Fleet Health Monitoring of Large Populations: Aged Concrete T-Beam Bridges in Pennsylvania

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ABSTRACT

The importance of rational decision-making for optimum resource distribution of civil infrastructure systems (CIS) management is well recognized. Bridges, serving as node points of the highway transportation system, are critical components of the nation's infrastructure. As the nation's bridge population is aging, management decisions must be based on an objective, complete, accurate and compatible information for maximum reliable bridge lifecycle. For bridges sharing common materials, similar geometric design attributes and behavior mechanisms, fleet-strategies for health monitoring would offer significant advantages. Improvements from fleet health monitoring would lead to objective engineering knowledge for optimal decision making. This paper provides an overview of fleet health monitoring concept, then summarizes an on-going research on re-qualification of reinforced concrete T-beam bridge population in Pennsylvania.

Keywords: Constructed facilities, civil infrastructure systems, health-monitoring, fleet health monitoring, statistical sampling, T-beam bridges, visual inspection, NDT, load test, dynamic test, FEM, non-linear FEM

1. INTRODUCTION

As the nation's bridge population is aging and available funds for renewal are not increasing, it is becoming more important to objectively evaluate the bridge conditions. Bridge damage and deterioration have major impacts on the safety and serviceability of the critical nodes of the transportation network adversely affecting local, regional and national economy. As a result, there is a great research thrust for objective condition assessment, repair and renewal technologies, and non-destructive evaluation methods especially for aging bridges.

Bridge management requires careful evaluation of economical, ecological and social conditions in addition to operational and structural conditions. This paper focuses on how the information on bridge conditions may contribute to bridge management. The principal requirement of effective bridge management is the development and implementation of a comprehensive database that objectively describes the bridges and their conditions. In the National Bridge Inventory (NBI), there are approximately 600,000 bridges the conditions of which are described by subjective data acquired from biennial visual inspections. Clearly, this can lead to variations in the reliability of the overall management process. In addition, each bridge is considered as a unique structure although there might be a significant number of the bridges contained in this inventory with geometry, material, design and behavior similarities that are not effectively exploited in the management process. Improvements to the quality of the data contained in the NBI and improvements in the effectiveness and consistency of management can be accomplished by statistical analysis and grouping of similar structures or structural components, combined with practical and objective field-test data acquired through a "fleet health monitoring" strategy. The integration of information technology (IT) and geographic information systems (GIS) coupled with an improved database containing objective data on bridge conditions can be utilized to improve bridge operations and management decisions.

The writers are exploring how to implement fleet monitoring concepts for re-qualification of aged reinforced concrete bridges. This paper first overviews the fleet health monitoring concept and the use of emerging technologies for objective condition assessment. An overview of the issues related to fleet health monitoring is also provided, including a discussion on the relationship between the bridge inventory and fleet monitoring, and the resulting advantages for bridge engineering. Finally, experimental and analytical results from a recent bridge study that is part of the on-going re-qualification research of the aged reinforced concrete T-beam bridges in Pennsylvania are presented.
2. BRIDGE MANAGEMENT PRACTICE

2.1 Review of Current Practice

The National Bridge Inventory (NBI) contains 116 data fields for each bridge irrespective of the bridge type, importance and other possible distinctions. There are three data fields containing information for the structural condition rating, five data fields for the appraisal ratings as well as several fields for general attributes of a bridge. The structural condition is mainly evaluated through data from the biennial inspections that are conducted in accordance with the guidelines set forth in the National Bridge Inspection Standards (NBIS)\(^1,2\). The data contained in the NBI is updated on a regular basis. This data is stored in an ASCII format and the Manual\(^2\) explains the data fields. Since the inception of the NBI after 1970, it is in need of improvement especially with the recent advancements in information technology. Tools such as relational databases, GIS and web-based technologies can transform the NBI into a vehicle that will facilitate better and more objective analysis and synthesis of data and information for interpretation. Digital images would also enhance the information included in the database since available technologies currently permit transferring and linking of digital images to databases.

