Modal Testing for Structural Identification and Condition Assessment of Constructed Facilities

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MODAL TESTING FOR STRUCTURAL IDENTIFICATION AND CONDITION ASSESSMENT OF CONSTRUCTED FACILITIES

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ABSTRACT

Condition assessment based on modal testing and structural identification is discussed. This technique was successfully applied to seven highway bridges. Modal flexibility obtained by post-processing the frequencies and mass-normalized modal vectors was used as a structural condition index. The reliability of modal flexibility was verified by comparing bridge deflections obtained from modal flexibility to those measured during static truck-load tests. 3D analytical models of the bridges were calibrated by the experimental data, the calibrated models were then used as a basis for condition assessment in the absence of baseline experimental data.

1. INTRODUCTION

Due to a lack of objective and reliable condition assessment techniques for constructed facilities, it is not possible to implement cost-effective management techniques for infrastructure preservation. For example, presently in the U.S. a major portion of the highway bridge stock is deemed in need of repair and/or replacement, and the corresponding financing need is estimated as $90 Billion [2]. Since in U.S. bridge conditions are typically determined by visual inspection and expressed in terms of a subjective "condition index", the estimated financing need may not be accurate. If a certain portion of the financing need could be provided, it is questionable whether it would be possible to rationally prioritize these funds for the maintenance, retrofit, upgrade and replacement of bridges which are deemed structurally deficient. Since our knowledge on fundamentals of bridge behavior (i.e. the actual critical limit states, capacities and failure modes of different types of bridges) is incomplete, we may be investing scarce resources into bridges that have adequate reserve capacities (such as reinforced concrete slab bridges) while we may be delaying replacement of those bridges that may be susceptible to sudden collapse (such as older truss bridges with eye-bar connections). Therefore, the writers are motivated to discuss an objective condition assessment technique which is based on modal testing and structural identification that should help improve the current practice.

2. OBJECTIVES

The objectives of this paper are: (a) to discuss issues regarding definition and conceptualization of structural state and structural damage; and, to present a condition assessment technique based on modal testing and structural identification; (b) to discuss issues regarding reliable modal testing of constructed facilities; and, (c) to exemplify the reliability of impact and forced vibration modal testing in leading to an accurate modal flexibility, based on applications to a steel stringer bridge and a steel truss highway bridge.

3. STRUCTURAL IDENTIFICATION METHODOLOGY FOR CONDITION ASSESSMENT

Condition assessment is defined as measuring and evaluating the current state of a constructed facility in terms of indices such as flexibility/stiffness, damping, toughness against fatigue, resistance to deterioration mechanisms and aging, and, the available strength, deformability and energy dissipation capacities under the probable failure modes. Condition assessment includes identifying any design,

construction or maintenance errors as well as any local defects, deterioration and damage such that the global state of health, i.e. the structural reliability of the facility may be established for rational management decisions.

The writers developed a condition assessment method in conjunction with the definition offered above. The method is described in the following, and is currently being applied to representative samples of recurring construction, such as common bridge types. In addition to condition assessment and reliability evaluation, applications also serve for calibrating design codes, maintenance management strategies and retrofit techniques.

(a) Data-base generation, measurement and A-priori analytical modeling; (b) parameter sensitivity studies; (c) designing and conducting modal tests; (d) post processing of the experiment and evaluation of the structural state in the modal and flexibility spaces. ***The modal flexibility based on a sufficiently fine spatial resolution is used as an experimental index expressing structural condition. Correlations with a baseline modal flexibility, or, in its absence, with an analytical flexibility reveal damage***; (e) global calibration of the analytical model in the modal space based on appropriate parameter optimization algorithms; (f) evaluation of the modal truncation, random and non-random experimental and linearization errors and those associated with post-processing by correlation studies; (g) verifying the "completeness" and reality-checking of the analytical model by correlating globally correlated analytical model responses with their experimental counterparts after correcting these for errors; (h) if necessary, conducting additional experiments for a better conceptualization and measurement of any missing or unknown-unknown local response mechanisms, and incorporating these in the analytical model; (i) formulating an objective function that incorporates experimental errors and any heuristic knowledge available about the structural type and/or the specific structure; (j) parameter identification and verification of the identified linearized analytical model by additional experiments conducted at higher stress-levels; (k) utilizing the field-calibrated analytical model for rating, reliability evaluation, etc.

