Field Testing and Analysis of 40 Steel Stringer Bridges

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INTRODUCTION

Research has shown that field testing, specifically multi-reference impact modal testing and crawl speed truckload testing, can be used to assess the structural state of health of highway bridges. Modal testing provides global structural information such as frequencies, mode shapes, flexibility, etc. Truckload testing provides detailed local information including unit influence lines, stresses, etc. The University of Cincinnati Infrastructure Institute (UCII) has more than a decade's worth of experience in these areas and in implementing these approaches in conjunction with calibrated finite element modeling in order to help identify and characterize structural damage and/or deterioration. This information has been used to help augment the current visual inspection techniques on a case-by-case basis.

A UCII research project, conducted under the auspices of the Ohio Department of Transportation (ODOT), is currently underway to field test 40 steel stringer bridges located throughout the state of Ohio. This paper is an overview of the outcomes from this research project. The 40 specimens have been selected specifically to mimic the statistical profile of the steel stringer bridge population within the state of Ohio's bridge inventory. Figure 1 shows a comparison between statistical profiles of ODOT's inventory and the 40 tested specimens based on various inventory parameters including year built, general appraisal, average daily truck traffic (ADTT) and skew angle. Figure 2 shows the geographic distribution for these bridges across the state of Ohio. The focus of this research project has been to establish a database of field test results together with nominal and calibrated finite element models for each bridge. Bridge load capacity ratings, obtained from field test data as well as FE models, were used as a measure of bridge health.

It is hoped that the results of this study will provide an objective idea of the state of health of a bridge population, shed light on the differences between as-designed, as-built, and in-service structures which will be of benefit to both bridge designers and transportation officials managing current bridge inventories.

UCII FIELD-TEST BASED RATING STRATEGY

The rating approach implemented by UCII incorporates field test data to provide results that are more objective than those obtained either by visual inspection or from theoretical/analytically based calculations. Figure 3 shows how field test operations/results are used to provide ratings. A nominal model is established based on details listed in the bridge plans, i.e., material properties, bridge dimensions, etc. This nominal model is used to design comprehensive test plans for both modal and truck-load tests.

Analysis of the preliminary 3D Finite Element (FE) model helps determine sensor layout and impact point locations to properly measure the dynamic characteristics of the bridge during modal testing. This is done to ensure that the global and local characteristics of the bridge's behavior are properly identified.

As with impact testing, the uncalibrated model is used to determine the maximum response locations for positive and negative moment so strain gages can be optimally installed during truck-load tests. Sensors are also located to measure how the applied load was distributed along longitudinal and transverse directions.

After test data has been collected from modal and truck tests, they are independently post-processed through a series of MATLAB scripts that have been developed by UCII. Modal test data is processed to extract natural frequencies, mode shapes, mass participations, and flexibility while truck test data is processed to extract stresses, moments, and axle unit influence lines (UILs). These parameters provide the necessary information for calibration of the 3D FE model. The calibration of the model is achieved by systematically varying parameters in the model input file to minimize the difference between the analytical and experimental quantities mentioned above[3]. Once the model has been calibrated to match the parameters (i.e. natural frequencies, mode shapes, UILs, etc.) measured from modal and truck-load test data, load ratings can be calculated. These ratings are based on the results of the calibrated model subjected to standard HS-20-44 truck and lane loadings per AASHTO guidelines[1].

CREATION OF NOMINAL MODEL

An FE model for a given concrete deck on steel girder bridge is created by the UCII Bridge Modeler software package. The Bridge Modeler software is a user friendly program designed to create a 3D FE model for various geometrically shaped bridges in minutes. The parameters from the bridge plans (span lengths, skew, girder type, etc) are entered into the Bridge Modeler software.

The software uses an accurate coordinate system, allowing consistent models to be created. The user has the ability to use different mesh sizes and number of frame elements. A graphics display shows how the bridge parameters change from the default values to the newly entered values. There are added error checks which, along with the graphics window, allow the user to check for errors before the model is created. The program outputs an ASCII text file that can be viewed and edited in SAP format if needed. This allows the user to create a FE model for a bridge without any knowledge of SAP2000. The 3D model will have the bridge superstructure along with the abutments and piers. The modeler software fixes one of the piers while allowing the others to move. The 3D model will have the nominal properties for that bridge as per the plans. The properties of the model used in the calibration process are the Bridge Girder Condition Indicator (BGCI), Modal Assurance Criterion (MAC), natural frequency, and Unit Influence Line (UIL)[6]. Figure 4 shows a typical 3 span bridge FE model created using the Bridge Modeler software.

