Experimental Methods to Identify Modal Parameters of Bridges, Viaducts, and Other Civil Structures

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1. ABSTRACT

Identification of modal parameters of a structure is useful for verification, validation, and improvement of Finite Element Analysis (FEA) models, identifying structural degradation and damping appropriate to anticipated structural response levels. Accurate identification of actual modal properties consequently leads to more accurate structural analysis and response prediction. Modal properties are defined as resonant frequencies, mode shapes, and modal damping. The effective values of these modal properties may vary depending on the excitation levels. The effective modal property variations with amplitude are gradual but shed light on the nature of these non-linearities and their relation to structural damage. These experimental studies focus on various experimental techniques to identify modal properties of bridges, viaducts, and other civil structures. These techniques include ambient vibration surveys, impulse excitors, eccentric mass vibrators producing sinusoidal forcing, and servo hydraulic vibrators producing impulsive, random, or sinusoidal forcing. Example results and applications are presented with emphasis on railway bridges and viaducts, but also dams and nuclear power plant structures. Many of the test and structural model identification techniques were developed at the University of California Los Angeles following the 1971 San Fernando Earthquake.

2. INTRODUCTION

Identification of modal parameters of a structure is useful for verification of Finite Element Analysis (FEA) models, identifying structural degradation, and identifying damping appropriate to anticipated structural response levels. Modal properties are usually defined as resonant frequencies, mode shapes and modal damping. To these can be added dynamic stiffness and modal mass. While these modal property concepts assume a linear structural model, many structures exhibit some non-linearity. Therefore, the effective values of these modal properties will vary depending on the excitation levels. The non-linearities are usually not severe. The effective modal property variations with amplitude are gradual but in fact shed interesting light on the nature of these non-linearities and their relation to structural damage. This paper focuses on various experimental techniques to identify modal properties of structures such as bridges, buildings, dams, power plants, offshore oil platforms, and harbor structures. These techniques include ambient vibration surveys, impulse excitors, eccentric mass vibrators, and servo hydraulic vibrators.

An example of non-linear variation of equivalent modal parameters is shown in Figure 1, which presents the response to sinusoidal forced vibration of a 4-story building attached to a larger structure. As can be seen as the excitation levels were increased, the shape of the first mode peak deviates from classical linear peaks, and this can be interpreted as changes in the effective modal damping and resonant frequency. The non-linearities evident in this data were due do nonstructural components connecting the 4-story structure with the larger structure, including HVAC ducting, cable trays, floor covering slices, and wall partitions. Figure 2 shows the response of a nuclear power plant containment to sinusoidal forces within an eccentric mass vibrator. Figure 3 shows the sinusoidal response of a 20-story office building to excitation within an eccentric mass vibrator.