Structural Condition Indices: Many researchers have recognized that frequencies, damping coefficients and mode shapes of a structure do not serve as reliable condition indices. The writers have made similar observations. For example, the maximum change in 20 of the frequencies of a RC slab bridge, after it yielded under a progressively increasing loading equivalent to 20 HS 20-44 trucks, was less than 5%. No appreciable changes were discerned in the mode shapes while the changes in the damping coefficients were of the same order as the errors that are typical due to linearization, experimentation, and post-processing. It has also been observed that, due to changes in ambient conditions, shifts in some frequencies and mode shape amplitudes exceeding 5% have been measured for both concrete and steel bridges within just a single day.

It was suggested that by directly transferring a sufficient numbers of modal frequencies and mass-normalized mode shapes into a close measure of the flexibility matrix, termed "modal flexibility", it is possible to obtain a reliable condition index for a constructed facility [5]. The writers demonstrate in the following that modal flexibility is quite sensitive to damage-induced changes in structural condition.

Damage Definitions: Damage has various definitions in the engineering literature at the material, element, or structural levels. Visible degradation of structural elements; reductions in the incremental structural stiffness, strength or energy dissipation properties; or changes in the structural state properties compared to a baseline state may be considered. **The writers describe damage as a measurable increase in the incremental local flexibility of a critical region.**

Some researchers have suggested that only the identification of dynamic properties such as frequencies, damping factors and mode shapes would be sufficient for damage detection purpose [3]. Others have developed methods to better quantify damage with the use of measured dynamic properties [4]. One method is the perturbation approach which relates changes in vibration response to changes in structural stiffness. Quantifying these changes is assumed sufficient for damage evaluation [1].

Damage detection based on only changes in frequencies, damping factors, or mode shapes might be applicable for certain test specimens in a controlled laboratory environment. Many times, damage in certain members of a structure would reveal itself only at the local modes incorporating those members; whereas at the global modes, a change would not be observed. It was suggested to compare static deflection patterns obtained by loading the experimental and analytical flexibility matrices of a constructed facility by a variety of loading patterns as a means of evaluating damage when baseline information is missing [6]. This approach becomes more reliable when a baseline flexibility is available. The writers show that application of static load patterns may reveal damage through deflection increases relative to the baseline values.

4. MODAL TESTING

Modal testing is the principal experimental component of structural identification. Issues which have to be resolved for reliable modal tests of constructed facilities may be classified into: (a) Test design, i.e. establishing test constraints, excitation, grid and site preparation; (b) setup and instrumentation; (c) pre-test debugging; (d) test in progress quality assurance; (e) post-test considerations. Each step has been observed as important for reliable experimental results. Based on the impact and forced vibration tests of constructed facilities with different geometry, condition and boundary conditions, it was observed that the reliability associated with individual mode shapes or frequencies of complex constructed facilities cannot exceed 90% due to errors in linearization and unavoidable experimental errors. As discussed earlier, changes in ambient conditions have been responsible for measurable short-term changes of 5% in the critical frequencies of most constructed facilities. The effect of changing stress and loading rates on dynamic properties depended on the test facility, their most significant effect have been observed on the boundary conditions.

5. SELECTED APPLICATIONS: A STEEL STRINGER BRIDGE

Test Bridge: The Westbound Cross County Highway bridge in Cincinnati was selected as a test specimen. The two-lane, three-span (55, 78, and 55 ft.) continuous, integral abutment, non-composite steel-stringer bridge was constructed in 1990 (Fig. 1). The new facility was used to test the level of correlation from forced-excitation and impact tests as well as to verify the reliability of modal flexibility from impact testing against the results of a truck-load test .

