Testing Civil Structures Using Multiple Shaker Excitation Techniques

Marcos A. Underwood and **Tony Keller**, Spectral Dynamics, Inc., San Jose, California

New multiple shaker excitation techniques offer both a means for more accurate testing of nonlinear structural characteristics and a way to control 6 degrees-of-freedom and torsional motion at virtually any selected point on a civil structure. This article surveys current literature on the use of single and multiple shakers for the forced-vibration testing of existing and prototype civil structures. Recent results are presented on the use of experimental modal analysis to predict damage in existing structures and how multiple shakers can be used to improve results using such testing methods.

Civil structures like buildings have been subjected to simulated earthquakes for many years. A growing number of structures have also been subjected to controlled random, swept-sine and transient inputs with the use of one or more exciters in either single axis or multiple axis configurations. These types of tests are commonly called forced-vibration tests (FVTs). Recent research[1-7] is exploring the use of FVT and experimental modal analysis to detect damage to existing civil structures.

Concurrent with these developments, multi-input-multi-output (MIMO) vibration control systems have also been developed[8-12] to control the relative phase[10] and coherence[10,12] between components of a response vector of a structure undergoing a FVT. This response vector could consist of the outputs of an array of transducers like accelerometers, load cells and/or LVDTs (linear variable differential transformers)[9,12] located at various locations throughout a structure. Figure 1 illustrates this idea. Note that in some cases, the objective of a FVT is to maintain an exact earthquake waveform at selected actuator input locations. Any modification of these patterns caused by feedback from the test buildings or structures must be removed.

Real-time compensation is possible with recent developments in MIMO control.[11] Typically, the MIMO control system creates a vector of n drive-signals, $\{d_i(t)\}$, which are used to drive Actuator 1 through Actuator n. In turn, this excites the structure under test, such that the vector of m control-response signals, $\{c_i(t)\}$, from the m attached transducers, matches a pre-specified reference vector, $\{r_i(t)\}$.[8-12]

Load cells could also be located between the actuator and selected points on a structure[4] to measure the force-time histories that are being used for excitation. In these cases, the MIMO vibration control system could be used to control the array of actuators and their respective load cells so that a predetermined force vector[9,12,13] can excite the structure during a MIMO FVT. By controlling the relative phase and coherence between the load cell responses, a particular force vector as a function of frequency can be used to excite the structure during a modal test. The shape of the vector will largely determine which modes respond to the excitation.[9,13] In this way, closely spaced modes can be separated or particular modes excited using this methodology.[9] These new MIMO techniques can offer both a means for more accurate evaluation of nonlinear characteristics and a way to improve FVT methods.

Currently, multiple shaker and multiple-axis testing is largely limited to scale-model and subsystem testing. Much of the newest research is exploring how experimental modal analysis can be used to predict damage in existing civil structures. In the United States, the Networked Earthquake Engineering Simulation (NEES) Program[5-6] is increasing this scope. Current literature[1-7] indicates that large-structure testing is largely limited to the use of single shakers for random testing and eccentric-mass shakers for swept-sine testing. But, some researchers[2] recognize that the use of multiple exciters would improve FVT results and applications.

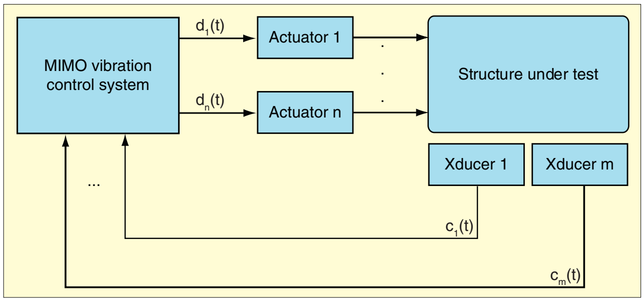

Figure 1. MIMO forced-vibration test.

The following discussion illustrates how and when multiple exciters can be used to improve existing methodologies. The discussion surveys existing literature[1-7] to understand the state of the art at this time. The discussion then indicates when and how MIMO methods can be used to extend the current state of the art. Although experience is limited, these MIMO methods[8-12] can improve the quality of modal characteristics used to detect internal damage in structures.