The Bridge Modeler software is also used to create truckload cases for the model using AASHTO or user defined parameters. Post processing software is used to create the modal test load cases. These two types of load cases are added to the bridge FE model file. They simulate the loads added experimentally from the truckload testing and modal testing. They are used by the UCII Bridge Calibration software to accurately compare the nominal model for a bridge with the experimental data.

MODAL TEST STRATEGY, IMPLEMENTATION AND DATA PROCESSING:

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 frequency of each mode provides the proper frequency bandwidth for a given bridge. This knowledge is used to configure the bandwidth of the data acquisition system to ensure capture of all of the necessary modes. Modal participation factors are also considered to help configure the test layout since it is common for a few modes to dominate the response; therefore, it is crucial to properly identify these modes through proper selection of locations for both input excitations and sensors[12]. Although the specific bandwidth may vary from bridge to bridge, the highest frequency modes for our forty bridge specimens have been found to be less than 100 Hz with the critical modes of interest typically occurring in the frequency range of 2-25 Hz.

The deployment of a modal test can be conducted within a three to four hour period (including, setup, execution and teardown), thereby minimizing interruption to traffic flow[7,8]. After the data has been collected, it is post-processed within MATLAB to extract natural frequencies, mode shapes and flexibility. The results provided by the nominal model (e.g., mode shapes and natural frequencies) aid in processing modal data by providing a preliminary estimate of the frequency value and shape for the modes of the structure. Since it is common for a few modes to dominate the dynamic response of the bridge, a list of these critical modes provides a roadmap for processing. There is a degree of consistency between mode shapes and their corresponding influence on bridge behavior. A mode naming convention developed by UCII to systematically label the mode shapes identified from a modal test, or from an FE model, aided in establishing this relationship[15]. This correlation between a mode's shape and its contribution has been observed to be consistent over a wide range of bridge designs, i.e. varying span lengths, number of girders/spans, etc. The order of the mode shapes also follows a consistent pattern through the course of processing 40 bridges. After correlation of analytical and field data, these parameters are used, along with strain data obtained from truck testing, to calibrate the FE model[3]

TRUCKLOAD TEST STRATEGY, IMPEMENTATION, AND DATA PROCESSING

Load Rating is used to determine the structural performance of a highway bridge and its components that have deteriorated over a period of time. These ratings are generally conservative in nature. Truckload testing has thus been used to improve the ratings and to provide additional information that is required for evaluation.

Diagnostic load tests are used in the field. This involves exciting the test bridge by a load pattern which is generally the known weight of the truck and determining the effect on various components. Crawl speed tests are done so as to get continuous measurement of the load response for the entire traffic lane. The bridge is instrumented at worst case locations which are determined with the help of the preliminary 3D FE model of the bridge. Strain gages are installed at the top and bottom flange of the particular location. Though the access to the underside of the bridge girders provides a limitation to the installation of sensors, the plan is to maximize the number of sensors. Even with limited sensors, information regarding the distribution of applied load among the longitudinal girders and cross frames and the resulting deformations/forces in the bridge members is determined. These measured local responses are used as calibration data for the FE modeling to allow for simulation of critical behavior of various members.

Crawl-speed tests are conducted for each traffic lane. Field testing of the bridge can be completed within 5 hours including the installation of sensors, testing and teardown; thus, minimizing disruption to traffic. Strain values obtained from the field for all the instrumented locations are post-processed using MATLAB and Visual Basic. For each lane, Unit Influence Lines are obtained after the removal of unnecessary noise from the raw data. HS20 response is simulated for an HS20 truck weight by utilizing the corresponding Unit Influence Line response. Thus, the test truck need not necessarily be the design truck.

CALIBRATION

Calibration is an iterative process in which the nominal model of the bridge is changed to perform like the real world bridge. This process is done using the UCII Bridge Calibration program. The nominal FE model along with the experimental modal and truckload test data are entered into the program. The Bridge Calibration program utilizes the MATLAB and SAP2000 software packages in the calibration process. The Bridge Calibration software changes six different parameters, one at a time. The parameters changed and the order in which they are changed are the Area of the Support Links (A_{SL}) at model piers and abutments, Moment of Inertia of Support Links (I_{SL}) at model piers and abutments, Modulus of Elasticity of Concrete (E_C), Thickness of Deck (T_D), Modulus of Elasticity of Steel (E_S), and the Moment of Inertia of Rigid Links (I_{RL}) which connect the model's deck to the girder flange and simulate the effect of composite action. Each one of these parameters has a separate effect on the model's BGCI, MAC, natural frequencies, and UIL.

