Global Testing Application Scenarios

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Load Testing for Rating

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Overview of Current Load Testing Guidance (AASHTO MBE)

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Reinforced Concrete Multi-Girder Bridge Case Study

Reinforced Concrete Multi-Girder Bridge Case Study

# Global Testing Scenarios

## Load Testing for Rating – Link to Sections Below

### Bridge that Do Not Rate Using Conventional Approaches

### Bridges with Unknown Details

### Bridges Subjected to Super-Loads

AASHTO Manual for Bridge Evaluation guides the inspection, analysis and calculations for determining load rating and for reviewing overload permit applications (AASHTO 2011). Load ratings in conjunction with inspection findings are expected to assist in determining a need for posting, strengthening or closure of a bridge. Load rating may be based on approximate or refined methods of analysis unless load testing is leveraged. In an approximate method of analysis, the bridge is modeled as a line-girder, with its share of loading assigned based on the distribution factors used in design. In the case of refined analysis, the stiffness of each element of a bridge needs to be explicitly represented in an analytical model, and finite element modeling (FEM) has become quite common. It is well known that a FEM will require many assumptions regarding the geometry, materials, boundary and continuity conditions of a bridge, and analysis results may further vary significantly (25%-50%) depending on the FEM selection, mesh size and configuration. Obviously, without an analysis model that reflects the as-is dimensions, conditions, movement systems, continuity and supports, the results of load rating analyses may have unacceptable levels of uncertainty.

The 2013 National Bridge Inventory (NBI) included 609438 bridges and culverts with a span greater than 20 ft. Of those structures, 131200 bridges (21.5% of the NBI) were indicated as structurally deficient or functionally obsolete. Furthermore, more than a half of the inventory corresponds to local bridges owned by Cities, Townships and Counties, of which 24% are structurally deficient or functionally obsolete, making up a large proportion of the structurally deficient bridges. One of the reasons a bridge may be considered structurally deficient is posting. As of 2013, over 10% of this nation’s bridges and culverts are posted for less than their legal load (FHWA, U.S., Department of Transportation 2014). Amongst many reasons for posting a highway bridge, a common one is a perceived loss of bridge capacity due to deterioration and damage. Another is missing documentation and unknown properties. For example, as of 2012, 36,076 bridges over waterways are identified as having an unknown foundation problem (Olson, Jalinoos and Aouad n.d.).

While the safety of our nation’s infrastructure is paramount, its mobility is also necessary for a thriving economy. Given the funding challenges faced by bridge owners, it behooves us to ensure that bridges are safely and accurately load rated and not unnecessarily posted. However, according to Hearn (2014), load testing for rating has been performed only on 464 bridges. The implication is that many owners are not currently convinced of the reliability or the benefits of a reliable and accurate load rating by testing, especially given the associated cost. Indeed, a safe and reliable load testing requires equipment, time and expertise that demand a substantial price, especially when the user costs due to disruption of operations are included. Furthermore, there is currently a lack of guidance for safely performing a load test and for load rating of bridges with unknown properties and/or foundations.

Section 8 of the AASHTO Manual for Bridge Evaluation (2011) provides guidance for load testing as an alternative evaluation methodology to analytically computing the load rating of a bridge. This Manual indicates two types of load tests available for bridge evaluation: *“diagnostic tests and proof tests. Bridges for which analytical methods of strength evaluation may significantly underestimate the actual strength are considered candidates for diagnostic load testing. Thus, candidate bridges are limited to those bridges for which an analytical rating model can be developed. Proof tests are used to establish the maximum safe load capacity of a bridge, where bridge behavior is within the linear-elastic range.”*

For proof tests, the Manual indicates that *“a bridge is subjected to specific loads, and observations are made to determine if the bridge carries these loads without damage. The proof test is terminated when: (a) a predetermined maximum load has been reached, or (b) the bridge exhibits the onset of nonlinear behavior or other visible signs of distress. Proof load testing of “known” bridges is called for when the calculated load ratings are low and the field testing may provide higher ratings. A second scenario is in the case of “hidden” bridges that cannot be load rated analytically because of insufficient information on their internal details and configuration. Bridges that are difficult to model analytically because of uncertainties associated with their construction and the effectiveness of repairs are potential candidates and beneficiaries of proof load testing.”*

