5 Bridge instrumentation and monitoring
Chapter 19

Modeling and instrumentation of the Tobin Memorial Bridge in Boston, Massachusetts, USA

B. Brenner
Fay, Spofford & Thorndike, LLC, Burlington, Massachusetts, USA

E. Santini-Bell & W. Durack
The University of New Hampshire, Durham, New Hampshire, USA

M. Sanayei & E. Pheifer
Tufts University, Medford, Massachusetts, USA

ABSTRACT: The Massachusetts Port Authority has contracted consultant services for the structural modeling and instrumentation of the Maurice J. Tobin Memorial Bridge. The consultant team, led by Fay, Spofford, & Thorndike, LLC, and supported by Tufts University, the University of New Hampshire, and Geocomp, Inc., began work on this project in the fall of 2008. This paper will present those representative analytical structural models, including several special studies focused on the rotational stiffness of the truss connections, boundary conditions, and built-up member properties. An instrumentation plan that included strain gages, accelerometers, tiltmeters, and temperature sensors was developed and deployed for the Little Mystic span of the Tobin Memorial Bridge during the winter of 2009. The collected data will be used to verify the analytical structural models. These models and instrumentation plans will be used as part of the structural health monitoring and condition assessment program for the management of the Tobin Memorial Bridge.

1 INTRODUCTION

The condition assessment of a bridge is traditionally carried out using subjective visual inspections and load ratings using guidelines set forth by the American Association of State Highway and Transportation Officials (AASHTO). Many states use PONTIS to manage the bridge inspection reports data and the regulations in the National Bridge Inventory Standards (NBIS) for inspection protocols. Bridge owners rely on the information obtained from visual inspections and load ratings for their decision-making purposes, both for repair or rehabilitation, as well as complete replacement.

Visual inspections currently serve as the primary means to evaluate the condition of virtually all highway bridges in the United States. The degree of deterioration in the structural components of the bridge is assigned a numerical rating from zero to nine, with zero being failed and nine being in excellent condition. The ratings are subjective to an extent, based in part on the experience and approach of the inspectors. Furthermore, visual inspections are, by definition, limited to what can be seen. Hidden structural members, or conditions that are difficult to directly view, may not receive the same level of inspection treatment (Farhey, 2005). The inspector’s expertise is required to evaluate the adequacy of the overall structural condition of the bridge.

In 2000, Brent Phares polled state and county DOTs as well as inspection contractors and found the most common form of nondestructive evaluation is through visual inspection (Phares, Rolander, Graybeal, & Washer, 2000). Visual inspections are typically scheduled every 24 months. Special inspections may be arranged at a more frequent interval to closely monitor any problem areas until issues are resolved by repair or replacement. This approach is adequate for most bridges under
normal conditions, but not if there is a damage-causing event such as impact or natural disaster between inspections.

Load ratings are performed using either the AASHTO allowable stress, load factor, or load and resistance factor rating methods. The purpose of load ratings is to determine the load capacity of an existing bridge. Development of a bridge’s load capacity indicates is a load limit should be imposed on the bridge, if special freight policies should be implemented, and to develop truck routes around congested urban areas. As with visual inspections, load ratings are another tool that bridge owners have become dependent on for decision-making purposes. Software is available to aid in the load rating process, including the AASHTO Bridge Analysis and Rating System that has been in use throughout the country since the early 1970’s. Advances in computing power and availability have provided a platform for consistently improving structural analysis and load rating software, including AASHTO’s new bridge load rating system named Virtis/Opis (Thompson et al. 2000).

1.1 Benefits of using modeling and instrumentation

Computer modeling of an existing bridge is an objective means of evaluating bridge condition. It can be used to supplement more subjective visual inspections. However, while the model seems to be more objective, errors in computer modeling of structural components can be significant. Errors include oversimplification of assumptions, uncertain boundary and continuity conditions, and unknown loading conditions. Instrumentation of the bridge with an array of sensors designed to capture structural responses of the bridge may be used to help validate the computer model.