The Bridge Calibration software uses a global objective function (GOF) to compare the results for the errors between the experimental data and the changed, or calibrated, model. The GOF is comprised of four different objective functions representing the error between the calibrated model and the experimental test results. These four functions are BGCI (OF_{BGCI}), MAC (OF_{MAC}), Frequency (OF_{FREQ}), and UIL (OF_{UIL}). Each objective function is different and has a different magnitude. Therefore they are scaled by a weighting factor (w_i) in order to prevent one objective function from over shadowing the rest. This formula is shown in equation 1.

$$GOF = w_1 OF_{BGCI} + w_2 OF_{MAC} + w_3 OF_{FREQ} + w_4 OF_{UIL} \qquad (1)$$

The Bridge Calibration program calculates an initial GOF value. It then changes one of the parameters (A_{SL}, I_{SL}, etc) by a given step size, then compares the resulting GOF with the initial GOF. The calibration program will continue to change the parameter until the resulting GOF is smaller than the initial GOF. The parameters have interdependent properties. The Bridge Calibration software is an iterative process that uses a steepest descent gradient algorithm to determine a minimum value for the GOF. The Bridge Calibration software is run multiple times using decreasing step sizes in determining the minimum GOF value. The calibration process for a typical 3 span 4 girder bridge takes approximately one week to complete. The calibration program outputs the BGCI, MAC, natural frequencies, and UIL data for each iteration along with the parameter value. This allows the progress of the bridge calibration to be compared with the experimental data.

LOAD RATING

Load rating for the bridge members is done at both Inventory and Operational levels. Both the Allowable Stress method and Load Factor design are used to determine the ratings. The Rating Factor (RF) is based on the following equation:

$$RF = \frac{C - A_1 D}{A_2 L(1 + I)}$$

where RF is the rating factor, C is member capacity, D is dead load effect, L is live load effect, I is Impact factor, A_1 and A_2 are factors for dead and live load respectively. Rating has been done for both the Truck load and Lane load, where one design load is present in each lane. Load effect considered for rating is with respect to bending moment.

Moment capacities are evaluated using the Four Analysis methods[2]. The four methods are described respectively as Axial Force with Full Composite Action, No Axial Force with Full Composite Action, No Axial Force with Partial Composite Action and Axial Force with No Composite Action. There is always some unintended composite action present between the steel girders and the deck. But since the bridges tested were designed for no composite action, Rating Factors for no composite action by method 2 and method 3 are calculated as well.

HS20 response obtained for each lane is used in conjunction with the bridge plans to get rating factors and sectional properties at all the instrumented gages. Some of the important parameters obtained by the four analysis methods are the Rating Factors, Live load moments (both Truck load and Lane load), Remaining Composite Action (RCA), and the location of truck for worst-case effect. Rating Factor evaluated by non composite method 2 and method 3 give the lowest rating factors of all the methods and hence they are used for comparison among the different gages.

The bridge is also rated using the UILs and HS20 response obtained from the FE nominal and calibrated model. The rating procedure for the nominal and calibrated FE model uses the same dead load and dead load moments as the experiment rating procedure. Rating Factors greater than one indicate that the bridge has safe load carrying capacity whereas a rating factor less than one indicates that the bridge is in critical condition. The rating of the bridge is controlled by the member with the lowest rating factor.

A condition assessment process has been developed to streamline the Bridge Load Rating program and is written in MATLAB, Visual Basic and Excel in order to reduce post processing to about 2 days. Further, this evaluation of accurate objective condition indices gives detailed, localized information about the state of health of the bridge.

CASE STUDY – PRE-725-0800

The PRE-725-0800 bridge located in Preble County, OH was chosen as a case study to illustrate the process discussed above. It consists of three spans of length 56', 80', and 56'. It has a skew of 10° R.F, is 38' wide, and consists of 5 girders.