Current Applications of Multiple-Shaker Testing

Multiple-shaker testing is currently being used to test scale models for studying the strength of designs[8,10-11] in resisting high-intensity seismic events. Tests using multiple shakers are also being used[3] to calibrate finite-element models and their ability to predict the modal characteristics of large structures. These testing applications can be improved with the use of recently developed MIMO methods discussed here.[8-12] For example, multiple shakers can be used to separate closely spaced modes or to only excite particular modes.[9] These improved estimates can then be used to help understand the effects of structural degradation on the modal characteristics of typical civil structures. Knowledge gained can be used to localize damage within civil structures. Extending modal analysis to determine localized damage is the subject of most of the surveyed literature that is referenced here.

Evolution of Experimental Modal Methods

Initially, the structural engineering community exclusively used FEM modeling to obtain the modal characteristics of large structures. However, the design and construction of complex and ambitious civil structures has motivated the development of experimental tools that enable accurate identification of the most relevant structural properties (static and dynamic). These help to provide reliable data to support the calibration, updating and validation of the structural analysis numerical models used at the design stage. These have evolved to provide methods to help assess the health of existing civil structures and are now being extended to determine where damage is occurring and where damage may soon occur.

Modal Characteristics

The methods[1,2] in use for determining modal characteristics are FVT and ambient vibration testing (AVT). FVT yields more accurate results but can be difficult to use with large structures since more shakers are needed as the structure size increases.

AVT is not as accurate but is easier to implement for large structures, since wind, traffic, tremors and other natural sources are used to excite the structure under study.[1,2] However, the spectral shape of these vibration sources is normally assumed to be flat,

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Figure 2. Steel structure tested in Reference 3.

which is rarely true in practice. AVT methods use these assumptions in the form of the ambient vibration spectral density matrix (SDM)[8-12] to obtain modal models, which can then be used to determine a structure's modal characteristics.

On the other hand, FVT methods measure the SDM of the excitation source and therefore give a higher quality estimate. However due to its simplicity, AVT is the method that is in widest use. This is mainly due to the early development of FVT technologies and methodologies. The NEES program in the U.S. is funding many multishaker facilities that can be used for FVT.

AVT vs. FVT Testing of Bridges

The choice of whether to use the AVT or FVT method is determined by the specific bridge under investigation. For example, it's very difficult to apply the FVT method to bridges with an overall dimension exceeding 100 m.[2] Additionally, it's equally difficult to find a single actuator that can excite the structure at frequencies that are less than 2 Hz.[2] An exciter of this kind is found only in Japan. But other applications[11] show that the use of multiple exciters can mitigate this problem. In Europe, the method of suddenly releasing heavy weights like a barge from the bridge superstructure has been applied successfully.[2] However, the most reliable FVT results are gained when using servohydraulic shakers.[2,11]

Forced-Vibration Testing (FVT)

FVT methods can be used to study the seismic resistance of an existing building or a civil engineering structure. To employ these methods, researchers must conduct on-site dynamic tests to obtain the dynamic parameters of a structure.

The structure shown in Figure 2 was tested using FVT by NCREE in Taiwan. The test methodology and the results are discussed more fully in Reference 3. The FVT method is considered to be one of the most direct and accurate methods to use for this purpose.[3] The structure was tested in Taiwan using an eccentric mass shaker. The goals of FVT were to develop methods to study the seismic resistance capacity of an existing building or other civil engineering structures.[3]

The methods studied[3] use FVT to determine the modal parameters of the tested structure. These parameters are then used to modify the theoretical models, which can then be used for predicting the seismic response of the structure. The basic idea was to use swept-sine excitation to determine frequency response functions between the excitation source and various response points throughout the structure. The swept-sine excitation used for the FVT is provided by slowly varying the rotation rate of an eccentric mass shaker that is mounted at the top of the structure.

The goal for the research was to develop general methods to assess the seismic resistance capacity for the following types of structures:

- Steel frame structures
- Bridge structures
- Arch dams
- Pile foundations
- Effect of soil and structure interaction[6]

The research results are covered more fully in Reference 3.

Applications of FVT at UBC

A study[1,4] was performed at the University of British Columbia (UBC) to measure the effects of structural degradation on the modal characteristics of a steel-framed building. The study also compared FVT and AVT methods, but only the FVT tests are discussed here. The goal of this research,[1,4] was to use the results of this study to guide future researchers in how changes in the structural modes can be used to locate where damage has occurred. Detecting damage,

Figure 3. Steel-frame scaled structure used for UBC study in Reference 4 and close-up of beam and column connections.