The combination of a calibrated analytical model along with sensors to measure the structure’s response can be used to develop a structural health monitoring (SHM) system. This system can provide supplemental data for reporting on the condition of a structure. Economic benefits of such a system include the reduction of costs associated with routine maintenance and rehabilitation, an increased serviceable lifespan of the bridge, and more effective repair efforts. Structural components that show signs of deficiency in the computer model may not be easily accessed using traditional visual inspection. Components appearing to have damage may still have sufficient capacity to carry design loads. Objective assessment, in combination with subjective assessment, helps to direct limited maintenance funds to components in need of repair. Also, a calibrated structural model can be used for load rating and permitting.

Safety in the operation of the structure is enhanced by modeling and instrumentation. A structural health monitoring system may detect unusual structural behavior at an early stage, thereby reducing the risk of sudden and catastrophic failure. Appropriate monitoring requires the development of an accurate computer model that effectively characterizes the entire structure, including the continuity and boundary conditions.

1.2 Special studies of connections and boundary conditions

Special studies of connectivity and conditions are needed to develop a computer model that accurately characterizes a real structure. Examples of factors influential to computed structural responses include connection stiffness and boundary conditions. Appropriate input of these factors into the model can have a significant impact on the overall accuracy of the model. Performing special studies on influential components of the structural model can help to improve the accuracy of global and local structural models.

2 TOBIN MEMORIAL BRIDGE

2.1 History of the Tobin Bridge

The Maurice J. Tobin Memorial Bridge carries US Route 1 across the Mystic River to connect the city of Chelsea and the Charlestown section of Boston, Massachusetts. Construction on the bridge began in 1948 and was opened to traffic in 1950. The bridge was originally designed
and constructed under the direction of the Mystic River Bridge Authority, a quasi-government group charged with developing a suitable crossing over the Mystic River. The Mystic River Bridge Authority later became part of the Massachusetts Port Authority, who serves as the current owner and maintainer of the bridge. The Tobin Memorial Bridge is considered a critical link in the network of Boston area highways, connecting metropolitan Boston with business and residential areas to the north. The components that compose the approximately 2½ mile long structure include 32 approach spans on the Chelsea side, 36 approach spans on the Boston side, the Little Mystic Span, the Big Mystic Span, and the Toll Plaza. Figure 1 shows a 3D rendered view of the components of the Tobin Memorial Bridge with Boston in the background.

The Tobin Memorial Bridge consists of three northbound lanes on the lower level of the structure and three southbound lanes on the upper level. The Big Mystic Span, also referred to as the Main Span, is a three-span cantilevered steel through-truss measuring approximately 1,525 feet in length. The Little Mystic Span is a simply supported Warren truss approximately 439 feet in length. Figures 2–3 are photographs of the Big Mystic Span and the Little Mystic Span. Truss
members in the Big Mystic Span and the Little Mystic Span are mostly built-up steel sections that are bolted and riveted to steel gusset plates.

2.2 Project for structural modeling

The Massachusetts Port Authority (Massport) sent out a Request for Qualifications early in 2008 seeking structural modeling and analysis of selected components of the Tobin Memorial Bridge. The winning consultant was to provide finite element (FE) modeling of the selected components, with the goal of helping improve future capital projects. The scope of work included review of existing construction documents, creation of computer models of selected bridge spans and components, development of a cost effective instrumentation plan, and verification and adjustment of the model based on the measured data.

Massport contracted the consultant services of a team led by Fay, Spofford, & Thorndike, LLC, and supported by Tufts University, the University of New Hampshire, and Geocomp, Inc.

2.3 The complexity of maintaining the Tobin Memorial Bridge

A bridge as complex as the Tobin Memorial Bridge requires a rigorous maintenance program that could benefit significantly from the implementation of a Structural Health Monitoring system. Maintenance of the bridge is complicated not only by the length of the structure, but also by challenges of access for physical inspection and by the large number of built-up steel sections and rivets in the structure. The bridge will be modeled and instrumented to help improve the maintenance program.

