Use of Field Testing in Delaware's Bridge Management System

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ABSTRACT

Since 1994, researchers at the University of Delaware have been working with engineers at the Delaware Department of Transportation (DelDOT) to develop methods for integrating bridge field testing and in-service monitoring into DelDOT's bridge management efforts.

Bridges have traditionally been evaluated and rated using rather simple analytical methods and without the use of site-specific data. Estimates of a bridge's load-carrying capacity made in this manner are often overly conservative. Because of the continued deterioration of our nation's bridges and the growing number of bridges that are being classified as "deficient," combined with limited financial resources in our bridge management programs, it is more important than ever that estimates of a bridge's capacity be as accurate as possible. Accurate condition assessments and load ratings can allow bridge engineers to more effectively manage their bridge inventories.

This paper will summarize the efforts to date and give specific examples of how bridge field testing and in-service monitoring have been used to enhance the bridge management efforts in Delaware.

INTRODUCTION

As the condition of our nation's bridges continues to deteriorate, and the weight of trucks on our highways continues to increase, the importance of being able to determine accurate load-carrying capacity has become paramount. It has been estimated that 100,000 bridges in the United States are currently posted, and another 50,000 bridges should be posted (*1*).

Bridge ratings have traditionally been based upon a conservative, non-site-specific calculation of a bridge's load-carrying capacity. Calculated load-carrying capacities are usually underestimates of the safe load-carrying capacities of a bridge (*2*, *3*, *4*, *5*). Parameters used in design and evaluation are by necessity conservative. Many secondary sources of strength are either neglected (such as the stiffness of continuous parapets) or have not been quantified (such as the stiffness of cracked concrete). Other sources of stiffness are too bridge specific to be included (such as unintended composite action or continuity) without field experimentation. Among the assumptions commonly used in bridge load-carrying capacity rating which may not be true in terms of behavior of the as-built bridge are:

- conservative estimates of load distribution,
- original section properties,

- non-composite action,
- uniform section loss due to corrosion,
- simply supported spans (no fixity at supports),
- unyielding supports (full fixity at supports),
- conservative impact factors,
- material strength based upon minimum acceptance criteria,
- conservative estimates regarding the effect of fill.

Bridge Field Testing

When it comes to determining a safe and accurate load-carrying capacity for a bridge, the best model of the structure is the bridge itself. During design of a bridge, we do not have the luxury of utilizing this resource. Fortunately, during subsequent evaluation, we can utilize it. Field testing is one method for determining the strength capacity of existing bridges (*6*).

Due to the rapidly decreasing cost of non-destructive evaluation technologies, the cost of field testing a bridge is now quite reasonable, and the information gained from the test can help bridge management engineers decide which bridges to post, rehabilitate, or replace with their limited financial resources. Field testing can help public monies to be spent where they are most needed, and can help prevent public monies from being used for unnecessary bridge repairs and replacements. For example, a public agency decides to replace a well-used bridge due to findings during a visual inspection. Before they replace the bridge, they hire structural engineers to field test the bridge and determine the bridge is stronger than it appeared, and not in need of repair or replacement. Now the money can be better spent on another bridge that does need repair. In addition, the public does not have to face the inconvenience of unnecessary construction.

Bridge Field Testing in Delaware

Since 1994, University of Delaware researchers have been working with DelDOT engineers to develop methods for integrating diagnostic bridge field testing and in-service monitoring into DelDOT's bridge management efforts. Based on several field load tests, an efficient procedure for load rating bridges utilizing diagnostic field test results has been developed. A primary objective in the development of this procedure was that it be easily integrated into DelDOT's current bridge rating process. Still further research has led to the development of an innovative in-service strain monitoring system. This system, used alone, or in conjunction with field test results, provides very useful information about the actual service condition of a bridge. Together, these new techniques are being used to re-evaluate the rating of posted bridges, and bridges whose current ratings present stringent limits on the weight of permit vehicles (or superloads) allowed to use critical routes within the state.