## Deterioration Suspected to Arise from Structural Responses – Link to IBS

## Excessive Vibration – Link to I-76

# Overview of Current Load Testing Guidance

## Diagnostic-Level Load Testing

## Proof-Level Load Testing

# Concerns Regarding Current Load Testing Recommendations

## Implicit Inclusion of Uncertain Mechanisms

## Uncertain Location of Maximum Responses

## Safety Concerns during Proof-Level Tests

Section 8 of the AASHTO Manual for Bridge Evaluation (2011) provides guidance for load testing as an alternative to computing the load rating of a bridge solely by analytical methods. This Manual indicates two types of load tests available for bridge evaluation: *“diagnostic tests and proof tests. Bridges for which analytical methods of strength evaluation may significantly underestimate the actual strength are considered candidates for diagnostic load testing. Proof tests are used to establish the maximum safe load capacity of a bridge, where bridge behavior is within the linear-elastic range.”*

For proof tests, the Manual indicates that *“a bridge is subjected to specific loads, and observations are made to determine if the bridge carries these loads without damage. The proof test is terminated when: (a) a predetermined maximum load has been reached, or (b) the bridge exhibits the onset of nonlinear behavior or other visible signs of distress.”* It is envisioned that the proof load will correspond to a live load that will bring the bridge to a rating of 1. To provide the same level of safety inherent in LRFD, the live-load is increased by factor of typically 40%-55%. Proof load testing of bridges is called for when the calculated load ratings are low and the field testing may provide higher ratings. A second scenario is in the case of bridges that cannot be load rated analytically because some of the details or configurations are not documented and cannot be accessed for direct measurement and appraisal (e.g. undocumented components encased in concrete).

The proof load testing procedures described by the Manual implicitly disregard the temporal changes in capacity of the bridge system, assuming that capacity will remain constant. This, however, is extremely misleading. Even if a bridge may pass a proof-load test one day, it may fail under a lesser load at a later date. Not all mechanisms that contribute to load distribution and/or enhance the capacity of the structure will remain constant through all seasons and certainly not throughout the life-cycle of a bridge. Furthermore, bridge owners may wish to deliberately exclude some mechanisms. AASHTO guidelines specify that the effects of the barriers are not to be included. The contribution of certain elements or mechanisms to load rating cannot be discounted or excluded unless they are accurately quantified. The results from a load test alone (often just beam flexural strain responses) are insufficient for achieving this.

The bridge shown in Figures 1 and 2 was rated based on the measured bridge response (i.e. all mechanisms included). This rating (first column of Table 3) shows that the bridge offers nearly ten times the rating factor for a “design truck”, but provides no guarantee of that capacity at a future date. To provide a more conservative rating that is representative of the structure when some mechanisms become ineffective, a field-calibrated FE model was employed. Those parameters that were influential or to the load rating and uncertain or may lose effectiveness over time updated.

Table 3: Effect of Removing Unreliable or Unwanted Mechanisms on Load Rating

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Rating | Inventory | 9.10 | 4.49 | 2.17 | 1.76 |
| Operating | 11.79 | 5.82 | 2.81 | 2.28 |
| Mechanisms Included | Rotational Stiffness |  |  |  |  |
| Encasement |  |  |  |  |
| Barriers & Sidewalks |  |  |  |  |

Because the structure has integral abutments and piers, the boundary conditions exhibited considerable rotational stiffness. Over time, concrete cracking and changing earth pressures could cause that stiffness to diminish. Therefore, the rotational stiffness was removed from the model. Furthermore, the bridge owners did not wish to rely on the capacity provided by the concrete encasement, so the stiffness and load capacity provided by the encasement was also removed. Finally, as per AASHTO guidelines, contributions by the barriers and sidewalks were discounted. The final rating (last column) is much less than that directly obtained from test results, but comes with a level of confidence that this structure will maintain adequate capacity well into the future.