3 DEVELOPMENT OF COMPUTER MODELS

3.1 More than just “stick” models

To improve maintenance on the Tobin Memorial Bridge and address various concerns about the performance of the structure, a structural health monitoring system (SHM) is being implemented. The development of a “baseline” finite element (FE) model that accurately represents the geometry and structural parameters of the structure is the first step in the SHM process.

Selected components of the Tobin Bridge have been developed as AutoCAD “stick” models, or three-dimensional line models, using the original construction documents. Figure 4 shows the AutoCAD “stick” model of the Big Mystic Span. Each structural element is represented by at least one line element in the model. Every crossbeam, stringer, truss member, floorbeam, sway frame,
diaphragm, and bracing member is included in what is called a microscopic-level model. Previous research (Catbas et al. 2007) on a bridge similar to the Big Mystic Span demonstrated that a microscopic-level model could predict the structural responses of a non-destructive test with reasonable accuracy. Modeling at a highly detailed level eliminates many assumptions about the effective behavior of structural elements, which are assumptions typically made in a smeared modeling approach. Smoother modeling employs an approach combining a number of structural elements into a few finite elements with effective properties; microscopic-level modeling involves a geometrically complex model but the calculations and assumptions of effective properties do not need to be made.

The commercial finite element analysis programs SAP2000 and GTStrudl were chosen for this project. Both programs were readily available to the authors and can easily generate structural analysis models through their Application Programming Interface (SAP2000) and Text File Input (GTStrudl).

Creation of FE models from AutoCAD models is accomplished using a three step process shown in Figure 5.

The geometric “stick” models are transferred to an Excel spreadsheet using the AutoLISP programming language. Imported geometry is named and assigned important numerical inputs in the spreadsheet including material and section properties, connection stiffness, and loading conditions. Visual Basic routines create the FE models directly from the spreadsheet data.

Standard 3D frame elements compose the steel members of the FE models. Shear deformation is assumed to be negligible (Timoshenko and Young 1935). The concrete deck is represented as a mesh of shell elements with a specified thickness. Figure 6 shows the frame and shell elements that compose the SAP2000 model of the Little Mystic Span.

Frame elements were chosen over truss elements because they have six degrees of freedom at each node. The three rotational degrees of freedom in frame elements allow for proper characterization of the rotational stiffness of the connections.

3.2 Connections

Truss design typically assumes that the members are connected by frictionless pins and are free to rotate. Forces are assumed to be present only in the axial direction of connecting members.
However, the assumption that joints are free to rotate is inaccurate. Friction will always be present at the connections. Secondary stresses, due to shears, moments, and torsion, build up in the members due to the rigidity of the connections. In the case of the Tobin Bridge, truss members are connected by large, riveted gusset plates, probably leading to introduction of secondary stresses in the members.

Secondary stresses have been long considered in the design of truss bridges. In 1877, the polytechnic school in Munich offered a prize for the solution of how to calculate secondary stresses in a riveted truss. Heinrich Manderla proposed a method to calculate secondary stresses that won the prize (Manderla 1880). Manderla’s solution, along with other approximate methods proposed by various German professors, provide a way for engineers to calculate secondary stresses. These calculations require an extensive amount of time. It is interesting to note, however, that the study of secondary stresses in riveted trusses all but disappeared from research after the late 1930s.