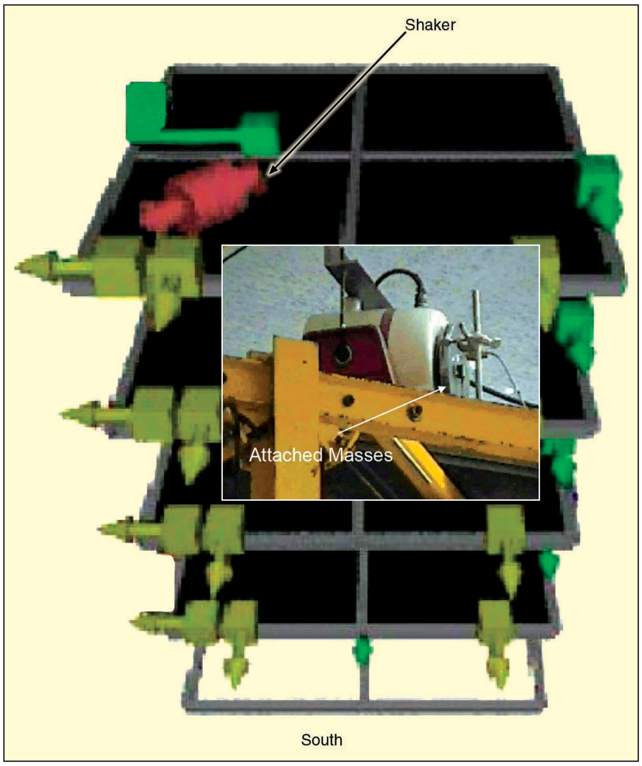

Figure 4. Overall structure used for modal tests and close-up of electro-dynamic shaker installation.[4]

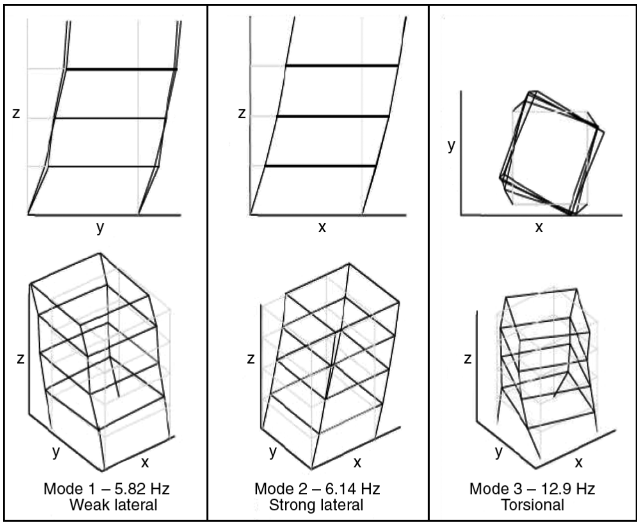

Figure 5. Typical mode shapes obtained in Reference 4.

with the use of either FVT or AVT methods, is one of the most active research areas, where the use of MIMO methods in conjunction with FVT shows the most promise. The steel-frame scaled structure that was used for the UBC study is shown in Figure 3.

The structure was used to study structural health monitoring techniques using data obtained from exciting a four-story steel frame with the use of an electrodynamic shaker. The purpose was to study how the modal characteristics of the building change as a result of structural damage. Removing or loosening bracing within the structure simulated structural damage. Figure 3 also shows a close-up of the column-beam connections and how the bracing is placed.

The columns are B100x9 sections, and floor beams are S75x11 sections, as shown in the close-up in Figure 3. Note that the fixture connecting the braces to the structure adds flexibility to the braces. The braces that are shown are removed or loosened to simulate damage.

An electromagnetic shaker and mass on the top floor of the structure was used to excite the structure with random vibration. Accelerometers were placed throughout the structure to study the effect of damage on the obtained structural modal model. The shaker and its placement are shown in Figure 4.