As it has been shown for this particular bridge, many others should be expected to possess a number of influential and yet uncertain mechanisms, some of may be ill-advised to include in load rating. Given that load distribution and capacity mechanisms may significantly vary between different types of bridges, load rating results from this particular bridge cannot be simply extrapolated to other structures (i.e. same increase in load rating of FEM over a single line girder model).

The AASHTO Manual indicates that *“during a proof load test, the loads must be incremented and the response measured until the desired load is reached or until the test is stopped if the bridge response exhibits the start of nonlinear behavior or other visible signs of distress.”* It is envisioned that the proof load will correspond to a live load that will bring the bridge to a rating of 1. To provide the same level of safety inherent in LRFD, the live-load is increased by factor of typically 40%-55%.

The concept of proof-load testing guiding the Manual appears to be the same one that was followed in ancient Rome – if the bridges safely carried the proof-level live load, it should remain safe under future applications of that load. This, however, is extremely misleading since even if a bridge may pass a proof-load test one day it may fail under a lesser load at a later day. Destructive testing of decommissioned concrete or steel bridges to failure have revealed bridge capacities 10-20 times that of a rating truck, governed by many mechanisms that are activated at various load levels, some of which may even make the bridge appear stiffer. However, the failure modes of aged and deteriorated bridges were all controlled by deterioration and damage, and failures were triggered through highly unusual and unexpected behaviors and mechanisms.

It follows that performing a safe proof-load testing of a bridge, especially one with unknown characteristics, requires a much greater understanding of a bridge than envisioning it as a line-girder. A test strategy should be developed based on analytical modeling and simulation of the actual 3D geometry, together with all of the mechanisms that may govern the primary and secondary load transfer paths, and how any of the local member or connection details may affect these mechanisms. The kinematics of the bridge under various load levels will drive the instrumentation. Unless a bridge is carefully modeled for simulating its behavior under realistic proof-level loads – typically much greater than just 1.5 times a rating vehicle – to explore under which load level the bridge may change its load resisting mechanisms and all probable failure mode(s), a proof-load test should not be recommended. It is critical to identify the mechanisms that contribute to a structure’s capacity in order to properly and safely design the load increments, load positions, the instrumentation, data acquisition, communication and visualization. Without a real-time feedback and visualization of critical bridge responses under load, safety may not be assured.

The capacity of a bridge is ultimately the capacity of the system, including the approaches, superstructure, substructure, foundations, soil and other attributes of the site. If load testing focuses only on the superstructure at one instant of time, and the uncertainty associated with all the other elements of the bridge system is ignored, a proof-level load test should not be advised for load rating. Structural identification (St-Id) concept provides the framework for capturing and considering these effects by integrating engineering heuristics and historical data.

# Overview of Best Practices Load Testing Procedure

## Structural Identification – A Guiding Framework

The term structural identification (St-Id) is an adaptation of the system identification concept from systems and control engineering to structural engineering of constructed systems. Douglas and Reid were early pioneers in applying the St-Id concept to characterize the lateral response characteristics of highway bridges by pull-release testing (1982). Gobel, Shultz and Commander leveraged a version of the St-Id concept for testing bridges under crawl loads since 1989 (1991). The writer has led an ASCE expert committee that issued a state-of-the-art report on St-Id (2013). The ASCE Committee formulated a 6-step iterative process, summarized below, to construct, calibrate and utilize a field-calibrated finite element model to capture, quantify and simulate the elements and mechanisms that influence the load effects such as intrinsic forces, live loads, corresponding internal actions and the responses of all the critical elements of the bridge system. The St-Id process ensures that a load test is planned, designed and performed competently and safely. Furthermore, it can be leveraged beyond the load rating to provide additional insight on the behaviors of bridge system and thus increase the value of the load test such as to design effective maintenance, repair and/or retrofit for the bridge. Each of the Steps of St-Id is described in the following

## Step 1 – Observation and Conceptualization

Establish clear objectives for the St-Id effort and identify critical constraints and any with the owner and visiting the bridge. Collect and evaluate the reliability of all available legacy data missing information by meeting and information. Objectives that are in addition to load rating, such as how to effectively repair or retrofit the bridge, or an evaluation of the substructure and foundations for safety and scour may be included. Given that the ability to reuse foundations and substructure could save as much as 50% of the cost of constructing a new bridge, there may be compelling reasons for St-Id as long as the method is planned and resourced for accomplishing all the objectives.