The limited amount of structural condition information in the NBI consists of subjective condition ratings based on visual inspection. The NBI contains five data fields for condition rating. Two of these fields are reserved for condition rating of culverts and channels/channel protection. The three remaining data-fields are used to rate the structural condition of primary bridge components including the deck, superstructure and substructure. Each data field contains a single digit code, which is described in the Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation’s Bridges\(^2\). The coding descriptions are relatively global in nature and subjective. A recent study\(^3\) by FHWA has indicated that at least 56% of the average Condition Ratings were incorrect with a 95% probability from visual inspections, the variations are a result of factors such as the inspectors experience, type of bridge, type of condition of the bridge. Therefore, evaluations based on visual inspections can provide significantly different results than evaluations based on objective methods such as load tests combined with FEM\(^4\) analysis. Here we note that there have been efforts by some states such as California for a more detailed element-level inspection recording\(^5\). It is desirable to make visual inspections and the procedure for recording conditions more rigorous, however the need for objective, experiment-based data to quantify bridge conditions remains unresolved.

2.2 Suggested Improvements

Additional research is needed for practical implementation of advanced engineering technologies for bridge condition assessment and incorporation of the findings into the NBI to improve the current bridge management practice. Some of the issues needing consideration are:

- Use of digital images for condition documentation, measurements and controlled experiments in the field.
- Analytical modeling and finite element analysis of representative sample populations to estimate structural capacities and failure modes that current over-idealized analysis approaches fail to simulate.
- Development of practical experimental tools and objective indices to relate experimental findings to structural condition parameters and performance indicators based on rational statistical correlations.
- Development and adoption of information technologies to help overcome the challenges in experimental and analytical evaluations. Also, use of information technologies and GIS for purposes such as image documentation, data archival, data collection, storage, retrieval, analysis and synthesis to assist bridge managers.

3. FLEET HEALTH MONITORING OF T-BEAM BRIDGES

Health monitoring\(^6\) utilizes various experimental and analytical tools to capture a structure’s existing condition. These tools have been effectively used for structural identification and development of field-calibrated models of long and short span bridges in the past\(^6\). Structural identification and fleet health monitoring of a statistically representative sample of bridges based on detailed experimental and analytical studies can objectively characterize the overall population of the deteriorated bridges.

Following a decade of research on health monitoring of steel stringer bridges, the writers have been investigating fleet health monitoring concepts for single span, T-beam bridges in Pennsylvania. A large number of existing Pennsylvania reinforced
concrete T-beam bridges are aged, deteriorated and posted because they are at or close to the end of their anticipated design life. It is well known that a typical T-beam bridge with sound abutments will provide capacity with longitudinal flexure and shear-flexure response as considered for the rating. In addition, the flexural response of the slab as a 2D plate in flexure and axial restraints from the abutment interfaces inducing axial compression are mechanisms that need to be incorporated in the analysis for objective rating of the bridges. Currently, the transversal direction is included by means of axle load distribution which underestimates the 2D plate contribution and may be very conservative for certain types of bridges. Also, material non-linearity of concrete and steel should be properly included in non-linear analysis for the actual capacity. For example, it is well known that cracking of concrete provides a very effective redistribution of stresses within a plate, and this effectively provides a much higher rating for yielding of steel rebars. The critical issue is to determine whether these mechanisms can be relied on each and every case. To answer these questions, evaluation of a statistical sample is proposed and the sampling is based on hypothesizing mechanisms and identifying parameters that would affect the actual capacity. Similarities in design, construction, age, and deterioration characteristics of the stock of T-beam bridges are used to develop representative sample groups for a bridge type-specific research program. In this manner, a representative stock of T-beam bridges are selected for combined experimental and analytical studies, leading to the development of experimental and analytical tools and technologies that would apply to the entire population of the T-beam bridges. The concept of statistical sampling for a large bridge population is also being implemented by other researchers to investigate the causes of microcracking deterioration in concrete due to formation of the mineral ettringite.

In order to determine the parameters for statistical sampling, the writers hypothesized that the load carrying capacity is a function of nominal structural and as-is condition parameters. The nominal structural parameters include those related to materials, geometry, detailing, substructure, and boundary conditions such that a detailed FE model may be constructed and analyzed for load rating based on the nominal design. The condition parameters include age, climate, location, maintenance, deterioration, damage, condition rating, and district engineers' input. It should be noted that some of these parameters might be dependent while some others may have less impact on the actual load carrying capacity of the bridges. Different parameters were analyzed to determine statistics, histograms, population characteristics and geographic distribution within the state of Pennsylvania. The majority of the T-beam bridges were constructed in the 1930s using a standard set of drawings. In the standard design drawings, the structural details and element dimensions are dependent on the span length and width of the bridges. For example, when a bridge with a certain geometry is selected, the beam sizes, reinforcements and all other details are automatically established. This greatly reduces the number of structural parameters.