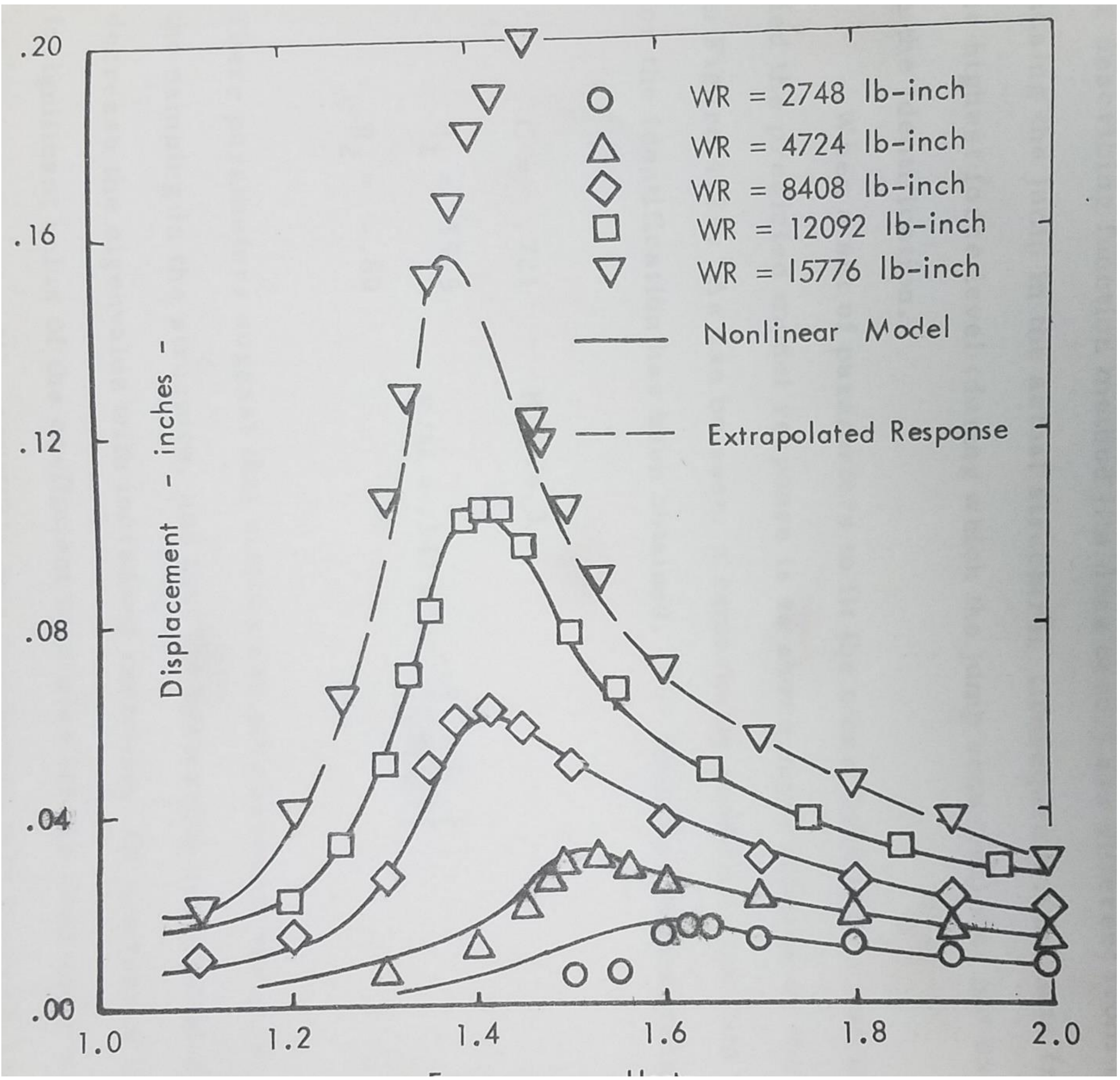

Figure 1. Non-linear response of a 4-story structure due to changing in force amplitudes. (UCLA Math-Science Addition)