## Step 2 – A Priori Modeling and Simulation

Observe the bridge system and measure selected responses under different operational and environmental conditions to conceptualize the system for a-priori modelling. This includes checking the dimensions, sampling and coring to verify material properties, scanning for rebar details, and boring to evaluate the soil conditions. The data and insight from these studies will help construct a 3D FE model that will simulate the important structural mechanisms. A model-builder must have experience with FE modelling, as well as an understanding of the kinetics and kinematics of the constructed system by actual on-site visits and observations. It is important to note that an infinite number of FE models can be constructed that are geometrically consistent with the structure, but may still fall short of accurately capturing the behavior of the structure. Given that the model should simulate all movements, restraints, joint and member deformations and mechanisms such as composite action or lack of, and continuity between spans and or approaches as well as any soil pressures, selecting the right mesh resolution and element choices becomes important.

Furthermore, boundary conditions and connectivity between elements must be considered and modelled effectively. The FE model below was constructed by reducing the girders to beam elements, modelling the deck and saidewalk with shell elements. Geometry was retained by connecting the elements with link elements which enforce relationships between degrees of freedom of the connected nodes. Boundary conditions are modelled as rotational and translational springs. The bridge represented by the below FE model has foundations resting on rock. While the rock was not explicitly modeled, it was included with springs beneath the foundation with stiffness corresponding to the stiffness of the rock.