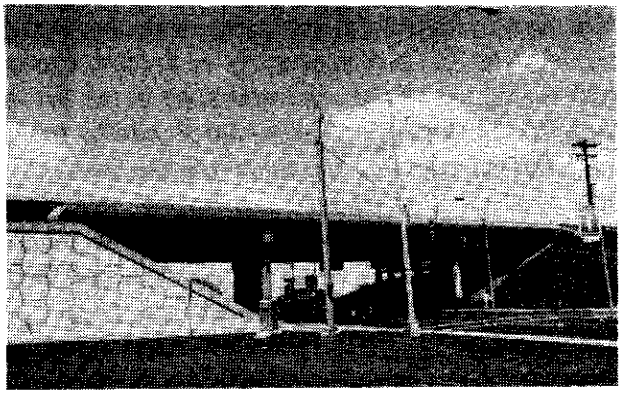

Fig. 1 Steel Stringer Bridge

Modal Test Results: The bridge was subjected to impact test and vertical and horizontal forced-excitation tests to capture the dynamic characteristics in both the vertical and horizontal directions. Some of the frequencies, damping factors, and mode shapes obtained from the tests are summarized in Figure 2.

Multi-reference impact testing was considerably more feasible than forced-vibration testing on account of the hardware requirements. Impacts from a 12-pound hammer provided sufficient input energy, and data of good quality was obtained by averaging five impacts per node. With proper post-processing tools and techniques, 18 mass-normal modal vectors within a 24 Hz bandwidth were obtained (Fig. 2).

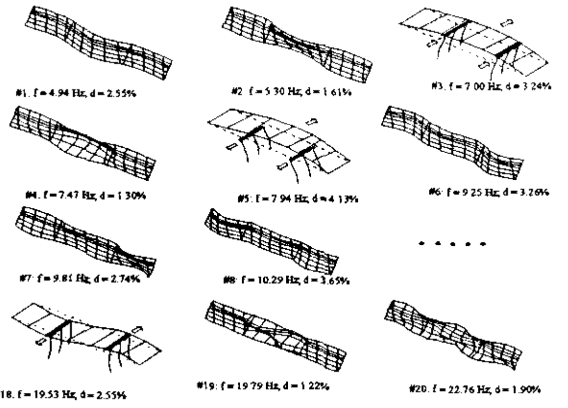

Fig. 2 Experimental Results

Swept-sine testing required considerably more effort to conduct. The linear mass-inertia exciter was controlled to limit its force input at 5000 lbf as opposed to a maximum impact force of 2000 lbf which could be induced by the impact hammer. Therefore, swept-sine testing provided data with a higher signal-to-noise ratio than that obtained from the impact test, and permitted better control of the frequency content and amplitude. A disadvantage of single-reference modal testing, which is the case when a single exciter is used, is that repeated roots and/or closely-spaced modes cannot be reliably identified. Also, if the location of the exciter is on a null-point of a mode, or when a mode has high damping, it may be missed. In the case being discussed, two modes which were reliably identified by impact testing could not be identified by swept-sine testing. Figure 3 compares the driving point FRF obtained from the forced-vibration test with the corresponding node's FRF from the impact test. The results are quite close, and any quality difference is not apparent. It is of interest that impact test results were post-processed twice, considering the reference with the highest modal participation factor and a weighed average of all the references, respectively.

Figure 4 compares the MAC values of the corresponding mode shapes obtained by the forced-vibration test and from the impact test following the two different post-processing approaches. Clearly, post-processing the impact test based on a weighed-average of all the references is the recommended approach.