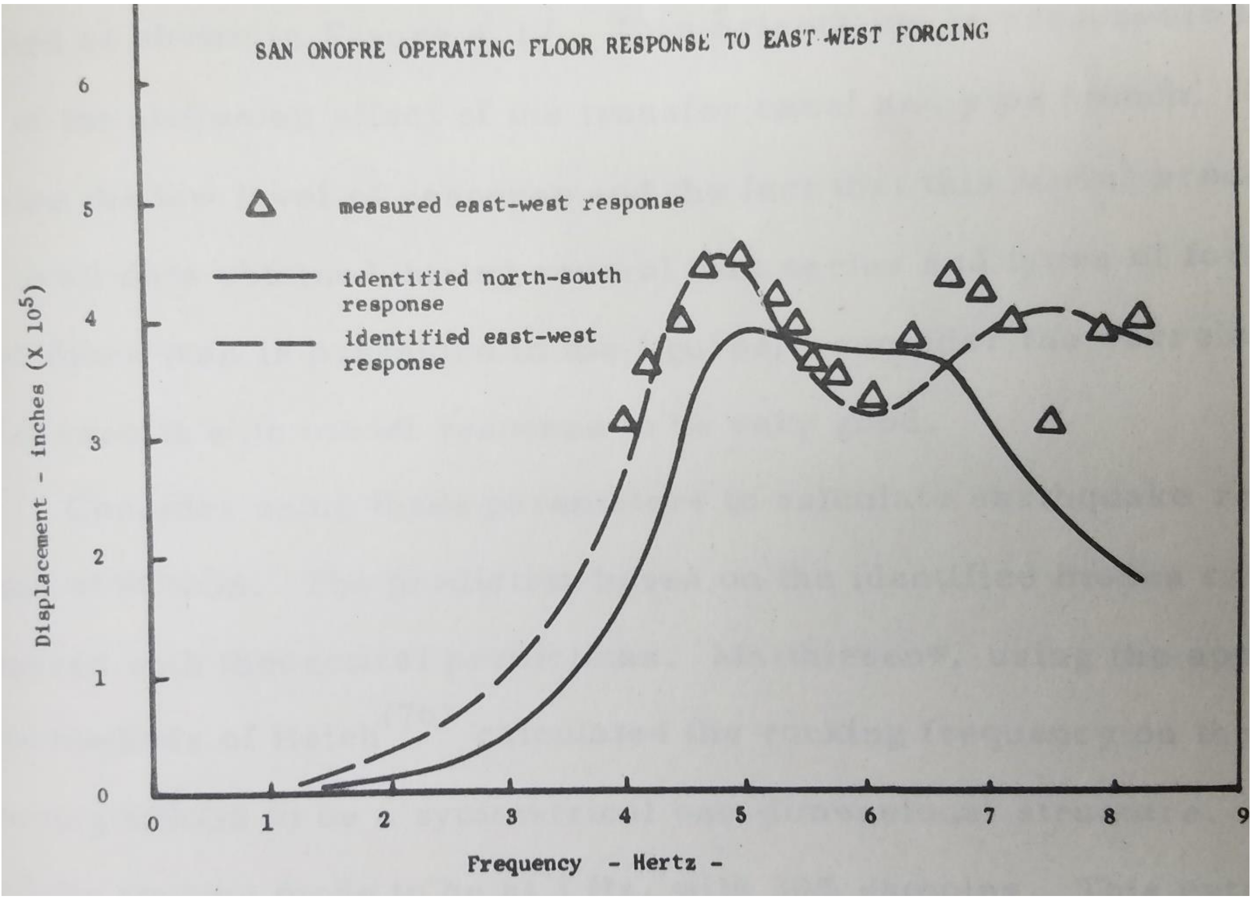

Figure 2. Example of the dynamic response of a nuclear power plant containment. (San Onofre Nuclear Generating Station.)