Diagnostic Load Testing

Diagnostic load testing involves driving pre-weighed trucks across a bridge along various transverse paths at both a crawl speed (pseudo-static test) and at full speed (dynamic test). The weight of the trucks is chosen to not exceed the bridge's current rating level. Before testing starts, numerous fast-mounting strain transducers, and in some cases other instruments such as displacement gages, are set up at predetermined locations on the bridge. Measurements are recorded as the test vehicle is driven across the bridge. From the data collected during the diagnostic test, a number of significant properties that affect the bridge's actual load-carrying capacity can be determined. These properties, which are typically estimated in order to perform a traditional load rating, include (1) load distribution, (2) support restraint, (3) flexural resistance of the superstructure elements (cross-sectional properties including the state of composite action), and (4) effects of impact. Furthermore, the recorded strain can also help indicate the level of other, more difficult to quantify, sources of strength. By gathering enough response data, a more accurate structural model of the bridge can be created and used in the final bridge rating. In Delaware, bridges are rated using the Bridge Rating and Analysis of Structural Systems (BRASS) program (*7*). Key parameters that are used in BRASS are revised based on the results of the diagnostic field test.

It should be noted that diagnostic testing has the benefit of explaining why the bridge is performing differently than assumed (this is especially useful if structural models such as those used in BRASS are used to rate the bridge). The disadvantage to this method, as opposed to proof load testing, is that the results are determined for service loads, and need to be extrapolated to ultimate load levels.

In-Service Monitoring

In addition to load tests that are performed at a specific time, an instrumentation system has recently been developed, and is currently being evaluated, to measure peak live-load strains in bridges due to site specific traffic, over extended periods of time. The rapidly deployable system is small, lightweight, and battery powered. As such, the system is perfectly suited for use in routine bridge inspection and field evaluation. The monitoring system provides a unique statistical measure of the in-situ strain cycles in the bridge, and can be used for fatigue or strength evaluation, or to alert engineers regarding possible structural damage.

Using the strain monitoring system, live-load strains caused by site specific traffic can be measured and average daily number of cycles and the stress levels can be determined. This data can then be used to investigate and help understand the actual live-load stresses that are experienced by the structure as a whole, or in specific details that are prone to fatigue. The data can then be used to evaluate load-carrying capacity due to the quantified site-specific loads, or used to "predict" the remaining fatigue life of a fatigue critical detail.

The strain monitoring system may also be used as a tool to help monitor the "health" of the bridge and identify and diagnose structural damage and deterioration. In this application the monitoring system and the data are an integral part of the bridge maintenance and inspection program: the information provided by the system could be used to alert engineers to a potential problem in the structure.

USE OF LOAD RATINGS IN DELAWARE'S BRIDGE MANAGEMENT PROGRAM

Located in one of the older sections of the United States, Delaware's bridge population consists of many different material types, structural configurations, and ages. DelDOT's inventory ranges from structures constructed of new composite materials to stone masonry arches that date back to the 1800s. Because of this variety, load rating or capacity determination of bridges is often difficult. Older structures many times have limited plans and associated documentation. Other than destructive testing to determine section properties, many of these bridges cannot be analyzed. Situations also exist where the in-service condition of a bridge does not reflect the low capacity calculated by using the standard specifications. An inspection of the bridge condition sometimes indicates an excellent or good condition, but the load rating of the bridge indicates that the bridge should have substandard capacity.

Load rating information is used for various purposes in Delaware's bridge management program. The information is utilized to determine routes for vehicles greater than 120,000 lbs (also known as permit vehicles or superloads). These vehicles exceed the legal loads for traveling in the state and require a hauling permit. Permit vehicle types can range from high capacity stand alone cranes to flatbed trailers hauling anything from construction equipment to tanks. The capacity of bridges on the route must be evaluated because, although the bridge may be adequate for legal loads, it may not have enough residual capacity to carry these excessive loads. This review protects the hauler as well as the rest of the motoring public.

Load ratings are also used by DelDOT bridge managers to restrict loads on bridges. Some bridges do not have enough capacity to carry legal loads due to deterioration or older design criteria. These bridges are posted, allowing only lighter vehicles to cross legally. Unfortunately, one finds that these restrictions are often not observed. Usually the violator gets across the bridge, possibly causing damage without regard for the next vehicle to cross.

Load rating information is also used to prioritize structures for repair or replacement, as well as being used to determine allocation of federal dollars for bridge construction. A bridge, which has a low capacity, may qualify for federal funding for replacement due to its condition rating and sufficiency rating from the National Bridge Inventory information.

In order to provide accurate load ratings for the wide variety of purposes mentioned, including the prioritization of maintenance needs, Delaware has initiated an active load testing program.