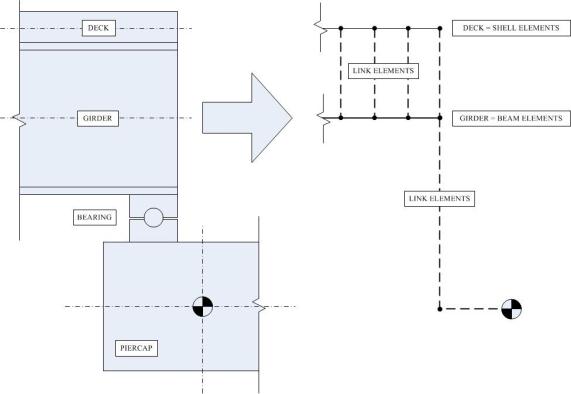


Figure : FE Characterization of Structural Components and Boundary Conditions

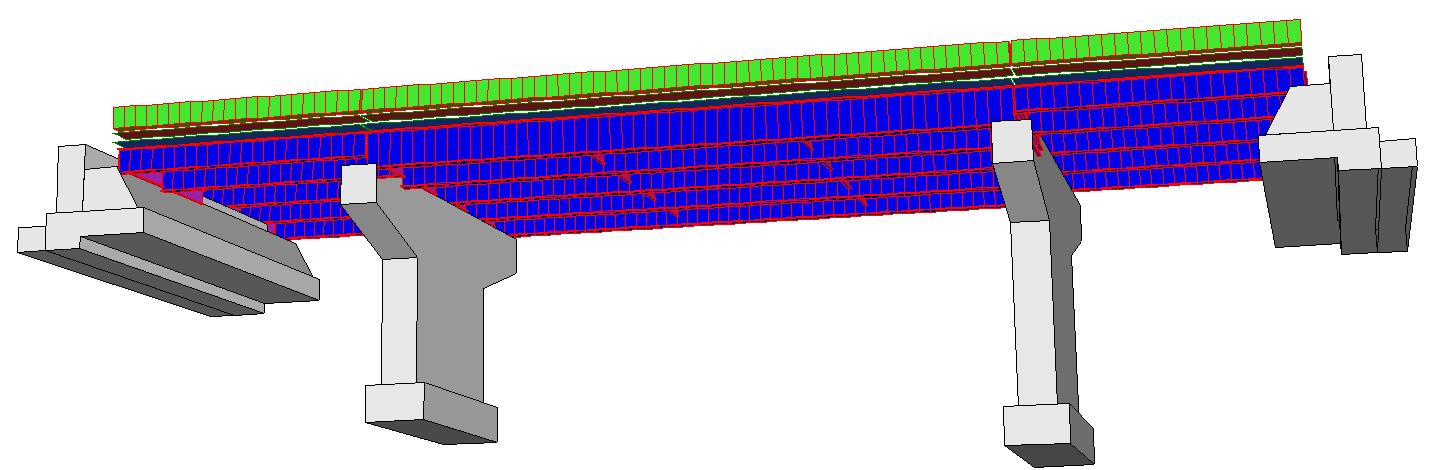


Figure : Example FE Model

The completed a-priori model serves for sensitivity studies to estimate failure modes and the bounds of critical responses that should be measured for a safe conduct of the test and for acquiring the data that will provide information to calibrate the model. This will help design the load levels and positions for the load test instrumentation and ensure that data captured during the load test will serve all of the objectives.

## Step 3 – Experimental Program Design and Execution

Instrument the bridge to perform operational monitoring of critical temperatures, strains, rotations or tilts and displacements in addition to accelerations. For a typical bridge span, a sensor density corresponding to 12 to 24 sensors would be recommended. It is important to have redundancy and a variety of sensors with appropriate gage lengths (0.5 – 6 inches), sensitivity and accuracy. Sensors should include vibrating wire as well as resistive types.

|  |  |  |
| --- | --- | --- |
| Figure : Superstructure Instrumentation Example | | |
| Figure : Strain Gages on Girder | Figure : String Potentiometer | Figure : TML's Measure Joint Movement |

|  |  |
| --- | --- |
| Figure : Pier Instrumentation Example | Figure : Tilt Meter |
| Figure : BDI Strain Gage |
| Figure : Accelerometer |

The load test is performed by positioning a number of trucks to incrementally increasing load levels up to the target proof load level. It is desirable to repeat operational monitoring following the load test. The load test will require extensive planning, rehearsals and execution by specialized engineers who will monitor bridge responses in real-time as trucks are positioned for increased increments of load. Writers recommend applying at least 2 to 2.5 times the legal load during a proof load test in order to activate all of the critical response mechanisms of a bridge while assuring a reliable signal-to-noise ratio for all sensors. This is quite different from the recommendations of the AASHTO Manual suggesting load levels of about 1.5 times the rating load. If a bridge exhibits any signs of distress such as cracking or yielding at less than 2.5 times the rating load, such a bridge should indeed be posted or decommissioned. It is desirable to include strain and tilt measurements of the substructures during such a test. Measurements by leveraging one or more core holes drilled from the top of the deck all the way to the bottom of the footings may provide a definitive documentation of the foundation and soil conditions and may help to infer any scour risk through the rigid body displacements and/or rotations.

## Step 4 – Data Analysis and Interpretation

The metadata, operating and proof load test data as well as images are evaluated, synchronized and data quality is verified before archival. Data is visualized and interpreted for patterns and response quantities. This will start during the experiment in-situ to identify and rectify issues and mistakes. For example, real-time data interpretation should be compared to model predictions and any discrepancies should be evaluated to determine if the predicted failure modes and ultimate capacity should be revised along with subsequent load cases. Especially, the linearity of the structure and the critical elements should be continuously monitored to identify members that may approach cracking or yielding.

## Step 5 – Model Updating/Calibration

Modify, validate and finalize the a-priori FE model before calibrating it with selected data sets from the operational monitoring and load test. A critical issue is making sure that the model is complete, i.e. the model can explicitly simulate all of the critical loading and response mechanisms and especially the measured kinematics at the supports and boundaries of the bridge. The bridge dynamic characteristics such as frequencies and mode shapes that may be extracted from operating responses, displacements, tilts and strains under known-measured tire loads and at different positions will constitute various data sets to calibrate and then validate the FE model. There will always be a larger number of parameters to calibrate (material properties and dimensions of all elements as well as all joint, bearing, connection and boundary properties, including those at foundations) than the number of measurements, therefore one cannot expect a unique calibrated model. However, if a model is calibrated to mimic all of the measured input-output or load-response relations of the bridge with acceptable level of discrepancy, it may be considered suitable to serve the objectives of St-Id such as load rating, maintenance, repair or retrofit design, or renewal by reusing various elements such as foundations.

