Abstract of Dissertation

Measurement and Damage Detection in RC Railway Viaducts Under Diverse Vibration Sources

（様々な入力外力条件における **RC** 高架橋の振動計測に基づく損傷同定）

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RC railway viaducts supporting entire railway systems are deteriorating due to age, increased loads and frequency of use, and frequent mild to strong earthquakes. These structures link many cities and prefectures in Japan, playing a vital role in the socio-economic life of the country, so that maintenance and monitoring of these structures are of crucial importance.

Without prior knowledge of the existence of damage, structural health monitoring (SHM) methods are used to detect, locate and assess damage. Many SHM methods use vibration-based procedures and algorithms for damage detection. SHM is a wide research field that includes development of new measurement systems and effective excitation methods, modal analysis and system identification techniques, determination of damage-sensitive features, damage quantification and finally, structural evaluation.

Past earthquakes showed that RC railway viaducts are susceptible to different forms of damage. Damage to structural members above ground are easily found by visual inspection but damage to substructures below ground will require excavation to be seen. This requirement is difficult to meet as it will not only be expensive but will require an extended amount of time, keeping the railway system out of service. Further, damage in foundation elements after an earthquake event may even go undiscovered, become worse over time and slowly reduce the carrying capacity of the structure. With these considerations, a vibration-based method that can detect and quantify the severity of unseen damage by measuring the vibration of structures above ground alone will be very useful.

In this dissertation, two sensor systems with different characteristics are used to measure the vibration of RC viaducts in service. A system using Laser Doppler Vibrometers (LDV) for monitoring Shinkansen RC railway viaducts is first presented. The LDV with its high accuracy, frequency resolution, and scanning capability, is an ideal non-contact tool for monitoring large structures. This system is shown to be superior to other sensor systems in terms of safety for monitoring personnel on site. Wireless and ordinary cable-connected accelerometers and velocimeters are also used to measure vibration of the viaduct in one direction and three-perpendicular directions.

The RC viaducts are subjected to diverse excitation sources that cause it to vibrate in distinct ways. A particular form of excitation may be more effective in detecting damage. Thus, structural vibrations under three excitation sources are investigated. Ambient vibration due to wind or other naturally occurring vibration source is measured using the LDV system and velocimeters. Ambient vibration measurement simplifies the measurement process because controlled input excitation or input force measurement is not involved. However, ambient vibration is small compared to surrounding noise because the viaducts are very stiff. Compensation for tripod vibration is achieved by removing from the recorded data, vibrations measured by a velocimeter

attached to the LDV. Train-induced vibrations in three-perpendicular directions are measured as well using accelerometers to gain more insight in the vibration behavior of a viaduct caused by a passing train. Free vibration responses of columns after an impact excitation using a wooden hammer are also measured because the ambient vibration level of the columns is found to be very small to excite high frequency modes. Structural state of the RC viaducts are investigated by analyzing structural vibrations under these excitation sources revealing dynamic behavior that is unexpected and providing valuable insight on how to best pursue development of a damage detection method suited for RC railway viaducts.

Two system identification techniques are used in the analysis: Peak-picking method and Eigensystem Realization Algorithm (ERA). From ambient vibration, the Natural Excitation Technique (NExT) was used to derive cross-correlation functions which were used as input for ERA. Thus, with these techniques, the global mode natural frequencies and mode shapes of a viaduct are derived from ambient vibration data measured using the LDV system. It was observed that the global mode shapes derived from modal analysis are not pure torsional and lateral modes but a combination of the two. To begin with, the RC viaducts have unsymmetric cross-sections so that the center of mass does not coincide with the center of the viaduct. This already complicates the basic mode shapes of the viaduct. Moreover, the complicated mode shapes derived from ambient vibration reveal the presence of dynamic interaction between adjoining viaducts because of the continuity of the rail tracks connecting them. This discovery implies that it will be difficult to use changes in global mode shapes of the viaduct as an indicator of damage because the effect of damage will be masked by the existing dynamic interaction.

The same system identification techniques were used in deriving local column mode shapes from free vibration response after applying an impact load using a wooden hammer. The local column mode shapes derived are stable. Also, the local column mode shapes of a regular RC column and a steel jacket retrofitted column were compared. The results show that the local column mode shapes are sensitive to changes in the stiffness distribution of the column. Moreover, the first (single curvature) local column modes of three unretrofitted columns from two viaducts are shown to be the same, allowing the adoption of a standard undamaged mode shape for monitoring. Thus, the local column mode shape is a good index for damage detection and localization.

Analysis of train-induced vibrations show that the frequency peaks are mainly dependent on the train speed and that resonance in the global modes of vibration of the viaduct is reached at the current maximum speed of Shinkansens. The root-mean-square (RMS) of train-induced acceleration in the vertical, lateral and longitudinal directions were compared for two adjacent RC viaducts. Comparison shows that the RMS accelerations in the longitudinal direction for the two viaducts are nearly the same. If damage occurs, this parameter may change so that it may be a useful indicator of damage. Similarly, the RMS accelerations between two opposite columns were compared. The comparison showed that the lateral RMS acceleration is almost equal for the opposite columns and may serve as an indicator of damage.

A new method for detecting damage on substructures below ground by examining changes in the modal properties of the exposed part of the viaduct alone is developed. From the different damage-sensitive features identified, the method uses the curvature of the first local column mode shape. There are three reasons: the first local column mode is the easiest to excite among the local column modes, it is not affected by dynamic interaction between viaducts, and a standard undamaged mode shape can be used for monitoring. This requires many measurement points to derive an accurate mode shape curve fit. In order to model damage, a three-dimensional elastic solid finite element (FE) model of an RC viaduct was made, calibrated with modal properties identified from field measurements. In the FE model, impact loading is simulated and the resulting free vibration response is measured. To simulate actual analysis steps subsequent to field measurements, velocity responses of the FE model were recorded at twelve measurement points in two opposite columns and then analyzed using the peak-picking method and ERA. Different damage cases were considered by reducing the modulus of elasticity of concrete at different locations on the viaduct model. Once the modal properties are estimated, the Modal Strain Energy Change Ratio (MSECR) quantifies the severity of the existing damage. The results show that minor to medium-scale damage occurring within the active pile length can be detected. However, after adding random noise to the simulation results and analyzing using peak-picking and ERA, the method can no longer distinguish between minor damage and effect of noise. Medium-scale damage equivalent to 33.3% reduction in modulus of elasticity at the bottom layer of a column is the least amount of damage that can be distinguished from noise effects. Damage equivalent to 66.7% reduction in modulus of elasticity at the top layer of piles can also be distinguished from noise effects. These localized damages do not substantially change the natural frequencies of the viaduct. Thus, this new method, coupled with the LDV measurement system shows promise in detecting medium-scale localized damage in substructures below ground without the need for numerous sensors.

Finally, an experiment using a two-storey steel model was conducted to demonstrate the principle used in the new damage detection method. The experiment also demonstrated the applicability of using free vibration response at many points, measured by scanning with the LDV measurement system, in deriving column modal natural frequencies and mode shapes. The results show that the modal properties of a column changes by loosening its supporting bolt. This verifies the assertion that damage at foundations, acting like changes in boundary condition of the column, can be detected by measuring changes in its modal properties.