As a result of the statistical analysis of the PA T-beam bridges, writers established a sample of 60 bridges that adequately represents the entire PA single span T-beam bridge population of 1,651. Please note that the total number of single span bridges in PA is 1,899 however the bridges with incomplete information were excluded from the statistical analysis. Writers hypothesize that the condition parameters and the nominal structural parameters can be correlated with the actual capacity rating for the bridges provided that undesirable brittle failure modes due to any deterioration of the superstructure or any deficiencies due to the substructures are eliminated. The characteristics of the sample 60 bridges and the overall population are presented in Figure 1. The distribution of the sample bridges within the state along with the overall population is shown in Figure 2. The sample 60 T-beam bridges are being visited for visual inspection and NDE studies. Out of the 60 bridges, 12 will be identified for a detailed system identification study. The detailed analysis includes linear and non-linear analytical modeling and simulations, and non-destructive experimental techniques. A rigorous system identification study of the selected 12 bridges will help determine the actual load capacity of the T-beam bridges. The following sections present an overview of field inspections, in-depth testing and analysis of one of the 12 bridges that was determined from the sample population.

4. EXAMPLE STUDY – MANOA BRIDGE

4.1 Visual Inspection and NDE Studies

The preliminary field studies, bridge visits and considerations included in the scope of the research project on fleet health monitoring are described in this section with an example from Manoa Bridge. Manoa Road Bridge, which was constructed in 1929, has a skew of 15 degrees, a span length of 32.80 ft and a width of 53 ft. It has 11 reinforced concrete T-beams that carry a 8.5 inches thick reinforced concrete deck (Figure 3).

This stage of the studies included the following:
• Collecting all documentation related to the bridge from District engineers
• Identifying test access and traffic control requirements
• Identification and checking of latitude and longitude information using GPS
• Visual inspection and documentation of the existing conditions
• Obtaining geometric measurements, surveying, photographs
• Obtaining concrete samples, and, rebar samples if possible
• Qualifying variation in the concrete properties by rebound hammer
• Comparing actual conditions with inventory rating or postings.

From the PennDOT archives, the results of the most recent inspection conducted in 1999 are found to assign a condition rating of 5 for deck condition, 4 for superstructure condition and 5 for substructure condition. In the Coding Guide for structural assessment, 5 is described as fair condition indicating that all primary structural elements are sound but may have minor section loss, cracking, spalling or scour. A condition rating of 4 is described as poor condition with advanced section loss, deterioration, spalling or scour. The bridge had spalling, concrete section loss, steel corrosion and section loss at varying levels at all beams except one as exemplified in the inset of Figure 3.

Although significant deterioration was observed at certain locations, the substructure was in relatively good shape, with no apparent settlement, scour or damage at the abutments. In addition, the boundary conditions and regions of the beams closer to the supports where shear demand is higher were in good shape for most of the beams. If shear failure can be ruled out, the flexure will then be the governing mechanism providing the critical capacity supply for the loading. From their past research, the writers have observed that the flexural capacity of the concrete bridges is generally higher than what is identified from idealized rating analysis.

4.2 Field Experimental Studies

Field testing is an essential technology in the condition evaluation of bridges however it is important to understand the policies and procedures relating to testing and evaluation of bridges. In this study, writers employ field experiments as a major component of the fleet health monitoring approach. The detailed field experimental studies mainly include load testing, modal testing, falling weight deflectometer (FWD) testing and local NDE applications. The results of the field experimentation are used for the calibration of the linear and non-linear finite element models of the bridge and structural identification of its as-is condition. Some of the objectives of the Manoa Bridge field studies are to investigate the following:

• Safety of a representative bridge against undesirable failure
• Maximum concrete and rebar strains (stresses)
• Bond between concrete and steel rebars
• Lateral distribution of the load between adjacent T-beams
• Arch action that provides an enhancement to flexural capacity
• Utilization of flexibility generated from dynamic impact test
• Use of FWD for possible bridge condition evaluation
• Use of test data for the calibration of Finite Element Models for load rating