Since it is difficult to have the shaker fixed while exciting the structure, a mass is attached to the end of the shaker to provide force input to the structure by using the shaker to drive the overall moving mass. The moving mass is the armature and attached mass. The shaker is located at a top corner[4] of the structure. Here, the use of multiple shakers and a MIMO controller could have improved the tests by controlling the load cell output and thus control the geometric shape[12] of the resulting input force vector.

Adding more shakers and MIMO methods would also increase the magnitude force vector input to the structure and also the lowest frequency that could be excited. Controlling the phase and amplitude of the applied forces could also be used to excite only certain classes of modes.[9]

The close-up in Figure 4 shows where the shaker is placed and its orientation with respect to the overall structure. Reference 4 discusses a series of tests conducted on the structure with various simulated damage scenarios. Damage was simulated by removing braces in the structure or by loosening connections for the various tests performed. Many combinations of removing or loosening connections were tested, and the perturbed modal characteristics were measured.

Figure 5 shows the various mode shapes typically obtained. It shows the weak lateral, strong lateral and torsional modes at 5.82 Hz, 6.14 Hz, and 12.9 Hz. Although the results are still preliminary and more studies are yet to be performed, they show promise in helping to develop methods that can be used to correlate measured modes in particular damage scenarios.[4]

Table 1 shows the type of damage scenarios that were part of the study performed at UBC. Although the table does not show each combination that was tested, it should give a flavor of the various damage scenarios that were simulated. These scenarios are typical of what could happen to a typical structure as a result of aging and being subjected to seismic events of various magnitudes that don't result in structural failure.

Table 1. Typical test cases.[4]

Case	Braces	Location of Brace
A	All braces present	—
B	Remove one brace on Floor 1	Remove brace on N face, W bay
C	Remove brace on Floor 3	Remove brace on W face, N bay
D	Loosen another connection	Loosen bolts on N face to outside of W bay
E	Remove all braces and tighten loose connection	—
F	Loosen one more connection	Loosen bolts on N face to outside of W bay
G	Loosen second connection	Loosen center bolts of connection in the E bay of N face
H	Reattach beam and repeat Case G	—

NEES-Funded Multishaker Facilities

Figure 6 shows the locations of NEES-funded facilities, including the Tsunami event simulation capabilities at Oregon State University. However, we only discuss the multi-shaker facilities at this lab.

Figure 7 shows the two moveable six DOF shaker tables that are installed at the State University of New York (SUNY) in Buffalo. This multishaker installation will be used to improve the understanding of how very large structures react to a wide range of seismic events. It is intended to be capable of testing a structure to complete failure.

Figure 8 shows the multishaker facility at the University of Nevada at Reno. It consists of three 450-kN shaker tables that can host specimens up to 1.35 MN total weight. The shakers can be separated anywhere from 9 m to 36.5 m, centerline to centerline. Each table can also be operated independently of the other, in-phase with the other two tables (forming a single large table) or differentially with the other two tables for the simulation of spatial variation effects in earthquake ground motions.[5]

Figure 9 shows the multishaker facility at SUNY, Buffalo. It provides real-time dynamic hybrid testing (RTDHT). In this case, NEES has funded an upgrade to an existing facility. Key elements of the upgrade includes new reaction walls, significant enlargement of the strong floor area, dynamic and static actuators and associated control systems integrated into a new dual-shaker table facility. This is an upgrade of what is shown in Figure 9. The upgraded facility will be capable of testing large-scale structures using static or dynamic loading. The test methods include: pseudo-dynamic; effective force; real-time dynamic/pseudo-dynamic hybrid; and static, quasi-static and dynamic force techniques.[5]

Figure 10 shows the system that is being installed at the University of Minnesota. It will be called the Multi-Axial Subassembly Testing (MAST) System. It will be housed in a new laboratory on the Minneapolis campus and is one of four large-scale structural testing facilities awarded through the NEES program. The MAST system enables multiaxial, cyclic, static tests of large-scale structural subassemblies, which can include portions of beam-column frame systems, walls and bridge piers.[5]

Figure 11 shows the fast hybrid test (FHT) system that will be installed at the University of Colorado, Boulder. It's intended to provide model-based simulation of overall structural response with physical testing of key structural elements. The figure shows a ground-story shear wall. The testing capability is based on the pseudo-dynamic test concept, which combines physical testing with model-based simulation.[5]