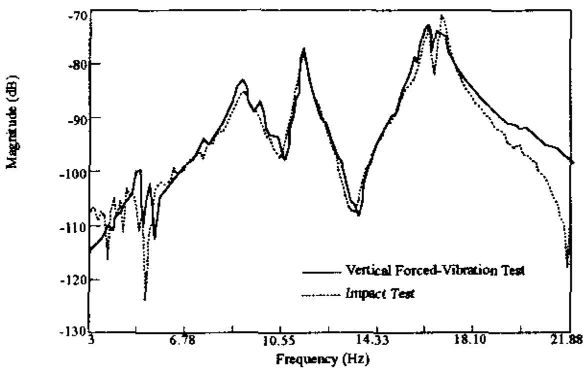

Fig. 3 FRFs of Impact and Forced-excitation Tests

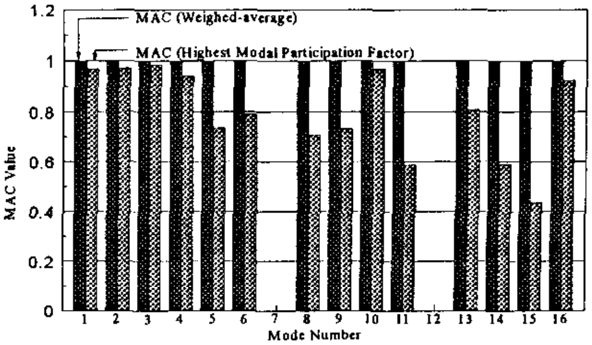

Fig. 4 MACs of Impact and Forced-excitation Tests

Modal Flexibility: Mass-normalized modal vectors could be identified reliably from either test. Modal flexibility of the test bridge was derived from the 18 vectors obtained from the impact test without requiring an estimate of inertia. A sensitivity study on modal truncation revealed that 18 modes were quite adequate for the convergence of modal flexibility. In fact, the truncation errors in modal flexibility became especially insignificant (about 2%) when a deflection profile of the bridge was generated under a uniform loading.

The test results were used for calibrating a finite element model in the modal and flexibility spaces. Figure 5 compares the 3D displacement profiles of the bridge obtained by applying the same uniform vertical loading to the calibrated analytical model and the modal flexibility. Modal flexibility yields a slightly stiffer response as expected due to modal truncation, and the results reveal a successful structural identification. The analytical model could then be used for rating. Modal flexibility was further verified by truck-load tests. In one of these tests, the bridge was loaded statically by positioning four trucks as shown in Fig. 6. The total load of 178 Kips, when concentrated within an end-span, represents several multiples of the legal load. Therefore this test also served as a proof-test. The bridge deflections measured along one girder and one cross-brace during the truck-load test are compared in Figure 6 with the corresponding responses obtained by analytical simulation and from the modal flexibility. Excellent correlations confirm the reliability of modal tests as well as the structural identification method.