An instrumentation plan (Figure 4) was designed for the load testing and dynamic testing of the Manoa Bridge. The concrete strains were measured at different locations with 7 clip gages mounted under the bridge. Five strain gages, which were microdot welded to the steel rebars, were used. Also, four displacement gages were employed for the deflection measurements. Strain and displacements gages were all installed underside of the bridge. To measure the dynamic response, 14 accelerometers were used and they were temporarily mounted on the bridge during the dynamic testing (Figure 4). Several loading configurations were designed with loaded trucks. PennDOT provided loaded trucks, FWD device and also assisted in providing traffic control during testing. A representative measurement under truck loadings from the midspan is shown in Figure 5. From the strain measurements, it was observed that the level of maximum concrete and steel strain is less than 45 microstrain under the loading of two trucks (65 kip-truck and 42 kip-truck together). The corresponding concrete stress levels are less than 250 psi. The steel stresses are less than 1400 psi, which corresponds to 4.2% of the 33 ksi yield steel reinforcements. In addition, the maximum deflection measured under two trucks is 0.032 in. The L/800 serviceability limit as defined in AASHTO is 0.04. Under two trucks with a total of 107 kips, the measurements indicated that the bridge could safely carry the legal loads although visual signs of significant deterioration exist at some T-beams and concrete deck. The mechanisms that contributed to the bridge stiffness are currently being investigated by means of analytical simulation and
experimental verification.

In addition, the impact modal tests were conducted to determine the dynamic properties of the bridge and the flexibility matrix of the measurement locations. Nine modes were determined within the 0-65 Hz band. The first three modal frequencies, shown in Figure 6, are 16.61 Hz, 19.74 Hz and 23.71 and the total mass-participation of these modes are almost 80% in the vertical direction. The first three modes were used for preliminary correlation and global calibration of the finite element model.

Flexibility coefficients at the deflection sensor locations were measured and calculated. In addition, writers conducted a FWD test in collaboration with the PennDOT engineers. At the mid-span of the bridge, the resulting flexibility coefficients that were generated from load test, impact test and FWD are within 4% to 7%. The result is promising in that a rapid test can be designed and conducted to determine the flexibility coefficients, which may relate to the load carrying capacity of the T-beam bridges.

4.3 Analytical Modeling Studies

An important component of the fleet health monitoring is developing linear and nonlinear finite element models. The models are calibrated using the current state characteristics of the bridges as determined from experimental data. The FEM of the Manoa Bridge was developed using shell and frame elements in SAP2000 element library. The number of shell and frame elements is 1,696 and 417, respectively. Shell elements were used for both the reinforced concrete deck and the T-beams. The total number of degrees of freedom is more than 12,000. Firstly, the preliminary model frequencies were compared with the experimental frequencies. The preliminary model frequencies were identified to be 10-20% different from the measurements. In order to match the model response to the experimental results, a parameter study was conducted. In addition, mechanisms such as parapets, sidewalks that were not intended to contribute to structural flexibility were included. The boundary conditions were investigated for possible lateral compression that can be simulated with lateral springs. The final model included parapets, sidewalks and more importantly longitudinal springs. This model was then correlated with the test results. The frequency comparison reveals better correlation (Figure 6). Deflection and strain measurements also give better correlation with the test data (Figure 7). The model matches reasonably with most of the measurements, although it should be noted that it is somewhat more flexible at midspan. Using the model, additional analyses were conducted by incorporating different levels of deterioration and damage. The damage simulations were based on partial beam damage and full beam damage where half and full depths of the T-beams are removed. These models were then employed to determine the rating of the bridge under damage scenarios.

In addition to linear models, non-linear models will be generated throughout the course of the project. These models will accurately simulate the 3D geometry of all of the critical regions and elements of the bridge as well as the critical mechanisms of load transfer and load distribution. The non-linear models are essential in predicting the ultimate load capacity and possible failure modes of the bridges.

4.4 Information Technology Studies for Fleet Health Monitoring

As mentioned earlier, the NBI is the means commonly used to access information related to bridges in the US. An integrated information system is envisioned for access to fleet monitoring data and information on the T-beam bridge population in Pennsylvania. The system will carry out various actions at several levels. Data collection, signal processing and signal analysis from selected bridges will be streamlined and carried out simultaneously with storage and archival of the processed data. The individual characteristics of each bridge and observations related to the current state and condition of the bridge will be accessible through an electronic map of the T-beam bridge locations.

The writers are investigating integration of this database with GIS. From this engine, pertinent engineering information can be obtained from the post-processed data. This GIS-based database engine will house the NBI data, field experimental test data and results, representative analytical models as well as the global to local level, detailed photo documentation of the bridges. This engine will be developed as a by-product of this research, which is expected to serve PennDOT engineers for operation, management and decision-making.
4.5 Rating Studies

The condition rating of T-beam bridges reveals the condition as it appears to the eye of the inspector. However as experienced as the inspector might be, it might not be possible to objectively predict the load capacity rating of the bridge. Even certain analytical models, which do not properly incorporate the actual condition and the mechanisms such as 2-way slab action and axial compression, underestimate the actual load capacity rating of the bridges.