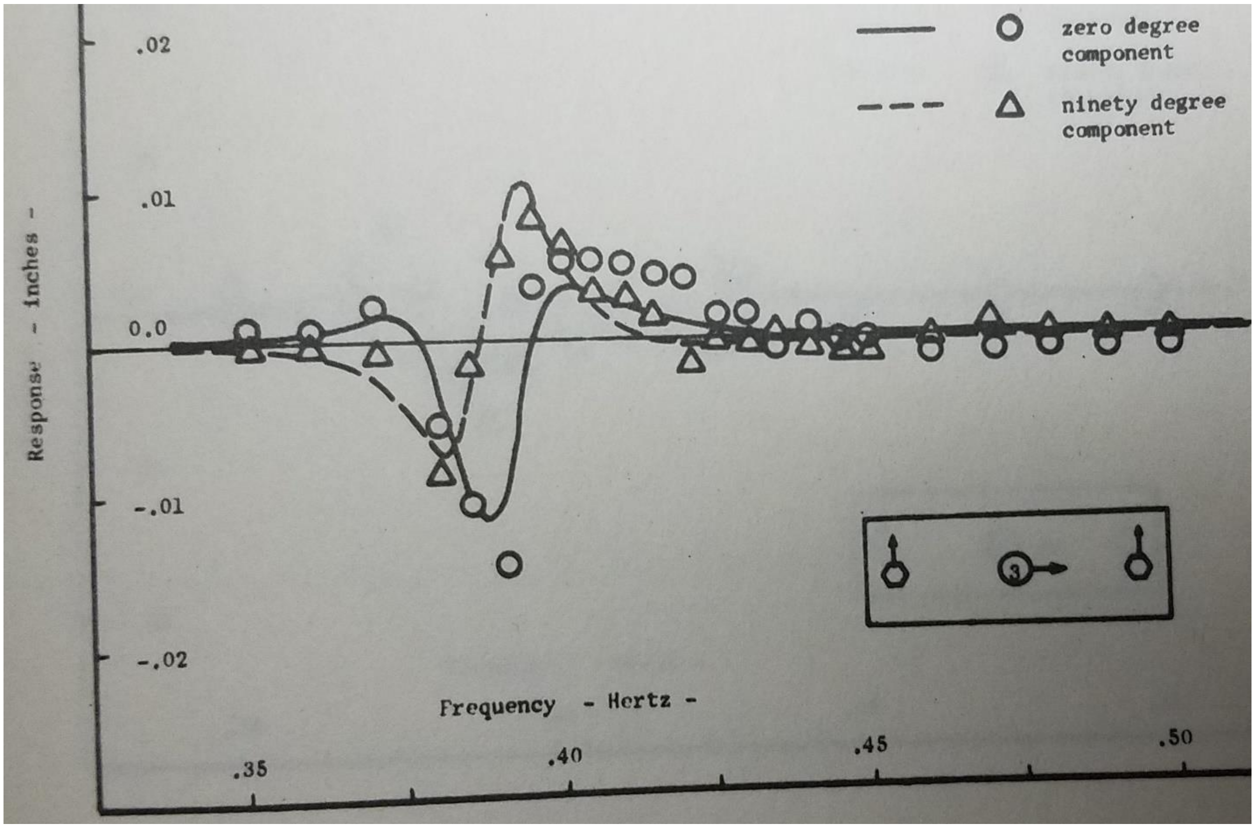

Figure 3. Sinusoidal excitation of a 20-story office building. (San Diego Gas and Electric Building.)

3. AMBIENT TESTING

Ambient vibrations are typically present in most structures (1 µ-g to 1 m-g) due to operating vibration, distant earthquakes, distant wave action, traffic, wind, and occupant activities. In some cases, wind and traffic excitation can result in even higher accelerations, as much as several tenths of a g. This ambient vibration can be monitored with accelerometers or other transducers and the random vibrations measured can be processed by spectral analysis (Fourier Transform, PSD, etc.) to reveal modal properties. The advantage of ambient testing is that no excitation equipment is required and so testing can be performed easily and quickly. The disadvantage of ambient testing is that the excitation cannot be controlled or even known, and the excitation may be much lower than the excitation of major events of concern (e.g. earthquakes). Therefore, it is sometimes difficult to separate structure resonant frequencies from peaks in the excitation energy which have no relation to the modal properties of the structure. Nevertheless, ambient testing can be useful due to its simplicity and speed, and to provide guidance for more elaborate testing methods as discussed below.

4. IMPULSIVE TESTING

Impulse excitation of a structure introduces a known force into the structure that can often produce responses well above ambient, and so it is easier to determine what are the modal properties of the structure and what these modal properties are at higher response levels. Impulse excitors include running a truck over a wooden beam, driving a heavy weight into the structure with a pneumatic actuator, or using a programmable servo hydraulic actuator as more fully discussed below. Another impulse technique is called a “snap back test”. In such a test, a hydraulic or pneumatic actuator is used to pull the structure with a cable attached to a ground point with a high force. Then, the cable is cut or released to allow the structure to snap back and vibrate. Impulse techniques tend to excite lower frequency modes, but some excitation of higher frequency modes can be achieved by narrowing the width of the force pulse. Impulse techniques are often convenient because the required equipment is relatively light and portable.

