes range of the natural frequency and the damping ratio depending on the acceleration amplitude of all cases of the specimen. Moreover, although the amplitude dependency of the natural frequency and damping ratio show similar tendency, it is obvious that when the damage occurred, the natural frequency decreased and the damping ratio increased remarkably compared with the others of the original specimen.

The dynamic characteristics of the repaired specimen were not improved by resin epoxy injection of the wide cracks. That could be attributed to the resin epoxy offer low viscosity and low surface tension, in addition to the existence of the fine cracks that are not possible to be repaired by epoxy injection. Therefore, to restore the pier model stiffness for re-improving the natural frequency and the damping ratio, the plastic hinge zone of the specimen was wrapped by CFS jacketing. As it is clarified in Figure 6, these values are close to the values of the natural frequency and damping ratio of the original and repaired specimen. Consequently, the repair technique has influenced the rate of stiffness degradation. Besides, the numerical value of natural frequency was calculated for the original, cracked and repaired specimen to be compared with the experimental value that derived from free vibration test. In the cracked specimen, the cross-section in damaged zone was assumed as fully cracked of concrete, while after epoxy injection in the cracks, the concrete mechanical contribution in compression side of the cross-section is assumed to be activated by the bond strength of the injected epoxy. As well, in the case of the wrapped cross-section by CFS jacketing, the CFS where taken into account in the wrapped zone. Table 1 shows the range of the natural frequency that derived from free vibration test in addition to their numerical values of the original, cracked and repaired specimen by epoxy injection and CFS jacketing. According to this table, the numerical value of natural frequency is remarkably larger than the experimental value in all cases of the specimen. It is expected that the fixation of the pier model to the shaking table was not fully fixed base. Therefore, the degree of the rotational movement of specimen was changed to simulate the actual support of the experimental model. Hence, to match the numerical natural frequency with the experimental values, the constant of the rotational movement values of the ground spring was changed according to fixation conditions as illustrated in Table 1.



(a)



(b)

Figure 8: Maximum acceleration response vs natural frequency and damping ratio

Table 1: Experimental and numerical natural frequency of original, cracked and repaired specimen

Specimen	Acceleration (m/s^2)	Natural frequency (Hz) (Experimental)	Natural frequency (Hz) (Numerical)	Constant of rotational movement (kNm/s)
Original	0.0086-1.28	3.42-2.93	5.92	554
Cracked	0.0134-0.78	1.83-1.47	3.42	150
Epoxy injection	0.0067-0.81	2.2-1.71	4.70	200
CF sheet	0.0038-0.875	3.17-2.81	5.13	515

7 CONCLUSIONS

A free vibration and shaking table tests are conducted on RC pier model for understanding the dependency of natural frequency and damping ratio on vibration amplitude in inelastic stage of the bridge piers. After the damaged pier model was repaired by resin epoxy injection and CFS jacketing. The following conclusions can be made:

1- The natural frequency was decreased due to the degradation of the pier model stiffness caused by damage sustained. The natural frequency declination ratio of the original specimen is remarkably larger than the one of the damaged specimen.
2- The variation of the damping ratio against damage level due to seismic excitation showed a scattering with respect to damage progress. This damage caused dissipation of excitation energy through the defects and the friction between the cracks surface.
3- In all cases, a similar tendency of the dependency of natural frequency and damping ration on the amplitude is observed in the elastic and inelastic stage of the pier model. Namely, as the maximum acceleration amplitude increases, the natural frequency tends to decrease, while the damping ratio tends to increase remarkably. Furthermore, it was obvious that when the damage occurred in the specimen, the natural frequency decreased and the damping ratio increased compared with the others of the original specimen. However, the changes trend of damping ratio is more sensitive than that of the natural frequency.
4- Finally, when considering the dynamic characteristics of a structure, we need to pay special attention to the vibration amplitude before using those values for design.

ACKNOWLEDGMENTS

The authors are grateful to Structural Laboratory members of Architecture and Civil Engineering Department at Utsunomiya University, especially Dr. Y. Suzuki, for their help during the preparation of specimens. Also we are grateful to Mr. A. Kobayashi of Composites Company, Nippon Steel & Sumikin Materials Co., Ltd for providing carbon fiber sheets materials.

REFERENCES

[1] Committee of Structural Engineering, *JSCE (2000) Guidelines for Bridge Vibration Monitoring.* (in Japanese).

[2] Concrete Committee, *JSCE (2007) Standard Specifications for Concrete Structures*. (in Japanese).

[3] Egba Ernest I. (2012) Detection of Structural Damage in Building using Changes in Modal Damping Mechanism. *I.J.E.M.S. 3 (3), pp 250-255*.

[4] Fukuwa N, Nishizaka R, Yagi S, Tanaka K, Tamura Y (1989) Field Measurement of Damping and Natural Frequency of an Actual Steel-framed Building over a Wide Range of Amplitudes. *Journal of Wind Engineering and Industrial Aerodynamic 59, pp 325-347.*

[5] G. Zafra R, Kawashima K, Sasaki T, Kajiwara K, Nakayama M (2013) Seismic Performance of a Full-scale Polypropylene Fiber Reinforced Cement Composite Bridge column Based on E-Defense Shake-Table Experiments. *Proceedings of the international Symposium for Bridge Earthquake Engineering in Honor of Retirement of Professor Kazuhiko Kawashima, Tokyo, Japan.*

[6] Kawashima K (2000) Seismic Design and Retrofit of Bridges. *12WCEE*.

[7] Magalhães F, Caetano E, Cunha A, Flamand O, Grillaud G(2012)Ambient and free vibration tests of the Millau Viaduct. *Evaluation of alternative processing strategies, Engineering Structures 45, pp 372-384*.

[8] Peeters B, Ventura C.E, (2003) Comparative Study of Modal Analysis Techniques for Bridge Dynamic Characteristics. *Mechanical Systems and Signal Processing. 17(5), pp 965-988*.

[9] Priestley M.J.N, Seible F, Calvi G.M (1996) Seismic Design and Retrofit of Bridges. *TG300.P64 1996.*

[10] Saito T, Nakajima A, Takeshima R, Al Sehnawi R(2013) Experimental Investigation on Vibrational Property Change of Bridge Model under Various Input Level. *Journal of Structural Engineering. Vol.59A, pp 261-271*. (in Japanese).

[11] Shoji G, Kitahara J, Kojima A, Kanakubo T, Shimizu K, Sakai Y (2008) Mechanism of Seismic Response of a PC Cable-Stayed Bridge Subjected to a Long-Period Seismic Excitation. *Doboku Gakkai Ronbunshuu A. Vol.64, No.4, pp982-1001*.

[12] Tamura Y, Suganuma S (1996) Evaluation of Amplitude-Dependent Damping and Natural Frequency of Buildings during Strong Winds. *Journal of Wind Engineering and Industrial Aerodynamics, Vol.59, pp 115-130.*