Figure 12 shows the mobile laboratory capability that NEES funded at UCLA. The mobile laboratory includes four vibration

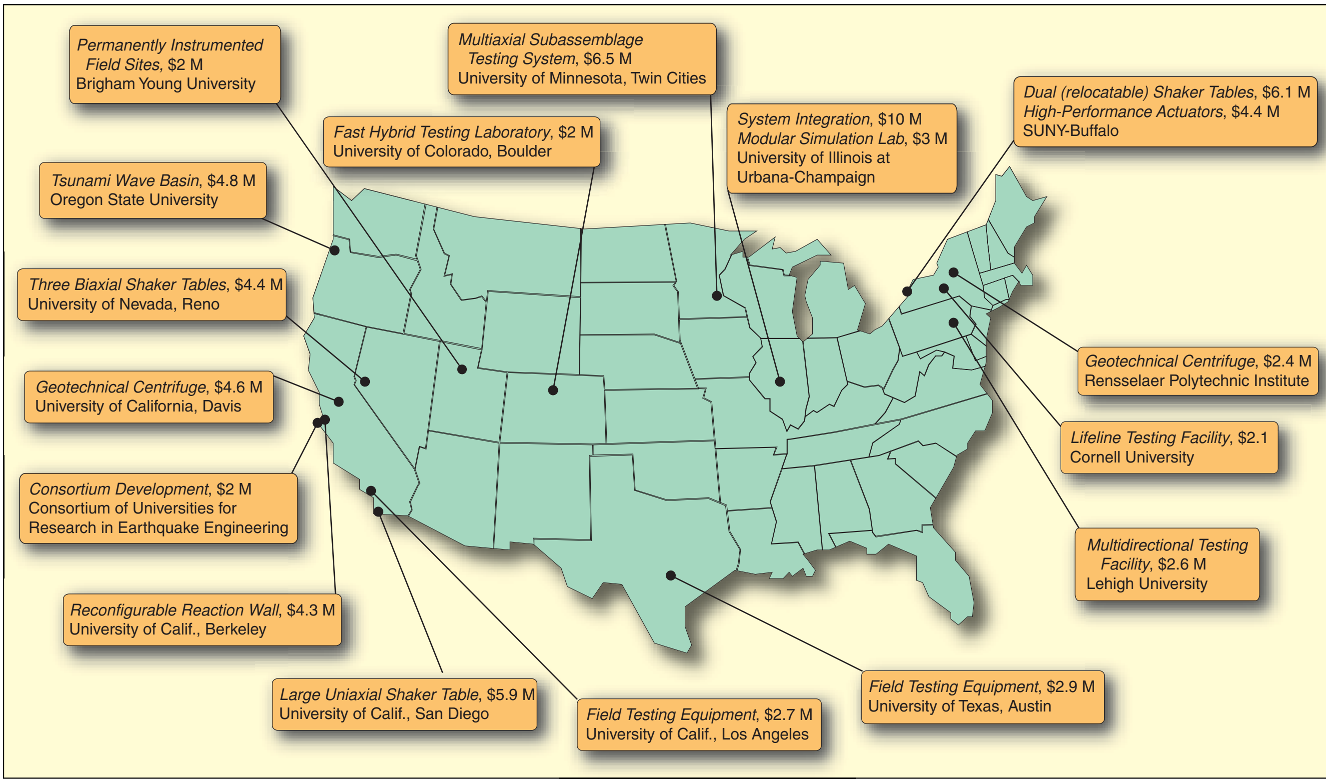

Figure 6. NSF funded NEES multishaker test facilities in USA.[5]