5. ECCENTRIC MASS VIBRATOR TESTING

Eccentric mass vibrators use one rotating weight or two counter-rotating weights to produce a rotating or uniaxial sinusoidal force into the test structure. The weights are driven by a precision speed electric motor that sweeps the frequency of excitation over the frequency range of interest to obtain frequency response plots of the structure from which modal properties can be estimated. Typical eccentric mass vibrators can produce forces from 10 kN to 500 kN and require equipment weighing between 100 kg and 2000 kg. These vibrators can cause motion of large civil structures up to 10% g or more. They can investigate both low frequency and high frequency modes, but their weight does tend to increase significantly for modes less than about 1 Hz. This is because the force created by a rotating eccentric mass is proportional to the square of the rotating frequency. Therefore, at lower frequencies, very large eccentric masses must be used. Typical eccentric mass vibration data was presented in Figures 1, 2, and 3, and a typical eccentric mass vibrator photograph is shown in Figure 4 below. This vibrator is capable of a force up to 100 kN and operates in the frequency range between 2 and 30 Hz.

Figure 4. Typical eccentric mass vibrator (ANCO MK-139).

6. EXCITATION USING PROGRAMMABLE ACTUATORS

A programmable servo hydraulic actuator moving a heavy reaction mass can introduce a variety of force wave forms into a structure including sine sweeps, impulses, random forcing, etc. Such vibrators typically have a force level between 10 kN and 500 kN. Such systems are quite versatile but do require a portable hydraulic power supply as well as a heavy reaction mass, and so these systems are often heavier than eccentric mass vibrators or impulse vibrators.

Figure 5 below shows a vertical servo hydraulic impulse/sinusoidal vibrator used to measure modal properties on viaducts in order to monitor potential long-term degradation. This vibrator has a force capability of 100 kN and operates in the 2-30 Hz frequency range.

Figure 5. Typical servo hydraulic vertical vibrator.

7. DATA ANALYSIS AND MODAL PARAMETER ESTIMATION

The above excitation techniques produce data in the frequency domain: either Fourier transforms or sinusoidal frequency response plots. Such frequency response data typically shows resonant peaks corresponding to the modes of the structure. In many circumstances, the resonant frequencies can be estimated by looking at the frequency of the peak response. The mode shapes can be estimated by looking at the relative peak height and phase from different transducer locations. The modal damping can be estimated by the bandwidth formula. (The critical damping is given by the width of the resonant peak at the square root of 2 divided by 2 of the height of the peak, divided by twice the resonant frequency.) In more complex situations, when there is high damping and closely spaced resonance, more complex multi-mode curve fitting techniques must be used to identify the modal properties.

Once modal properties have been identified, they can be used to improve FEA models and detect structural changes. Among many different methods, the evaluation of changes in modal parameters of the structure between the undamaged and defective states has been used as a good indicator to detect, localize, and quantify the defects [1][2]. The basic idea is that the presence of defects in a structure will cause variations in its dynamic response and modal properties.

Even though some of these methods are based solely in the analysis of the experimental data to identify damage, most of them use numerical models, mostly FEA models. Although a priori FEA (before damage or degradation), based on theoretical properties of the structure, provides useful information, such a model often cannot predict the modal parameters with a high level of accuracy due to some uncertainties in mechanical and structural properties. There are also uncertainties in modeling assumptions, nonstructural components, boundary conditions, as-built variations, how soil-structure interaction is accounted for, etc.

While results vary significantly from structure to structure, and with various analysis techniques and level of analysis skill, most comparisons of experimental data to a priori FEA analysis will often show differences in, for example, resonant frequencies of 10-50%. This must be compared to the variations in resonant frequencies that can be caused by long-term degradation or post-earthquake damage. These degradation changes are often smaller, on the order of 1-10%. Therefore, it is necessary to modify the FEA models to more closely match the experimental data before these degradation issues can be detected by repeated experimental tests. Note also that mode shape changes are more sensitive to degradation than changes in resonant frequency.