SUMMARY OF FIELD TESTS PERFORMED IN DELAWARE

Since 1994, more than ten diagnostic load tests have been conducted on Delaware bridges in order to help DelDOT better manage the state's bridge inventory. The tests have been performed for a variety of reasons including: (1) evaluating the load-carrying capacity of a posted bridge, (2) evaluating the load-carrying capacity of bridges on major state routes for the purpose of routing superloads, (3) evaluating a non-standard, highly skewed bridge, (4) evaluating an innovative bridge made of advanced polymer composites, and (5) in-service monitoring of bridges on Interstate I-95.

The following sections briefly detail the tests used to perform the mentioned evaluations, and summarize both the load test results and how they are being used by DelDOT's bridge managers. It should be noted that standard three-axle, single unit trucks weighing between 25 to 30 tons were used to load all of the bridges discussed below (except for the in-service monitoring, which utilized ambient traffic). In all cases, fast-mounting strain transducers were used to record live-load strains.

Posted Bridges

The first application of bridge load testing in Delaware related to the current program took place in the summer of 1994 and involved the evaluation of a posted bridge. The purpose of the test was to determine whether or not the bridge, which is located on a heavily used route in northern Delaware, needed to have traffic restrictions.

The tested bridge, built in 1939, has no skew and has a non-composite slab-on-steel-girder superstructure. Inspection reports for the bridge indicated that corrosion (and associated loss in section) played a major role in causing the bridge to be posted.

During the test, the peak bending strain that was measured was 60 percent lower than the predicted strain based on the existing model of the bridge. By studying the load test data, it was determined that the actual transverse load distribution was considerably better than predicted by the American Association of State Highway Transportation Officials (AASHTO) formulas (*8*). Furthermore, the girders were acting compositely even though they were designed non-compositely. Based on careful consideration of the test results, the bridge parameters were updated, new ratings were computed, and the prior load restrictions for the bridge were removed.

Permit Vehicles

To date, eight bridges have been tested in order to enable DelDOT to better plan the routing of permit vehicles (superloads) through the state. Five of the bridges are located on US 13 (the major north-south route through the state), while the remaining three bridges tested are located on Interstate I-95 (the major east-west route through the state).

The construction of State Rt. 1, a major north-south road that connects southern and northern Delaware, is well underway. This road provides high capacity bridges for permit loads passing through the state. However, until the road is completed, some portions of US 13 will continue to be utilized. Along one of these sections, several 65 to 80 year old short-span, concrete slab bridges were identified by DelDOT as potentially representing a temporary weak link in the north-south artery. If the bridges did indeed represent a weak link, their immediate replacement may have been needed. As a result, five concrete slab bridges, built from 1920 to 1932, were tested in the fall of 1998.

The evaluation of these bridges included both diagnostic load testing of the concrete slabs, as well as material testing of the concrete (from cores). In the field load tests, the primary variable that was quantified was the transverse load distribution of the concrete slab. In all cases, it was determined that the slab was distributing loads nearly twice as effectively as one would predict based on AASHTO equations (*8*). Some of this enhancement may also have been due to the 0.25 to 1 meter of fill that separates the current asphalt wearing surface and the top of the concrete slab. Based on the better load distribution that was measured, it has been determined that none of these older structures should represent a severe limitation to superloads passing along this route, and their replacement is not needed.

The three bridges on I-95 that were tested to evaluate permit load capacity included two slab-on-steel-girder structures (both tested in 1995), and one concrete multiple cell box culvert (tested in 1997). Like the posted bridge mentioned previously, the two girder bridges exhibited better than expected live load distribution. The culvert, that had considerable fill on top of it, proved to have little to no effect of live loads. In all three cases, the capacity for permit vehicles was significantly increased.

Nonstandard Designs—Highly Skewed Bridges

In the early 1990s, DelDOT constructed several highly skewed bridges as a part of the new State Rt. 1 construction. The skews of some of these bridges were on the order of 60 degrees, and DelDOT design engineers were interested in seeing how these bridges were performing relative to their design expectations. In the summer of 1997, a two-span, 100-meter, slab-on-steel-girder bridge having a 60 degree skew was tested using two heavily trucks. Based on the results of the diagnostic test, it was found that AASHTO distribution factors for skewed girders appear to be fairly accurate (*8*). The field test results also matched well with finite element analyses of the bridge.

