Field Test-Based Calibration of Bridge Finite Element Models for Condition Assessment

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Introduction

According to the National Bridge Inventory, many of the highway bridges that were built from the 1950's to the 1970's are experiencing deterioration after 30 to 50 years service [4]. Studies have shown that about one-third of these bridges are either structurally deficient or functionally obsolete [3]. Efficient and reliable diagnostic methods used to evaluate remaining capacity and service life are critical for effective infrastructure management.

3D finite element analysis can be an extremely efficient tool for condition evaluation. The process consists of generating an FE model, calibrating the model to field test data, and using the results from the calibrated model to rate the bridge or investigate unique loadings or retrofit schemes. Several difficulties are routinely encountered. Field testing can be laborious and result in traffic delays, the development of accurate models can be time consuming, post processing of data can be overwhelming, and without carefully incorporating field observations and calibration, erroneous or incorrect conclusions can result.

This paper summarizes ongoing work at the University of Cincinnati Infrastructure Institute (UCII) aimed at streamlining this process. More efficient testing methods have been developed to reduce the effort required to obtain reliable field data, an intuitive GUI based preprocessor has been developed dramatically reduce the time and effort required to generate accurate and comprehensive FE models, a process is being optimized to provide automatic model calibration, and a postprocessor has be developed to generate load ratings from the calibrated model. These developments are described and are illustrated for a representative bridge.

UCII Bridge Modeler Software

The UCII Bridge Modeler is a comprehensive software package that can efficiently create 3D FE models (including nearly all the common features found in) concrete slab on steel stringer bridges from plan data using a simple Graphical User Interface (GUI). Given the bridge plans, a typical FE model can be generated in less than 30 minutes. The data required for the model generation is collected through eight tabbed dialog boxes in the program. A diagram of the respective bridge feature being defined is shown in each tab to aid the user get and reduce errors. Default values are defined for all required parameters. The user is also able to save and reload model data.

The major assumptions used in the software include: girders are modeled using shell elements for the web and frame elements for flange; bridge deck, sidewalks, and parapets are modeled using shell elements; the deck and girders are connected using rigid links; piers and abutments are defined using springs; cross frames are defined as frame elements; cover plates, variations in flange thickness, and haunches are incorporated; the preprocessor provides complete flexibility in the generation of truck/lane loads (via AASHTO, FHWA, and state loading conditions); and the program allows users density of the generated mesh as well as locations of outputs.

Modal Test Strategy, Implementation, and Data Processing

Until recently, field testing of bridges has been limited to the acquisition of strain responses to a truck loading. A complementary testing method is modal testing. In general, accelerometers are placed on the bridge deck and the bridge is systematically excited using an instrumented hammer while acceleration data is recorded.

After a 3D FE model of the bridge has been generated, dynamic responses of the bridge may be simulated to help define a comprehensive modal field test plan. Determining the natural frequency of each mode provides the proper frequency bandwidth settings for the data acquisition system. Modal participation factors are also considered indicating how much influence an individual mode has on the overall response of a structure [2]. It is common for a few modes to dominate the response, so it is crucial to properly identify these modes through proper selection of locations for both input excitations (i.e. hit points) and sensors. Accelerometers are typically placed along girders at cross frame connections and at supports and impact locations are typically specified at the middle of each span.

The actual deployment of a modal test can be conducted within four hours (including, setup, execution and teardown), thereby minimizing interruption to traffic flow. After the data has been collected it is post-processed in

MATLAB. Natural frequencies, mode shapes, modal mass and flexibility are extracted. Quality checks are done on the data to provide confidence in the final results. Comparisons to the FE model analytical values provide further confidence. The identified modes are used to compute modal flexibility, which is sensitive to damage, can be correlated to the bridge condition, and can be independently compared to any displacement measurements made during truckload testing [1]. The flexibility displacement profile, or Bridge-Girder Condition Indicator (BGCI) is computed by multiplying the flexibility matrix with a load vector comprised of downward loads of unit magnitude positioned at each accelerometer location along the girder line of interest. The BGCI is used in determining how many modes are required to characterize the bridge behavior and is used along with the frequencies, mode shapes, and strain data in calibrating the finite element model.