8. TECHNIQUES FOR FEA MODEL VERIFICATION AND VALIDATION

Model updating techniques have been widely applied to adjust theoretical structural models using modal data obtained experimentally in civil engineering during the last three decades [3]. Model updating procedure can be treated as a problem of optimization, in which the weighted differences between experimental and theoretical values of some of the modal characteristics of the structure are computed to optimize a chosen objective function. On the other hand, regular inspections of in-service structures could allow the detection of changes in the dynamic response of the structure and its modal properties. These changes can be analyzed to detect structural damage at an early stage, so allowing an evolution from corrective maintenance to predictive maintenance, improving safety and allowing a reduction in repair costs.

9. EXAMPLE: RAILWAY VIADUCTS IN LEON, SPAIN

High speed trains (200-300 km/hour) are proliferating in various countries, including areas in Europe, China, Japan, and soon coming to California in the United States. The high speed of these trains imparts unique and high inertial and vibratory loads into railway viaducts (bridges) during passage. Some of these viaducts have previously been used by conventional speed trains, and some are newly designed specifically for high-speed traffic. First, it is necessary to make sure that the FEA analysis to determine the bridge capability to withstand high-speed traffic loads is correct. Second, there is a desire to periodically monitor these viaducts to detect incipient degradation or damage early and take remedial actions. ANCO and associated railway partners are performing vertical dynamic tests on viaducts using a programmable servo hydraulic actuator that is portable, and can be easily moved on, and attached to, the rails on a viaduct (See Figure 5 above). Rated at a peak force of 100 kN, this servo hydraulic actuator can impart impulsive and sinusoidal loads on viaducts in the 2-30 Hz range, where typically 3-10 resonant frequencies can be identified. Peak accelerations achievable on spans up to 100 m are on the order of 1% to 10% g, and these are comparable to dynamic response levels experienced during high-speed traffic.

Once the modal properties are identified (resonant frequencies, damping, mode shapes, and dynamic stiffness and mass), the FEA models are adjusted to better reflect the experimental data, thereby increasing the confidence in the dynamic load capacity predictions provided by the FEA. The long-term intent is to periodically (once every 1-3 years) retest the viaduct to detect changes in modal properties that could be indicative of incipient structural degradation or damage. Resonant frequencies are less sensitive to damage than are damping and mode shapes.

10. EXAMPLE: PACOIMA DAM IN PACOIMA, CALIFORNIA, USA

Pacoima Dam is a concrete arch dam in the San Fernando Valley, California, located within a few kilometers of the epicenter of the San Fernando Earthquake. Prior to the 1971 earthquake, eccentric mass vibrators mounted on the crest of the dam were used to measure the first few horizontal resonant frequencies of the dam. The 1971 earthquake caused some observable damage between the concrete dam and the rock embankments of the dam. After the earthquake, ANCO Engineers performed a new series of forced vibration tests with eccentric mass vibrators on the dam crest and remeasured the resonant frequencies. These studies showed that the resonant frequencies' values dropped by approximately 15%, most likely due to the embankment damage. While the damage was observable by physical inspection, it was relatively minor. This does show how forced vibration testing can be used to detect this damage, likely even if it is not physically observable.

11. EXAMPLE: NUCLEAR POWER PLANT VERTICAL PUMPS IN FLORIDA, USA

A nuclear power plant required two identical 5000 horsepower vertical pumps to provide cooling to the reactor. During startup testing, one pump operated within specifications, but the other pump, located a few meters away, experienced excessive horizontal vibration during operation. There was concern that the second pump might have unbalanced components that could lead to premature failure. In order to evaluate this possibility, forced vibration tests with an eccentric mass vibrator were used to evaluate the resonant frequencies and other modal properties in the 1-30 Hz range. Note that the operating speed of these pumps was 15 Hz.