Advancements in technology and computing power have improved the engineer’s ability to calculate secondary stresses and include these effects in the structural model. GTStrudl® and SAP2000® allow connection stiffness to be specified for each member. The connections can be modeled as fully-fixed, fully-pinned, a set of linear translational and rotational spring or a fully-populated stiffness and mass matrix, which could include off-diagonal terms that account the interaction between degrees of freedom. A study of the Little Mystic Span of the Tobin Memorial Bridge revealed that secondary stresses for a fully-fixed model were significant compared to primary stresses as shown in Table 1. The analysis was performed using two load cases: two HS-20 trucks on each deck at

### Table 1. Comparison of primary and secondary stresses and strains for the Little Mystic Span SAP2000 model.

<table>
<thead>
<tr>
<th>Member</th>
<th>Axial stress (ksi)</th>
<th>Bending stress (ksi)</th>
<th>Total stress (ksi)</th>
<th>Axial strain (με)</th>
<th>Bending strain (με)</th>
<th>Total strain (με)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L5L6</td>
<td>0.92</td>
<td>0.78</td>
<td>1.71</td>
<td>31.80</td>
<td>27.00</td>
<td>58.80</td>
</tr>
<tr>
<td>U5U6</td>
<td>−1.19</td>
<td>0.36</td>
<td>−0.83</td>
<td>−41.10</td>
<td>12.50</td>
<td>−28.60</td>
</tr>
<tr>
<td>L0U1</td>
<td>−0.67</td>
<td>0.26</td>
<td>−0.41</td>
<td>−23.20</td>
<td>8.96</td>
<td>−14.24</td>
</tr>
<tr>
<td>L1M1</td>
<td>0.02</td>
<td>−1.26</td>
<td>−1.24</td>
<td>0.69</td>
<td>−43.40</td>
<td>−42.71</td>
</tr>
<tr>
<td>U1L2</td>
<td>0.90</td>
<td>−0.09</td>
<td>0.81</td>
<td>31.20</td>
<td>−3.13</td>
<td>28.07</td>
</tr>
<tr>
<td>L0L1</td>
<td>0.30</td>
<td>0.05</td>
<td>0.35</td>
<td>10.20</td>
<td>1.67</td>
<td>11.87</td>
</tr>
<tr>
<td>L1L2</td>
<td>0.20</td>
<td>0.29</td>
<td>0.49</td>
<td>6.79</td>
<td>9.80</td>
<td>16.59</td>
</tr>
<tr>
<td>L0U1</td>
<td>−0.32</td>
<td>0.10</td>
<td>−0.22</td>
<td>−11.00</td>
<td>3.52</td>
<td>−7.48</td>
</tr>
<tr>
<td>L0M0</td>
<td>−2.69</td>
<td>2.21</td>
<td>−0.48</td>
<td>−92.80</td>
<td>76.30</td>
<td>−16.50</td>
</tr>
<tr>
<td>L1M1</td>
<td>−0.01</td>
<td>−0.86</td>
<td>−0.87</td>
<td>−0.09</td>
<td>−29.70</td>
<td>−29.79</td>
</tr>
<tr>
<td>N1U1</td>
<td>0.44</td>
<td>−0.19</td>
<td>0.25</td>
<td>15.20</td>
<td>−6.70</td>
<td>8.50</td>
</tr>
</tbody>
</table>
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the midspan and at the supports (Member designations are based on the grid shown in Figure 7). Books on the subject of secondary stresses contend that differences in primary stresses between the cases of fully-fixed and fully-pinned can be neglected for practical purposes (Grimm 1908). The SAP2000 analysis confirmed that primary stresses do not vary significantly between the fully-fixed and fully-pinned assumptions.

Characterizing the actual fixity of the connections is a complex process. Analytical studies of connections performed at the University of New Hampshire (UNH) will provide appropriate connection stiffness inputs to the baseline global FE model. The UNH researchers are currently creating detailed FE models of the typical connections on the Little Mystic Span of the Tobin Bridge. FE models of the connections are being created in SAP2000® to analyze the rigidity of the connections. Figure 8 shows a SAP2000® model of a typical L1 connection for the Little Mystic Span. Parameter estimation algorithms will be used to populate the stiffness matrix to represent the connection in the overall model of the Little Mystic Span. (Santini-Bell et al. 2008).