FE Model Parameter Sensitivity Analysis and Model Calibration

The calibration of the finite element model to experimental data is achieved by systematically varying parameters in the model input file. Sensitivity analyses are performed in order to identify the critical parameters including: (1) stiffness of vertical springs over supports, (2) stiffness of horizontal springs over piers, (3) stiffness of horizontal springs over abutments, (4) horizontal restraint cases in bridge length direction, (5) moment of inertia of rigid links, (6) thickness of concrete decks, (7) unit weight of concrete decks, (8) modulus of elasticity of concrete decks, and (9) nodal mass over piers. Two general groups are used to categorize these critical parameters. The first group, based on physical properties, includes parameters 1, 2, 3 and 4 (used to simulate boundary conditions), parameter 5 (used to simulate continuity conditions), and parameters 6, 7, 8 and 9 (used to simulate geometry of the critical regions and elements). The second group, based on influence on the stiffness and mass matrices, include parameters 1, 2, 3, 4 and 5 (stiffness matrix only), parameters 7 and 9 (mass matrix only), and parameters 6 and 8 (stiffness and mass matrices) [2,4].

On the basis of the sensitivity analysis, the calibration of the finite element model is started. Measured values such as the BGCI, mode shapes (using the MAC), modal frequencies, and truck load strains (represented by UIL's) are factored into the objective function as given in Equation 1. This objective function includes difference between the analytical and experimental quantities mentioned above and importance factors (c_1 through c_4). A systematic optimization procedure for minimizing the objective function has been developed [6] and automated.

$$OF = c_1\ BGCI\_err + c_2\ MAC\_err + c_3\ Freq\_err + c_4\ UIL\_err \qquad (1)$$

Finite Element Model Post Processing

Since the output files generated by the finite element analysis are enormous, manual reduction is cumbersome and inefficient. As a result, a post-processing software package was created for this task. This software uses the input file and scratch files generated by Bridge Modeler and the FE output files to extract the data that are required for creating load response curves and UIL's. The automation of the entire process of load simulation and post processing expedites sensitivity studies and bridge condition evaluation.

Case Study - BUT-732-1043

A representative bridge in Bulter County, OH, was chosen as for a case study to illustrate the procedure discussed above. BUT-732-1043, was constructed in 1951 and consists of three spans measuring 60', 75', and 60'. The bridge has no skew, is 36' wide, and consists of 5 (W33 x 141 and W36 x 194) girders spaced at 8'-4".

The preliminary FE model for this structure indicated that all pertinent modes were located below 50 Hz and so a bandwidth of 64 Hz was chosen. The test was implemented to monitor girders 2, 3 and 4 - the innermost girders of the bridge. The southbound test measured girders 2 and 3 and the northbound test measured girders 3 and 4. Girder 3 was included in both tests providing common data so that results from the 2 tests could be correlated. The accelerometers were evenly distributed along the bridge at girder-to-cross frame connections and girder support locations. The impact points for this bridge were located at mid-span for each of the 3 spans to ensure excitation of any locally excited modes.

For this bridge, 21 modes were identified from the northbound data set and 22 modes from the southbound set of data. These modes were used to create corresponding flexibility matrices for each test. These matrices were in turn used to create the BGCIs for girders 2, 3 and 4, (Figure 1). Looking at girder 3 reveals that the same measure of flexibility is achieved regardless of which lane test is used although these tests were performed independently indicating a consistent test. The BGCI for these girders indicated the displacement profile was dominated by the 4 modes; modes are the 1st, 5th, 6th and 9th modes of each test.

The mode shapes, frequencies, and BGCIs can be used to calibrate the nominal FE model as described above. Figures 2 and 3 provide examples of the comparisons between nominal and tuned model responses and field data. They illustrate a high correlation between tuned model and measured field data.