Innovative Bridges—Advanced Polymer Composite Superstructure

In the fall of 1998, DelDOT constructed an all-composite slab bridge on Bus. State Rt. 896 in Glasgow, Delaware. Because of the novel design, both laboratory and field tests of the actual bridge components, and the bridge during construction, were performed (field tests of the completed bridge, including long-term monitoring, are scheduled for the summer of 1999). The tests have been used to help quantify the transverse load distribution of the polymer composite slab, as well as to monitor the magnitude of strain induced during construction and due to the dead load of the concrete wearing surface. Thus far, the field test results indicate the bridge is exceeding all design requirements (the bridge was designed using AASHTO's new LRFD design philosophy). In terms of bridge management, the ability to monitor this structure through field testing will be a great aid in rating the bridge (no guidelines for rating polymer composite bridges currently exist), in monitoring the bridge's ongoing "health," and in indicating whether or not maintenance or repairs are needed.

In-Service Monitoring

Field tests using the newly developed strain monitoring system were conducted over a ten week period in the summer and fall of 1998. The tests were conducted on an Interstate I-95 bridge in northern Delaware. The bridge is a three-span continuous concrete slab-on-steel-girder structure that carries a large volume of commercial truck traffic along the I-95 corridor.

Using the strain monitoring system, the in-situ stress state that exists in the bridge due to the site specific traffic was measured. The data allowed the average daily number of cycles and the stress levels at which they occur to be generated. Using this information, S-N curves for the bridge's critical fatigue details were created, and estimates for the expected remaining fatigue life of the details (i.e., number of cycles remaining to failure) were made. For all details considered, based on the current traffic, all estimates of remaining fatigue life exceeded 100 years.

SUMMARY

A bridge load testing program that utilizes both diagnostic field tests and in-service monitoring has been established in Delaware to help DelDOT more effectively manage their bridge inventory. Load testing of bridges provides more accurate information about bridge load-carrying capacity without eliminating needed factors of safety. In several cases the information gained has been used to determine accurate values for load distribution. Determinations have also been made as to the existence of composite action between a girder and deck. This information is used in load rating calculations, and has led to more accurate capacity assessments. While some benefits in response may be safely used to improve load ratings, other benefits may not be relied upon because they may be subject to unexpected change during the bridge life. One example is the fixity of bearings which could be eliminated during the next bridge painting contract. In the end, one must be careful not to be unconservative in estimating bridge load-carrying capacity based on field testing and monitoring. This may subject the bridge to many cycles of near capacity loads, reducing its service life.

Values used from the load testing of bridges have allowed DelDOT to remove load restrictions for a bridge on a major truck route. Also, the information has allowed for the passage of superloads on bridges on the two most major travel routes through the state. This extra capacity has allowed us to postpone the replacement of substandard structures, as well as eliminated extensive detour routes around these structures on rural secondary roads. Further tests have been used to verify non-standard designs involving highly skewed bridges, to evaluate the performance of an innovative composite material bridge, and to monitor the accumulation of fatigue on a heavily traveled highway overpass.

The implementation of an ongoing bridge capacity evaluation and monitoring program through field testing has already had significant impact on DelDOT's ability to manage its bridge inventory. Future plans include utilizing load testing to determine the capacity of some of Delaware's older structures which are still in fairly good condition, but for which plans do not exist. One such example is old masonry arches.

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REFERENCES

1. Pinjarkar, S. G., Guedelhoefer, O. C., Smith, B. J., and Kritzler, R. W. (1990). "Nondestructive Load Testing for Evaluation and Rating." NCHRP Project 12–28(13) Final Report.

2. Aktan, A. E., Chuntavan, C., Lee, K. L., and Toksoy, T. (1993). "Structural Identification of a Steel-Stringer Bridge." Preprint, TRB Paper 930560, Transportation Research Board, 72nd Annual Meeting, Washington, D.C.

3. Bakht, B., and Jaeger, L. G. (1990). "Bridge Testing - A Surprise Every Time." *J. Struct. Engrg.,* ASCE, 116(5), 1370–1383.

4. Commander, B. C. (1989). "An Improved Method of Bridge Evaluation: Comparison of Field Test Results with Computer Analysis." Master Thesis, University of Colorado, Boulder, CO.

5. NCHRP (1998). "Manual for Bridge Rating Through Load Testing." *Research Results Digest, No. 234,* Transportation Research Board, National Research Council, Washington, D.C.

6. Schulz, J. L. (1993). "In Search of Better Load Ratings." *Civil Engineering,* ASCE 63(9), 62–65.

7. BRASS, Wyoming State Highway Department, Cheyenne, WY, Copyright 1998.

8. AASHTO (1992). "Standard Specification for Highway Bridges." Washington, D.C.