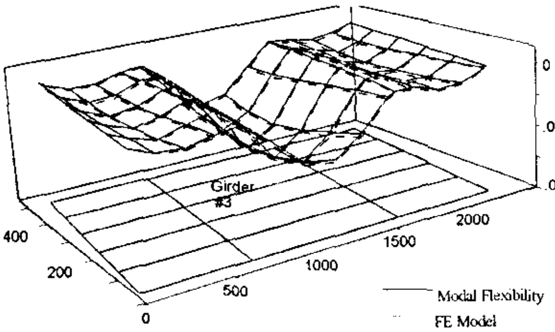

Fig. 5 Experimental and Analytical Flexibilities

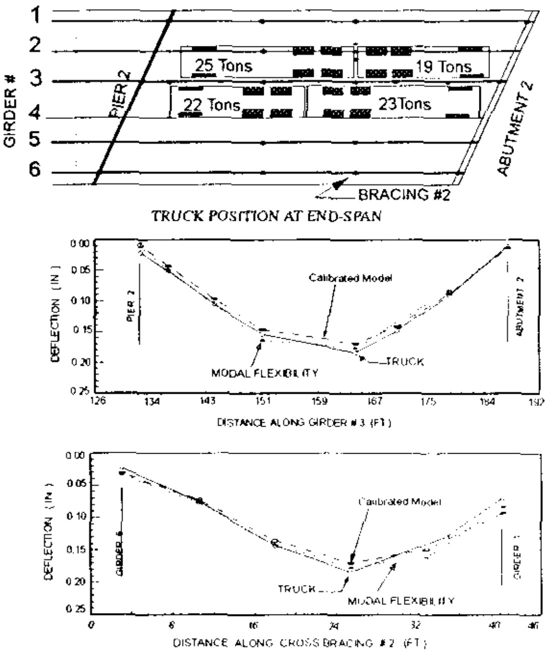

Fig. 6 Experimental and Analytical Deflection Profiles

A STEEL TRUSS HIGHWAY BRIDGE

The Test Bridge: The bridge (Fig. 7) is an eight-panel, through Pratt-truss bridge (the Pratt), with a span of 152 feet and a roadway width of 20 feet. The bridge was constructed in 1914 with pre-A7 steel. Truss members were fabricated with built-up members riveted in place. The floor system consisted of main girders, stringers, and a wood deck. The bridge was loaded such that the truss labeled "B" was subjected to about 70% of the load and yielded while the truss labeled "A" remained elastic.

Results of Modal Testing: Modal tests were conducted by forced-excitation. The bridge's force-displacement state corresponding to the modal tests is shown in Figure 8. The first modal test served as a baseline to Test 2 conducted after inducing structural yielding to the bridge.

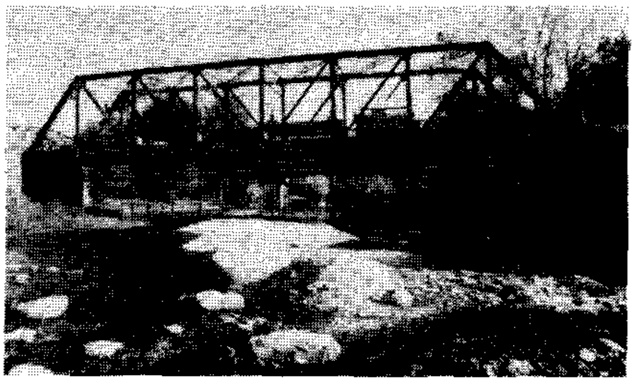

Fig. 7 Steel Truss Bridge

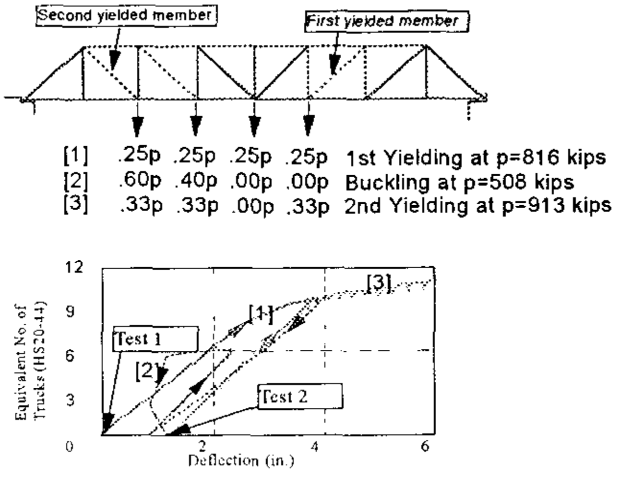

Fig. 8 Force-Displacement State

Damage Detection: A review of the frequencies and damping factors of the Pratt before and after yielding revealed less than 5% difference between the baseline and post-damage frequencies. The extend of damage induced to the Pratt is revealed by the force-deflection response in Figure 8, showing the influence of initial yielding, buckling and additional yielding of the structure during a third loading excursion. It is noted that the errors and uncertainties inherent in the modal test and post-processing were assessed to lead up to 2% variance in the frequencies and up to 100% variance in the damping coefficients. Therefore, while the variances in the frequencies and damping from before and after damage tests indicate some changes in structural state these are not conclusive.

The modal flexibilities were verified by correlating with the deflections induced during static tests. The margin of error in the modal flexibility coming from the data acquisition and parameter estimation stages was found to be under 12%. Figures 9 and 10 illustrate how a distributed load pattern and a diagnostic single-load pattern are used to detect damage on the Pratt. The uniform load pattern in Figure 9 shows that Truss B has become more flexible following yielding, and Truss A has become relatively stiffer, indicating that Truss B might be damaged. Application of a load pattern with a concentrated load help localize this damage. The 35% of difference between the two deflection profiles in Figure 10 clearly indicates that there should be significant damage in the vicinity of the region where the concentrated load is applied.