## Step 6 – Model Preparation and Rating

Leveraging the calibrated model for the objectives of St-Id. The calibrated model is especially powerful when used to identify mechanisms contributing to the bridge’s actions and the corresponding capacity. There are numerous mechanisms providing stiffness and contribute to the capacity of a bridge at the time of load testing, but these contributions may diminish or disappear under different environmental conditions or after several years. These may include but are not limited to: composite action between deck and girders, diaphragms, concrete and soil stiffness and conditions, contributions of sidewalks and barriers, locked movement systems, arching action of a slab, etc.

Although the FE model is foremost used to compute a load rating, it can be further leveraged to simulate other loading scenarios and to gain a better understanding of the structural characteristics of the bridge. The natural frequencies can be analyzed in an effort to reveal the influence of the superstructure vibrations on deck deterioration or substructure durability. Seismic loading can be simulated to help inform the owner of the risk of damage or failure in the event of an earthquake. Long term loading, such as differential temperature and settlement effects may be simulated. Fatigue-life may be estimated based on operational monitoring and measured responses. Repair sequencing can be examined to ensure construction activities do not pose a risk of damaging other elements in the bridge. A more detailed description of the structural identification process can be found elsewhere, but the above discussion sufficiently summarized the process. Given that a load test may be executed at the same cost but without following a St-Id framework and missing the reliability and benefits outlined above, all owners are advised to demand load testing by following the St-Id framework.

# Overview of Sample Case Studies

Since the 1980’s, the authors have had the opportunity to perform St-ID of several dozens of actual bridges, some of which had unknown foundations. The structural forms varied, consisting of concrete T-Beam (2005), concrete arch and RC deck on steel girders. The rating factors for a handful of these structures are presented in Table 4. For each of the bridges listed inTable 4, load ratings were first computed by the line-girder model. A 3D FE model of each bridge was also constructed. The results of the load tests were used to field-calibrate the FE models following the St-Id framework discussed in the following. These “field-calibrated” 3D FE models were then used to calculate the dead load and live load demands, and a second load rating in the column labeled FEM was computed.

|  |  |
| --- | --- |
| Figure : Concrete Arch Bridge (00000000054A035) | Figure : T-Beam Bridge (000000000005085) |
| Figure : T-Beam Bridge (00000000010A140) | Figure : Steel Stringer Bridge (00000000010A055) |

Table 4: Load Rating Comparison

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Structure**  **Description** | **Rating Factors** | | **Comparison** | |
| AASHTO | FEM | FEM/ AASHTO | Percent Change |
| Concrete T-Beam 1 | 0.92 | 3.25 | 3.53 | 253% |
| Concrete T-Beam 2 | 1.27 | 3.18 | 2.50 | 150% |
| Concrete T-Beam 3 | 1.22 | 3.35 | 2.75 | 175% |
| Concrete T-Beam 4 | 1.01 | 5.62 | 5.56 | 456% |
| Concrete T-Beam 5 | 1.2 | 3.3 | 2.75 | 175% |
| RC Jack Arch | 1.16 | 5.38 | 4.64 | 364% |
| RC Deck on Steel Girders | 0 | 1.29 | - | - |

The rating factors in Table 4 illustrate the importance of considering each structure individually, and identifying its critical mechanisms that control load distribution and capacity. While all structures exhibited an increase in load rating when computed using a field-calibrated FE model, the increase in load rating is not consistent, ranging from 2.5 to 5.56 times. Even within a group of bridges with similar form and geometry (e.g. the T-beam bridges for which consistent design specifications were used) the ratio of FEM to AASHTO load ratings vary greatly, based on span and level of deterioration.