3.3 Built-up members

The computer models are further complicated by the complexity of the steel members. Members are built-up sections consisting of plates and angles riveted together. Hand calculations and

![Figure 7. Joint and member naming convention for the Little Mystic Span model.](image1)

![Figure 8. SAP2000 model of typical L1 connection for the Little Mystic Span.](image2)
AutoCAD drawings of member sections were used to calculate section properties. Figure 9 shows an example cross-section of a built-up steel member.

Section properties were calculated based on the original design drawings. All of the steel in the model is assumed to have a modulus of elasticity of 29,000 ksi.

3.4 Piers

An important consideration in the modeling of any structure is how to represent the boundary conditions. This project will also model the support piers and calculate the support that they provide to the superstructures. This support will be compared with the typical pinned or fixed assumption.

4 INSTRUMENTATION

To calibrate and verify the FE model, selected components of the Tobin Memorial Bridge will be instrumented and non-destructive testing will be performed. Instrumentation used to capture the structural responses of the bridge will include strain gages, tilt meters, temperature sensors, accelerometers, and weather stations. Data will be collected by data loggers at various locations on the bridge and will then be streamed wirelessly to Geocomp, Inc. Post-processing of the data will provide strains and stresses in the actual structure that will be compared to the outputs of the FE model. The model will then be calibrated to reflect the measured data. Once the FE models is verified that it mimics the actual structural responses of the Tobin Memorial Bridge, the model eventually will be incorporated into the structural health monitoring and condition assessment program for the Tobin Bridge.

4.1 Little Mystic Span

An instrumentation plan has been developed, and is beginning to be implemented, for the Little Mystic Span. Table 2 gives types and quantities of instruments that will be utilized on the Little Mystic Span.

<table>
<thead>
<tr>
<th>Instrument type</th>
<th>Number of instruments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strain Gage—Member</td>
<td>80</td>
</tr>
<tr>
<td>Strain Gage Rosettes—Connection</td>
<td>12</td>
</tr>
<tr>
<td>Tiltmeters w/Temperature sensor</td>
<td>2</td>
</tr>
<tr>
<td>Accelerometers</td>
<td>6</td>
</tr>
<tr>
<td>Weather station</td>
<td>1</td>
</tr>
<tr>
<td>Temperature sensors</td>
<td>6</td>
</tr>
</tbody>
</table>

Figure 9. Built-up steel member cross-section.
Installation of instrumentation began with setting up the data loggers along the railing of the east side of the Little Mystic Span as shown in Figure 10. Geocomp, Inc. will be able to confirm that the sensors are functioning as they install them on the structure by plugging them into the loggers. Installing the loggers first is advisable to facilitate sensor calibration as they are installed.

5 CONCLUSIONS

A team of engineers and researchers is participating on a unique project to model and help evaluate the Tobin Bridge, the longest bridge in the Commonwealth of Massachusetts. The project has been authorized by the Massachusetts Port Authority to assist in maintenance and rehabilitation of the complex bridge structure. To date, the team has developed a group of three dimensional geometric and structural finite element models representing sections of the bridge. The combination of a global structural model that captures geometry of the truss member, floor beams, deck elements and diagonals with several detailed special studies finite element models will increase the potential use of this model and its ability to reflect the actual behavior of the Tobin Bridge. These special study models will focus on the connections and boundary conditions that are typical assumed to function as a pin or fixed connections in conventional structural modeling.

An instrumentation program has been developed for the Little Mystic Truss span to verify the model and eventually to be used as part of a Structural Health Monitoring System. The instrumentation plan was developed with input from the researchers, bridges designers, instrumentation specialist and bridge managers and owners. The inclusion of all parties related to the Tobin Bridge will help to insure the success of this project. Work proceeds on refining the modeling and developing instrumentation programs for other parts of the bridge. Thanks to this forward-looking project, it is envisioned that the Massachusetts Port Authority, the owner and manager of the Tobin Bridge, will be able to make use of the model to monitor the health of the bridge over time.
Bridge instrumentation and monitoring

Bridge, eventually will have a functional Structural Health Monitoring system that will greatly aid in maintenance of the Tobin Bridge.

REFERENCES