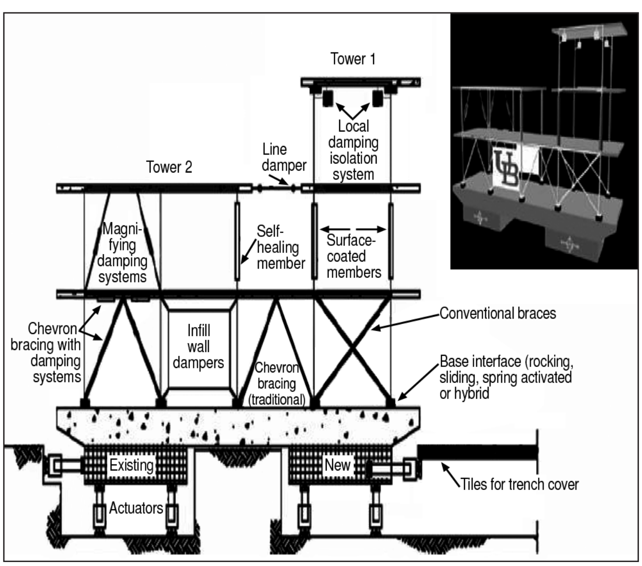

Figure 7. Relocatable shaker tables at SUNY-Buffalo SESSL.[5]

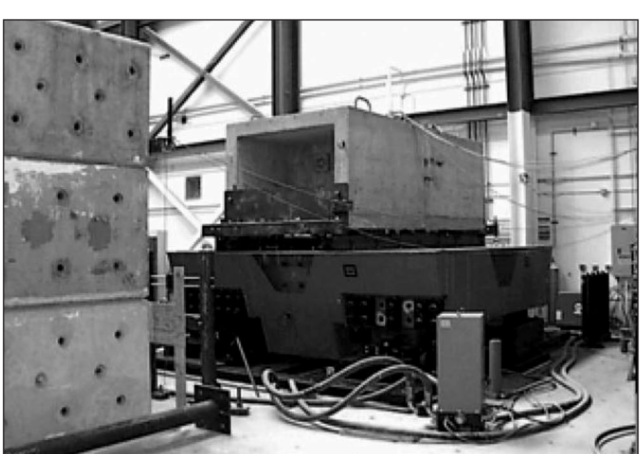

Figure 8. Shaker table at UN-Reno.[5]

sources. Three of these can be synchronized to produce greater excitation. The exciters are of the eccentric mass type, which can be used to perform sine sweeps of structures on site. Structural data can be captured via wireless sensors. Wireless sensors allow for rapid installation of high-density instrument arrays. As the figure shows, these data can then be captured and transmitted via a satellite link to the university for subsequent structural analysis.[5]

Structural Damage Detection

Current damage detection methods are either visual or localized experimental methods such as: acoustic or ultrasonic; magnetic field; radiographs; eddy-current; and thermal field. Current techniques require that the location of the damage be known *a priori* and that the portion of the structure being inspected be accessible. When the structural damage is small or it is in the interior of the structure, it cannot be detected visually. The newest research is attempting to address these shortcomings.[7]

Current research[1-7] directions are focused on developing methods that can use the changes in measured modal properties of a structure to predict the presence of damage and also where it's located, even if damage is small or located in the interior of the structure. One of the surveyed papers[7] has developed theoretical methods that are a refinement of these methods.

A useful tool that is being developed and refined is vibration monitoring, either as a result of FVT or AVT methods, where damage or fault detection is determined by changes[7] in the dynamic properties or response of structures. The basic idea of these new methods is that the occurrence of damage or loss of integrity in a structural system leads to a changed response to dynamic forces. In turn, these are caused by changes in the modal properties of the structure (eigen-frequencies, modal damping rates, mode shapes and/or the transfer functions).[7]

The basic premise of these research ideas is shown in Figure 13. These are based on modal-model methods that use the minimization of the residual error between the experimental modal model (EMM) and the analytical modal model (AMM) to determine the location and nature of cracks and the reduced stiffness that results. Various modal parameters are being studied to determine which can yield results to predict the existence of damage and to locate damage in the structure. The ones that are being studied include:

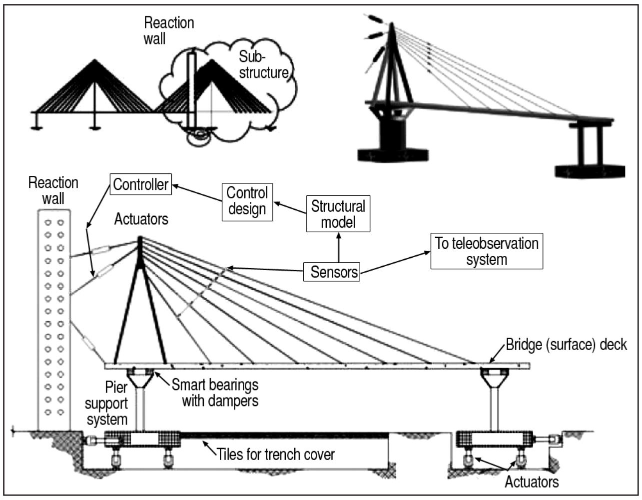

Figure 9. Multishaker facility at SUNY-Buffalo.[5]