The forced vibration tests indicated that the first pump had a first transverse resonant frequency of approximately 22 Hz. The second pump, however, had a first transverse resonant frequency of approximately 17 Hz, which was much closer to the operating frequency, and therefore accounted for the excessive vibrations during operation.

This information led to closer inspection of the two pumps and their design. It was discovered that the two pumps were actually manufactured by two different suppliers. The two pumps had the same operating specifications, and superficially resembled each other. On closer inspection, guided by the resonant frequency and mode shape discrepancy, it was discovered that the transition piece connecting the motor to the pump bearings and body was significantly more flexible in the second pump than in the first. This was, in part, due to the use of fewer bolts in the bolt circle, and thinner sections in the fabricated steel plate connection.

12. EXAMPLE: OFFSHORE OIL PLATFORM IN THE NORTH SEA, NORWAY

Offshore oil platforms in the North Sea typically have a structure about 50 meters above the water level and approximately 100 meters below the water level. Such platforms are subjected to significant dynamic fatigue loading due to wave action, especially during the winter when waves exceeding 30 meters can traverse these structures. Inspection of the above-water structures is relatively easy, but inspection of the below-water structures requires divers and is associated with a high risk to life and high cost. Forced vibration tests were conducted on such a platform by ANCO to determine if below surface damage could be detected by monitoring changing modal properties over time. If this screening could be successful, it would greatly reduce, but not totally eliminate, the need for underwater diving inspections. The tests were able to measure modal properties such as resonant frequency to approximately 1-2% accuracy/repeatability. There were two difficulties, however: The changing weight of equipment and supplies on the platform could also cause changes in resonant frequency on the order of 1-2%. In addition, FEA analysis with postulated structural failures in the highly redundant trust structure indicated that most damages below water would create less than a 1-2% change in resonant frequencies. It was concluded that only the most significant and major failure could be easily and reliably detected by measuring modal parameter changes over time.

The forced vibration test, however, did prove useful to another approach. The measured modal properties were used to optimize the FEA model of the platform. Then, an above water vibration monitoring system was provided to monitor tower vibration and motion 24/7 throughout the year. Using the optimized FEA model, the motions on the surface were reverse engineered (inverse dynamic analysis) to predict what the motions and stresses were below the surface. Using these stress time histories, it was then possible to monitor the fatigue loading on all of the underwater joints without the need for instrumenting the joints. In this way, the underwater joints receiving the highest fatigue loading were identified and could be used to guide underwater inspection to the most likely sites of fatigue failure.

13. CONCLUSIONS

The following conclusions can be drawn from field vibration testing of civil structures:

- There are a variety of effective techniques for full scale civil structures testing available.
- Some of the techniques can excite structures to levels of small to moderate earthquakes, and thereby provide equivalent modal parameter estimates accounting for non-linearities at seismic levels.
- Experimentally determined modal parameters can be used to validate, verify and update FEA models to more accurately predict seismic response.
- These experimental modal properties and updated FEA models can also be used to detect most earthquake structural damage and long-term structural degradation through the use of periodic retesting.
- Techniques have been developed to allow for economical rapid and repeatable retesting that make such techniques a useful tool for civil structures and damage monitoring.
- Potential users must recognize that some types of structural degradation produce only small effects on modal properties, and, in these cases, this may limit the utility of these approaches.

14. ACKNOWLEDGEMENTS

The use of ambient impulsive and sinusoidal excitation to investigate the dynamic properties of civil structures in the United States was pioneered in the 1950s and ‘60s by, among others, Professors Hudson and Paul Jennings at the California Institute of Technology, and Professors C. Martin Duke, Ralph (Fritz) Mattiesen, Craig B. Smith, and Gary Hart at UCLA. One of us (Ibanez) performed our dissertation research under the guidance of these professors and developed techniques for using this type of testing and parameter identification. The urgent need for this type of analysis was emphasized by the 1971 San Fernando Earthquake and was continued since then by the performance of over 300 field vibration tests at ANCO Engineers, as well as numerous other researchers in the field.

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