This model was then used for calculation of bridge rating factor per AASHTO guidelines. Both LFD and ASM inventory and operating ratings were computed using calibrated FE model simulations. The ratings so obtained are provided in Table 1. The governing rating is LFD at 187% legal load which is approximately 25% higher than the 150% load limit by which the structure is carried on the Ohio bridge inventory. The higher rating is attributable to several physical conditions existing in the real structure but which are not reflected in theoretical /analytical structural engineering calculations. Among these are a high degree of unintended composite action between the deck and girders and better than expected distribution factors. This situation is typical of many of the bridges UCII has field tested.

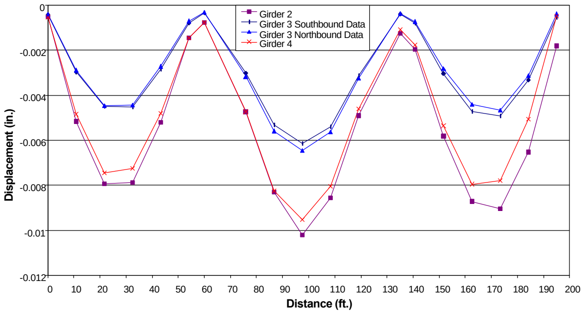

Figure 1 - Modal Test generated BGCI's

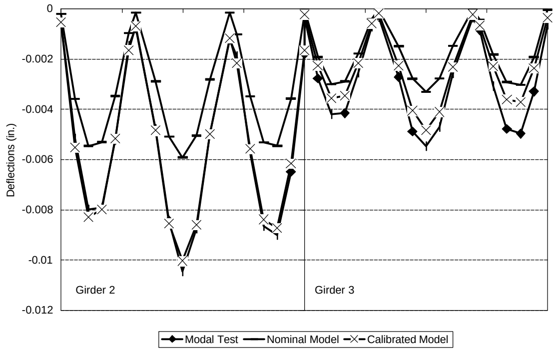

Figure 2 - Comparisons of Modal Test and FE Model BGCI's

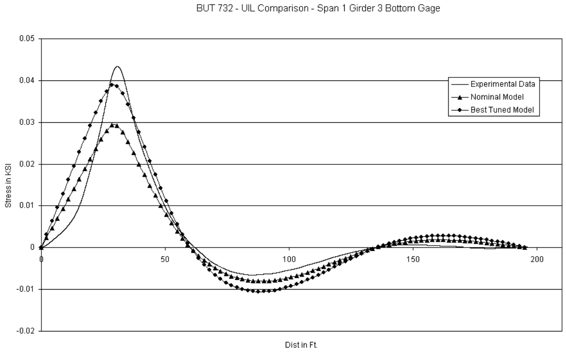

Figure 3 - Comparisons of Truckload Test and FE Model UIL's

Rating Method	Inventory Rating	Operating Rating
LFD	1.87	3.12
ASM	1.97	3.14

Table 1 – Field Test/Calibrated FE Model Based Ratings

Conclusions

This paper presents results from the application of a three-step process for assessing the structural condition of highway bridge using calibrated FE models The calibrated model is simulated to obtain the necessary live load responses for calculation of bridge ratings as per AASHTO guidelines. In addition, comparative studies of the baseline and calibrated models are used to identify regions on the structure where defects, damage, and/or deterioration may exist. This process has been established over the course of modeling and testing several dozen bridges in Ohio over the past 5 years. The results have been independently corroborated and complemented by comparison with controlled truckload testing conducted on the same structures where strains and/or displacements have been measured. The process has been optimized with respect to both the field test components and initial modeling/post-processing/calibration steps. At present, the combined initial modeling/post-processing/calibration steps can be performed in about a day. The results so obtained are more objective and less conservative that those obtained via either visual inspection or purely theoretical/analytically based calculations.

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