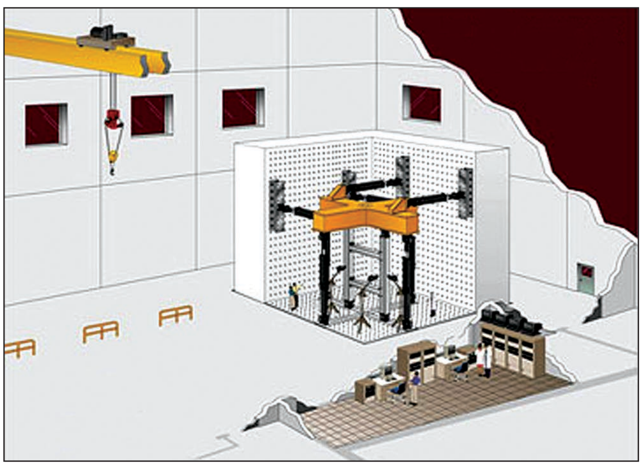

Figure 10. Multiaxial subassembly testing (MAST) system.[5]

- Shift in eigen frequencies
- Use of the modal assurance criteria
- Changes in damping
- Use of modal curvature to estimate bending and torsional stiffness of structural members[7]

The current research indicates that the shift in eigen frequencies can be small,[7] and damage prediction can be unrealistic. Additionally, the use of modal assurance criteria, where experimental and analytical modes are compared, has had limited success.[7] Furthermore, the use of damping change has also not been successful due to problems in measurement, both practical and theoretical.[7] However, recent research indicates that modal curvature[7] may be more sensitive to damage and may be very helpful in finding damaged locations. To address these limitations, the surveyed paper[7] goes on to develop the direct stiffness method (DSC), which is based on modal curvature. This approach seems to hold the most promise in detecting internal damage of existing civil structures.

The method presented is based on a basic characteristic of beam-like structures. As is well known, the bending stiffness EI in each section that is due to a particular bending mode ϕ_m^b can be obtained by dividing the modal bending moment M in that section by the corresponding modal curvature which is the second derivative of the m^{th} bending mode ϕ_m^b. Similarly, the torsion stiffness GJ in each section can be obtained by dividing the modal torsion moment T in that section, that is due to a particular torsion mode ϕ_m^t, by the corresponding modal torsion rate. This is the torsion angle per unit length which, in turn, is the first derivative of the m^{th} torsional mode ϕ_m^t to the distance. Equation 1 illustrates these ideas:

$$EI = \frac{M}{d^2\phi_m^b / dx^2} \quad \text{and} \quad GJ = \frac{T}{d\phi_m^t / dx} \tag{1}$$

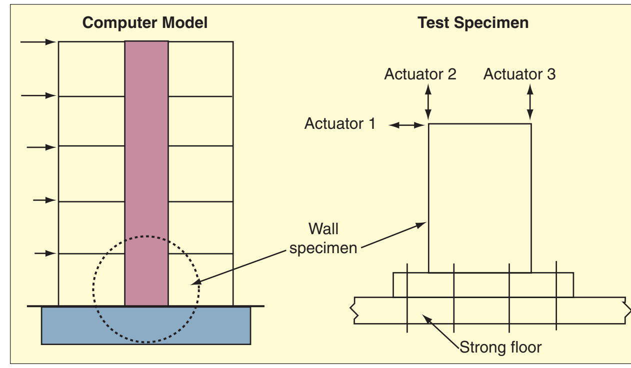

Figure 11. Fast hybrid test (FHT) system of University of Colorado-Boulder.[5]