The preliminary FE model for this bridge indicated that all pertinent modes were located below 30 Hz. Based on this, a bandwidth of 50 Hz was chosen for the field testing. The test was implemented on girders 2, 3, and 4. The eastbound test measured girders 2 and 3, while the westbound test measured girders 3 and 4. Girder 3 was used for both tests in order to have a common girder to compare test data. Accelerometers were placed along the bridge at the girder-to-cross from connections and the support locations. The impact points where chosen based on the preliminary FE model to be at the mid spans. This ensures the excitation of any local modes.

For this bridge, 19 modes were identified from the eastbound and westbound test data. These modes were used to create the flexibility matrices and the resulting BGCI's for the tested girders 2, 3, and 4. The BGCI for these girders indicated the displacement was dominated by the 1st and 5th modes on each test.

The mode shapes, natural frequencies, BGCI, and truckload data was used in the calibration of the nominal FE model as discussed above. Figure 5 shows the experimental and calibrated FE model's BGCI. Figure 6 shows the experimental, nominal FE model, and calibrated FE model's UIL. These figures indicate a high correlation between the calibrated model and the experimental field test data.

The calibrated model was used in the calculation of the rating factor for the PRE-725-0800 bridge per AASHTO guidelines. The LFD and ASM inventory and operating ratings were calculated using the calibrated FE model. Table 1 shows these ratings. The LFD rating found is 186% legal load which is approximately 24% higher than the 150% load limit by which the structure is given on the Ohio bridge inventory. Figure 7 shows the distribution factors for the AASHTO ASD and LRFD, along with the nominal and calibrated FE model[14]. ~~(reference Omkar's ASNT paper here for details).~~ The distribution factors using ASD and LRFD as shown to be conservation when compared to the nominal and calibrated FE model. Figure 8 shows the HS20 rating calculated by using the BARS software package, experimental truckload test, nominal FE model, and calibrated FE model. As with the distribution factors and the ratings, the HS20 ratings found both experimentally and through the FE model tends to be less conservative then the analytical ratings. This has been the case with a number of the bridges tested by UCII. The difference in rating and distribution factors found by truckload testing and FE models to the factors and ratings found analytically by BARS and analytical/theoretical structural engineering calculations can be

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attributed to the conservation inherent in the codes. It can also be due to the fact that these methods do not account for damage and deterioration which can only to determined by field testing.