The rating of a bridge based on calibrated finite element models will characterize the actual condition of the sample population. The rating of the Manoa Bridge was conducted using three different methods for demand calculation. It should be noted that several methods are possible for analytically computing the load demand. The first method used in this study is the standard method as given in AASHTO Standard Specifications for Highway Bridges\textsuperscript{12}. The second rating method is based on load test results as described in NCHRP Manual for Condition Evaluation of Bridges\textsuperscript{13}. Finally, the finite element model was used to determine the load demands for the rating calculation. Several damage simulations generated using the finite element model were also rated. The capacity computation is based on load factor methods as stated by the AASHTO Manual for Condition Evaluation of Bridges\textsuperscript{14}. The rating results are summarized in Table 1 for the different methods and condition simulations.

The damage simulations in column 6 represent the model that consisted of deteriorated beam depths. The deteriorated beams were determined from the visual inspection survey of the bridge. The full damage simulation in column 7 of Table 1 represents where all the beam depths are reduced to half. Contribution of stiffness by rebars is also eliminated at the reduced depth simulating full corrosion.

<table>
<thead>
<tr>
<th>AASHTO Load Factor Rating Method</th>
<th>BAR7 Analysis by PennDOT (HS20 Truck)</th>
<th>Standard AASHTO by Drexel (HS20 Truck)</th>
<th>Modified with Load Test (HS20 Truck)</th>
<th>FEM of the Calibrated Model (HS20 Truck)</th>
<th>FEM with Partial Damage (HS20 Truck)</th>
<th>FEM with Full Damage (HS20 Truck)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inventory Rating</td>
<td>0.96</td>
<td>0.92</td>
<td>4.99</td>
<td>3.77</td>
<td>3.59</td>
<td>1.69</td>
</tr>
<tr>
<td>Operating Rating</td>
<td>1.60</td>
<td>1.54</td>
<td>8.33</td>
<td>4.33</td>
<td>3.98</td>
<td>2.20</td>
</tr>
</tbody>
</table>

The rating results in columns 2 and 3 are based on standard AASHTO procedures, which are more conservative than the ratings based on load test and several FEM simulations. The rating results indicate that the bridge has far more capacity than anticipated even under the worst possible damage scenarios. At this point, it is important to determine which mechanisms contribute to the capacity of the bridge and whether these mechanisms are specific to this test bridge or will be observed consistently in the overall population.

5. CONCLUSIONS

In this paper, a review of the current bridge management practices is presented. In this context, the concept of fleet health monitoring of a representative statistical sample population is proposed and promises of the concept are summarized. It is clear that evaluating each of the nearly 600,000 bridges in the NBI as a unique structure requires time and funds that may not be available. Moreover, the condition of the bridges may be underestimated by conservative methods, which lead to unnecessary replacements, and requiring tremendous amounts of public funds. Even more important is the fact that structural reliability against collapse may vary widely between different bridge types, and this may not be properly incorporated in management decisions. Fleet health monitoring concepts can provide information that will help to improve current bridge management. The use of fleet health monitoring can be justified because large populations of bridges with similar attributes exist throughout the US. The proposed concepts are explored and refined in the current project on Pennsylvania’s aged,
reinforced concrete T-beam bridges. The paper presents an example application of the on-going study with the concrete T-beam bridges. The fleet health monitoring method could also be applied to fleets of other bridge types such as concrete slab, concrete arch bridges or reinforced concrete deck on steel stringer bridges for effective management of such large populations making up a large percentage of the entire stock.

Figure 1: Parameters for Statistical Sampling; a) Entire 1,651 T-Beam Bridge Population, b) Statistical Representative 60 T-Beam Bridges

Figure 2: Entire T-Beam Population & Statistically Representative 60 Bridges Distribution in Pennsylvania
Figure 3: Manoa Road Bridge

Figure 4: Instrumentation Plan for Manoa Bridge

Max deflection < L/800 = 0.04"

Figure 5: Displacement Measurements at Center
Figure 6: First Three Modes from FEM and Dynamic Test of the Manoa Bridge

Mode 1
f=16.93 Hz (FEM)
f=16.62 Hz (Test)

Mode 2
f=19.13 Hz (FEM)
f=19.77 Hz (Test)

Mode 3
f=21.18 Hz (FEM)
f=23.75 Hz (Test)

Figure 7: Measurement and FEM Results; a) Deflections Along Longitudinal Line, b) Strains Along Transverse Line
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