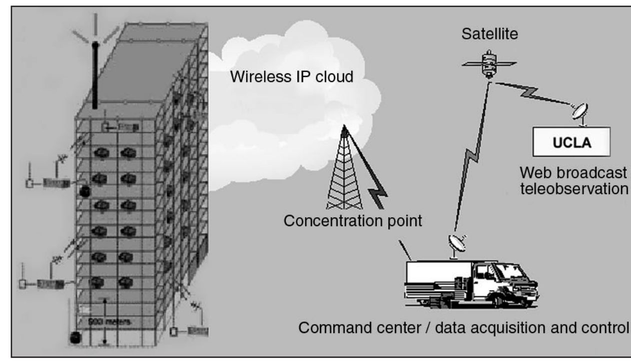

Figure 12. University of California-Los Angeles.[5]

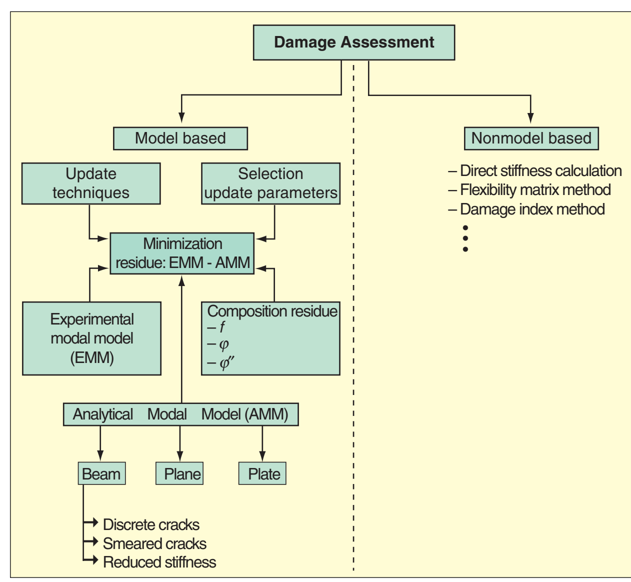

Figure 13. Model-based and nonmodel-based damage detection.[7]

where M and T are respectively the beam's internal bending moment and internal torsion moment due to the particular mode Φ_b or Φ_t. To calculate these internal member moments, the particular mode is interpolated between measurement points to obtain a continuous function of distance down the transverse length of the beam member. These are then used to calculate the internal shears, moments and torques:

$$M_{i+1} = M_i + T_i(x_{i+1} - x_i) - \int_{x_i}^{x_{i+1}} \omega_m{}^2 \rho A \phi_m^b(x)(x_{i+1} - x_i)dx$$

$$V_{i+1} = V_i - \int_{x_i}^{x_{i+1}} \omega_m{}^2 \rho A \phi_m^b(x)dx \tag{2}$$

$$T_{i+1} = T_i - \int_{x_i}^{x_{i+1}} \omega_m{}^2 i_a \phi_m^t(x)dx$$

where ω_m is the natural frequency in radians/second of the m^{th}

mode, ρ is the mass density of the particular section and A is the cross-sectional area of the section. Equation 2 is used to calculate the bending moment, shear and torsion moment at each measurement point. These moments and torques are then used in Equation 1 to calculate the bending stiffness EI and torsional stiffness GJ for each measurement point, which gives us the stiffness at each such point along the beam member.

The use of multiple shaker techniques in the dynamic testing of civil structures can improve damage predictions.

In Equations 1 and 2, the bending and torsion modes are measured with an FVT or AVT test and numerically differentiated after some smoothing that is performed on the measured modal displacement functions. The bending and torsion moments are calculated using the modal displacement functions of the two equations.[7] Sudden drops in calculated stiffness indicate a loss of strength and is a good predictor of hidden damage, such as cracked concrete beams. Results like this depend on an accurate experimental modal analysis.[7] The use of FVT methods with multiple shakers and multireference methods can enhance the accuracy of experimental methods.[9,12]

Conclusions

Multishaker testing of large civil structures is still early in its evolution. It's largely used to test structural models. Recent research is starting to change this as a result of the availability of NEES facilities. Theoretical advances in the use of analytical and experimental modal analysis shows much promise in localizing and characterizing damage. However, these methods require more accuracy in the modal analysis that is performed, which may not be possible with AVT and single-shaker FVT methods. The use of MIMO multishaker techniques can help expand the use of FVT methods to large structures, which can help provide the higher accuracy modal analyses that are needed to use these modal-analysis-based damage prediction and location methods.

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The author can be reached at: underwoodm@sd-star.com.