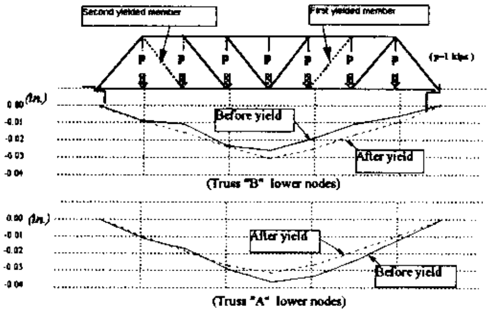

Fig. 9 Force-Deflection Response Before and After Damage

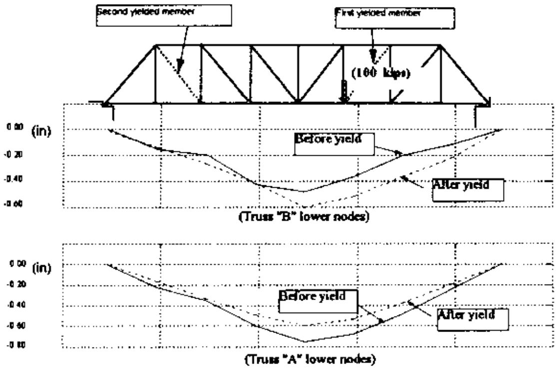

Fig. 10 Force-Deflection Response Before and After Damage

6. CONCLUSIONS

A lack of objective and reliable condition assessment techniques for constructed facilities is the most critical barrier obstructing cost-effective management of the infrastructure preservation. Even if the financing barriers for infrastructure maintenance backlog could be overcome, it is questionable whether such funds could be prioritized rationally. We need to improve our understanding of the fundamentals of bridge behavior, develop consensus definitions for condition assessment, and develop objective indices to quantify global structural condition for effective infrastructure preservation.

The writers have been exploring actual behavior patterns of common bridge types at all the critical limit states including failure. Based on their experiences in the course of nondestructive and destructive testing of new as well as decommissioned bridge samples, they have developed rational definitions for condition assessment and damage. "Condition" is defined as the current state of a constructed facility in terms of indices such as flexibility/stiffness, damping, toughness against fatigue, resistance to deterioration mechanisms and aging, and, the available strength, deformability and energy dissipation capacities under the probable failure modes. "Structural damage" is defined as a measurable increase in the incremental local flexibility of a critical region.

An objective index which is sensitive to structural damage is "flexibility" which may be obtained by post-processing an adequate number of unit-mass-normal modal vectors that are measured in a modal test. Typically, even when bridge stiffness and inertia may be uniformly distributed, about twenty modes have been sufficient to obtain an accurate measure of flexibility. It is possible to design, execute and post-process modal tests of bridges by impact and/or forced-excitation, such that an accurate measure of their flexibility may be obtained with a fine spatial resolution. The hardware demands of a multi-reference modal test by impact are quite reasonable, presently it is possible to develop an adequate capability with under $25,000. The standards in designing and conducting a test, followed by the post-processing requirements, however, should be quite exacting in order to develop a reliable modal flexibility. The researchers assessed that due to linearization and unavoidable experimental errors inherent in modal testing of large constructed facilities, the maximum reliability in the modal flexibility of a bridge should not be expected to exceed 90%. However, this type of reliability is adequate to evaluate damage in conjunction with the definition offered above.

Applications of the modal testing and structural identification based condition assessment technique to a newly constructed steel-stringer bridge and an old steel truss bridge have been summarized, demonstrating that modal flexibility is a reliable tool for condition assessment.

The writers are continuing research for exploring practical intermittent tests that will permit to monitor changes in some selected critical flexibility parameters as well as derivative indices following an initial implementation of the structural identification method. Once problems related to long-term sensor and data acquisition reliability under field conditions are resolved, it would also be possible to explore continuous health monitoring schemes.

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