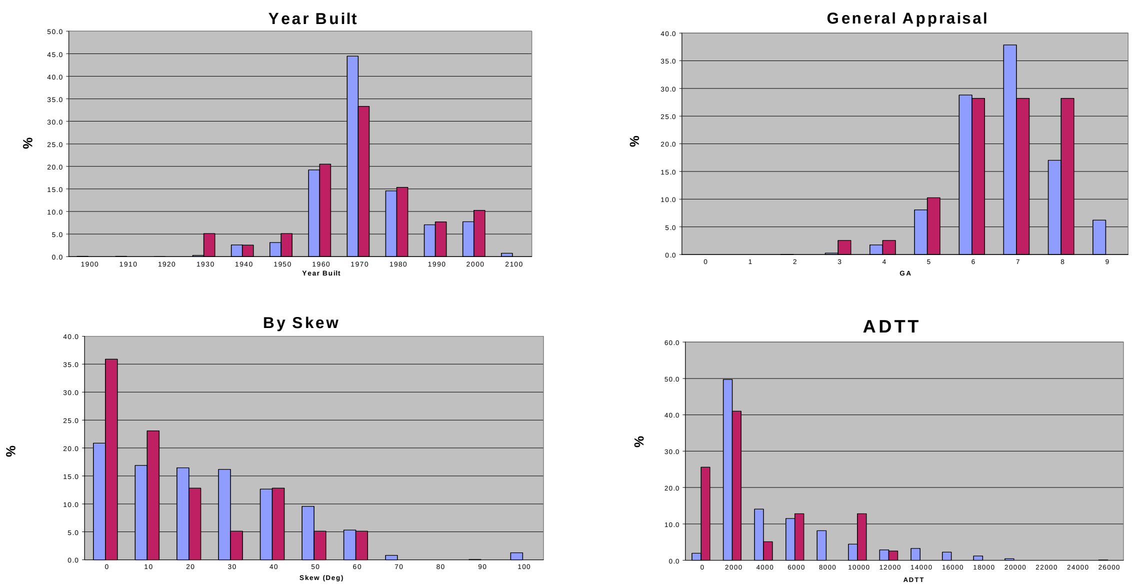

Figure 1: Comparison of Test Bridge vs. ODOT Inventory

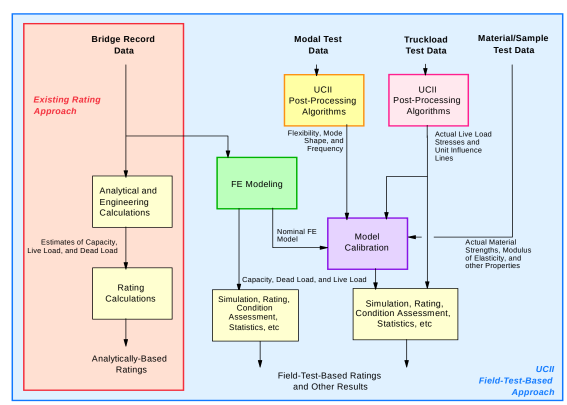

Figure 2: Ohio Bridge Distribution

Figure 3: UCII Field-Test-Based Rating Strategy

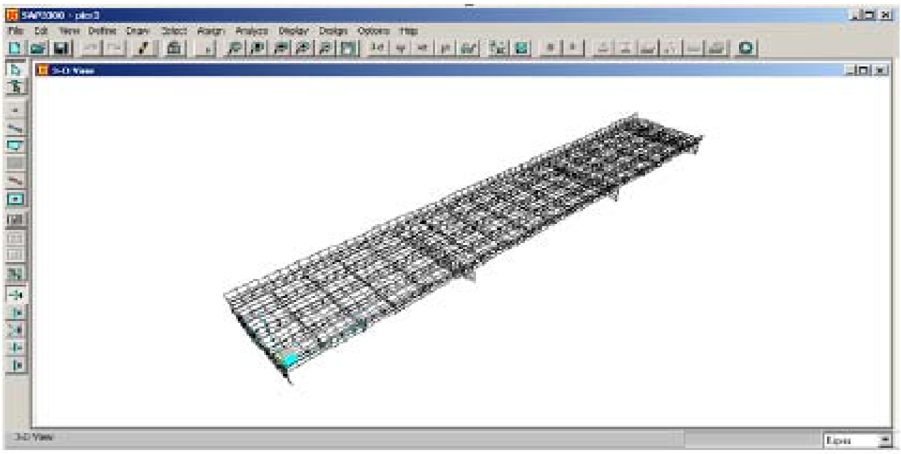

Figure 4: 3D FE Bridge Model in SAP2000

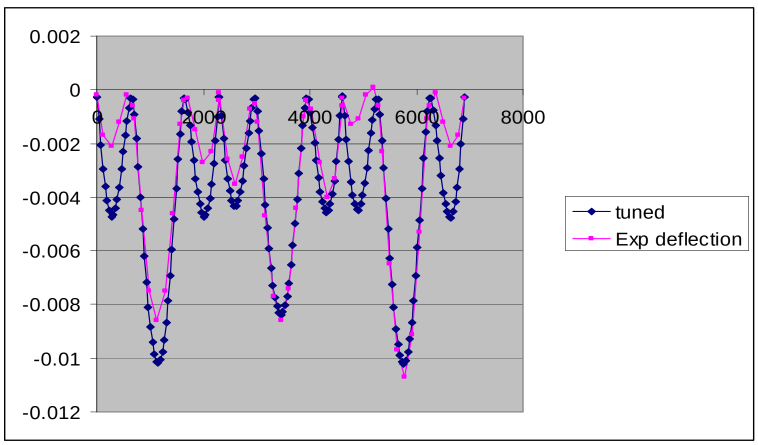

Figure 5: Comparison of Modal test and Calibrated BGCI

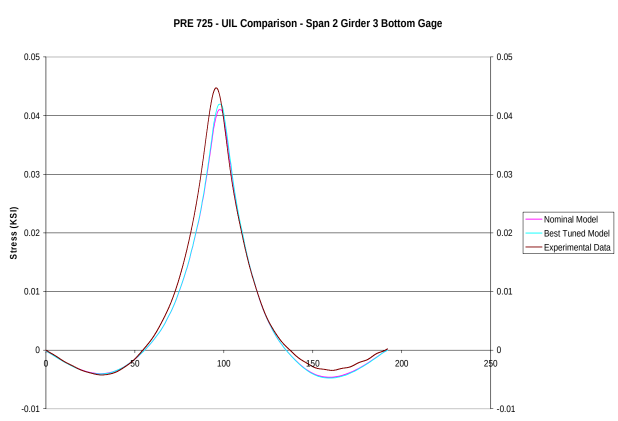

Figure 6: Comparisons of Truckload and FE Model UIL

Rating Method	Inventory Rating	Operational Rating
ASM	1.6	2.49
LFD	1.86	3.11

Table 1: Field Test/Calibrated FE Model Based Ratings

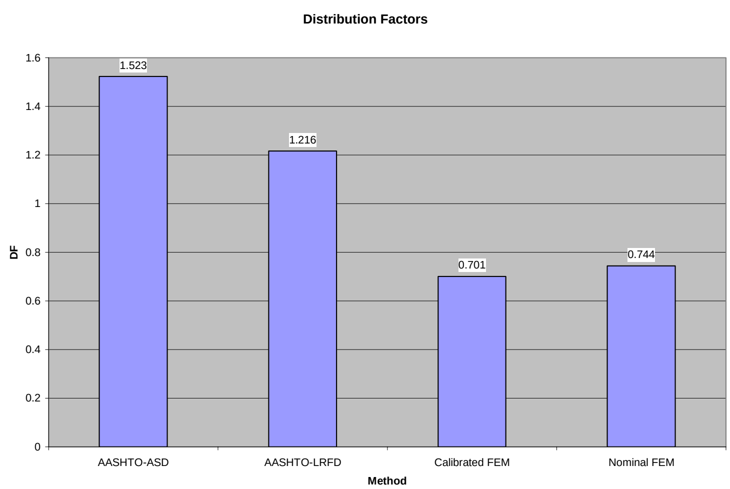

Figure 7: Comparison of Distribution Factors

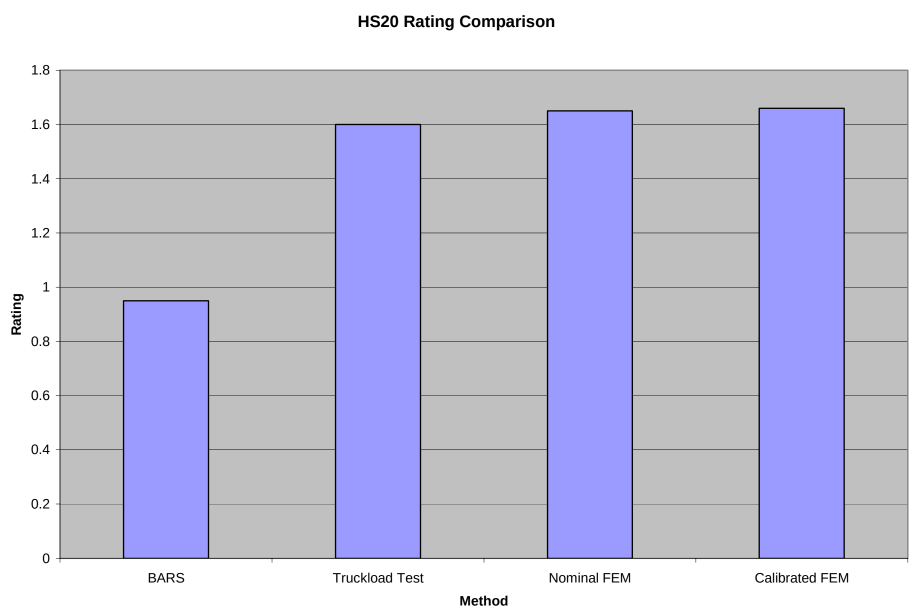

Figure 8: HS20 Rating Comparison

CONCLUSIONS

This paper presents an overview of the research done while testing and rating 40 bridges throughout the state of Ohio. These bridges statistically represent the total ODOT inventory of bridges. Through this research, bridges where found to contain certain modes. A naming convention was established along with the identification of critical modes that dominate the dynamic response of the bridge. Healthy and low rated bridges where tested. Testing the healthy bridges allowed baseline signatures to be established, that were then compared to the low rated bridges. The research led to development of a procedure for assessing the structural performance of highway bridges using FE models calibrated based on modal and truckload testing. The calibrated model is simulated to get the live load responses for rating the bridges as per the guidelines of AASHTO. Further, the comparison of nominal and calibrated models is used to determine the location of damage and/or deterioration on the structure. The results from the FE models have been independently verified and complemented by comparison with truckload testing on the bridge structure. The structural evaluation through field testing, calibration, and rating is more objective and the results have been found to be less conservative than obtained through visual inspection, theoretical, or analytically based ratings.

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