Furthermore, many interesting bridge-type specific behavior mechanisms were identified during the structural identification of these bridges. For example, for the cast-in-place T-beam bridges, the anchoring of the superstructure by dowels into the abutments had impact on load ratings. Even when the reinforcement within the girders was omitted to simulate extreme deterioration, the RC deck-slab was sufficient for achieving a favorable rating. These structures performed much better than predicted by single-line girder analysis even after their deterioration was simulated.

The reinforced concrete jack arch bridge (Figure 9) had received a sufficiency rating of 7 out of 100. However, testing revealed that the structure had significant reserve capacity due to lateral soil pressure compressing and enhancing the capacity of the arch. Further, the soil fill under the deck on top of the arch provided excellent load distribution from the deck. Tilt instrumentation was installed on the spandrel walls are monitored to ensure that these walls would continue to effectively contain the fill.

The steel girder bridge had received a line-girder rating of zero because a steel cover-plate retrofit detail failed to provide adequate development length and thus could not be considered in the capacity calculations for a section of the bridge. Modeling and testing revealed that, not only was this component effective for the section in question, but that the structure had adequate capacity even without the retrofit.

These results reveal that performing load testing of a bridge and explaining why the bridge passes will require a much greater understanding than what can be expected from an idealized FE or line-girder model. An instrumentation and loading strategy is needed based on a 3D modeling of the structure simulating its actual 3D geometry, and the simulation of all the mechanisms within the bridge system that may govern the primary and secondary load transfer paths. How member or connection details are simulated and boundary conditions are represented would affect load paths. Finally, the expected kinematics of the bridge under various load levels should be included in designing the instrumentation. Every component of the bridge system for which the capacity is being investigated must be modeled and instrumented for the load test (e.g. superstructure, substructure, foundations, etc.). It is critical to identify the mechanisms that contribute to a structure’s capacity in order to design the load increments, load positions, instrumentation, and data acquisition, as well as real-time communication and visualization such that the test may be performed safely and all relevant data gathered. Without the real-time feedback and visualization of critical bridge responses under load, safety may not be assured.

For each of the bridges listed in Table 1, load ratings were first computed by the line-girder model while a 3D FE model of each bridge was also constructed. The results of the tests were used to field-calibrate the FE models following the St-Id guidelines presented above. These “field-calibrated” 3D FE models were then used to calculate the dead load and live load demands, and a second load rating listed under FEM was computed.

Table : Load Rating Comparison for Bridges with Unknown Foundations

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | **NBI Structure Number** | **Rating Factors** | | **Comparison** | |
|  | AASHTO | FEM | AASHTO/ FEM | Percent Increase |
| T-Beam | 000000000015156 | 0.92 | 3.25 | 3.53 | 253% |
| 000000000010570 | 1.27 | 3.18 | 2.50 | 150% |
| 000000000000134 | 1.22 | 3.35 | 2.75 | 175% |
| 000000000005085 | 1.01 | 5.62 | 5.56 | 456% |
| 00000000010A140 | 1.2 | 3.3 | 2.75 | 175% |
| Arch | 00000000054A035 | 1.16 | 5.38 | 4.64 | 364% |
| Steel | 00000000010A055 | 2.14 | 3.55 | 1.66 | 66% |

As can be seen from Table 1, rating factors computed using a field-calibrated FE model are consistently and significantly greater than those computed using the single line girder model. Indeed, the sixteen structures, which the authors rated with calibrated FE models, exhibited an average increase of 171% over the AASHTO rating. This is due to the fact that the single line girder is too conservative as it assumes the bridge carries its dead and live loads only by bending and shear in its girders. The 3D FE model includes many additional distribution mechanisms such as the RC deck functioning as a plate and a diaphragm, working compositely with the girders (due to mechanical or chemical bond), and the lateral diaphragms and cross braces, any wind-bracing, boundary and bearing fixity, and possible lateral confinement from approach slabs at the abutments along with any confining soil pressures.

While the FEM load rating factors are greater than the line girder ratings, this cannot be generalized as the rule. It is possible to envision geometric properties (curved, skew and irregular bridges) that may lead to calibrated model demands greater than those predicted by the single line girder model. Further, so-called secondary elements that are ignored in the line girder model may prove to govern the rating. At this time of scarce resources, the availability of ubiquitous computing and the need to critically distinguish safe bridges from those that are indeed unsafe, the value of proof-level load testing of select bridges is clear. The critical question is how to perform such tests safely and properly so that we may learn about actual bridge behavior and the mechanisms that actually contribute to the load carrying capacity of a bridge, therefore informing the design and the load rating of other bridges.

# Detailed Reinforced Concrete Multi-Girder Bridge Case Study (Smithers)

## Structure Overview

## Finite Element Modeling

## Experimental Program and Results

## Updating Rating and Discussion

# Detailed Steel, Multi-Girder Bridge Case Study (MP 28.9)

## Structure Overview

## Finite Element Modeling

## Experimental Program and Results

## Updating Rating and Discussion

# Detailed Concrete Encased Steel Multi-Girder Bridge Case Study (Northampton)

## Structure Overview

## Finite Element Modeling

## Experimental Program and Results

## Updating Rating and Discussion

# Conclusion

Bridges that cannot be load rated due to missing information, or load rated at less than the legal loads and posted, may in fact possess excellent load capacity and significant remaining life, depending on their design and construction, even if they may appear to be at the end of their useful life. It is possible to identify these bridges by properly designed and executed proof-level load rating. While proof load testing in 2015 is NOT rocket science, it never the less does require experience and resources to design and perform field experiments, 3D FE modeling and simulation along with a heuristic understanding of bridge behavior. The value we may obtain from such tests is not just the removal of posting for a bridge, but a better understanding of how bridges of certain design and construction characteristics (i.e. a family or statistical population) that carry their loads by similar mechanisms, can be better evaluated and load rated.

The structural identification concept provides a framework that guides load testing, helping to ensure that it is designed and conducted safely, the resulting load rating computed accurately, and with due consideration of the uncertainty of contributing mechanisms. Structural identification is a mature concept and has been used extensively in several engineering fields including structural and geotechnical engineering for many years.

Currently there are no reliable guidelines from AASHTO or from NCHRP for executing proof-level load rating safely and meaningfully by leveraging the structural identification concept. Current guidelines for proof-level load testing are highly insufficient. We hope that this Tech Brief is a first step towards developing guidelines that will describe:

* How to observe and document the as-is conditions of a bridge and its site, together with its loading environment so that it is possible to model any impacts of existing deterioration and damage, as well as an appraisal of probable natural and manmade hazards that should be incorporated in a safety and resilience evaluation of the bridge.
* How to construct a-priori FE models for a bridge superstructure-bearings-substructure-foundation and soil system, based on an actual visual inspection of a bridge and its existing documents. ***It follows that an integrated analytical and real-life observation experience is essential for becoming a model builder.***
* How to design sensing, proper sensor calibration and installation, data acquisition and ***real-time data visualization*** for safely executing the load test.
* How to determine loading increments and ***the maximum safe and meaningful load level*** for a proof-level load test. In general, maximum loads should produce 2.5 times the legal load demands or higher, especially when there are unknown characteristics and as-constructed properties of a test bridge. The responses in the substructures and foundations should be well over the noise level especially if the foundation conditions are unknown.
* How to leverage small-diameter boring through the deck, sub-structure and foundation, in conjunction with special instrumentation for measuring soil properties ***under the foundation*** and the foundation properties, especially when there is uncertainty about the properties of the foundations and soil or in the case of scour risk.

The cost of a properly executed proof-load test and load rating of a typical bridge span by following the structural identification guidelines described in this brief may reach about $50K. This cost may be reduced to half by streamlining the modeling, instrumentation and load testing process, for example by leveraging wireless sensors and high-resolution photogrammetry or laser vibrometers for displacement measurements. There are great benefits for bridge owners to engage in proof-load testing of their selected bridges.

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