CONTINUED LONG-TERM MONITORING OF
HAM-42-0992 AND HAM-126-0881L:
INSTRUMENTATION, TESTING AND MONITORING OF REINFORCED
CONCRETE DECK-ON-STEEL GIRDER BRIDGES

Problem

According to the National Bridge Inventory (NBI), the most common type of short-to-medium span highway bridge in the U.S. is the reinforced concrete (RC) slab-on-steel girder (steel stringer) with RC abutment and pier systems. These bridges comprised 35% of the population in the 1977 NBI. 5,506 of the 11,370 medium-span bridges in the ODOT inventory are steel stringers. The replacement value of these bridges in the Ohio state system alone is estimated to exceed $2.5 Billion.

In view of our significant investment in steel stringer bridges, we should have a clear and complete understanding of their behavior including critical parameters that govern bridge behavior during service (e.g., normal traffic, environment, overloads, accidents, etc.), and we should be able to establish those mechanisms that affect deterioration and therefore long-term performance.

The University of Cincinnati Infrastructure Institute (UCII) has conducted field tests and structural identification studies on several representative samples of highway bridges. These steel-stringer bridges were tested, monitored, and studied in order to classify their similar bridge-type-specific behavior mechanisms, to validate the performance of various assessment methodologies, and to determine bridge capacity and condition. These specimens represent the critical life stages or events for a bridge: Birth, as represented by a recently-constructed bridge; service, several bridges in their prime; overload, an extreme case of traffic loading; and death, a 50-year old decommissioned bridge.

The results from this sample of bridges indicate that a number of very important response mechanisms that significantly influence bridge behavior are not completely recognized and incorporated in their design, evaluation, maintenance or rehabilitation. What is more important is
that we may not even be aware of many deterioration mechanisms affecting long-term bridge performance.

In addition, subjective or inaccurate condition assessment methods, such as visual inspection, have been identified as a critical technical barrier to effective infrastructure management. The difficulties of visually inspecting and evaluating an aging constructed facility accurately and completely, even when this may be conducted by experienced engineers, are well-known.

In lieu of these, UCII has focused on the development of non-destructive evaluation (NDE) technologies of a rigorous and objective nature to quantitatively identify and evaluate the “global” condition or health of highway structures.

The global NDE methodology employed here is based upon the structural identification concept, employing modal testing and crawl-speed truckload testing as its principal experimental tools. These testing approaches will provide best results under controlled loading conditions, which can be performed on a regular basis or in response to suspected or known damage. Ambient instrumented monitoring is conducted during the interim to track, document, and alert the bridge engineer to any gradual or sudden changes. Field test results are coupled to analytical methods through the use of calibrated finite element models which can be used for simulation purposes as well as rating.

Based upon recent observations and results from this research, the HAM-42-0992 and HAM-126-0881L bridges, which were extensively tested under prior research projects and which each have extensive permanent instrumentation packages, were selected for continued development of more advanced testing and monitoring regimens. These two structures are both located along the Ronald Reagan Cross County Highway in Cincinnati, Ohio.

Objectives

The research project had two primary objectives:

The first objective was to continue our documentation of the state-of-stress in HAM-42-0992 and HAM-126-0881L, reinforced concrete deck-on-steel stringer bridges. The actual absolute state-of-stress in HAM-126-0881L, together with the corresponding causative effects, have been evaluated from fabrication and construction and through the first two years of service. This research project extended the database well into its service life providing a comprehensive and continuous database on the life of this structure. The incremental state-of-stress in HAM-42-0992, have been evaluated periodically during the last 10 years.

The second objective was to continue the advancement of the state-of-knowledge in feasible and reliable bridge instrumentation, monitoring, and nondestructive evaluation technologies. This included the development of a remote web-based bridge monitor which could automatically record sensor data, post-process it (including generating ratings) and post it to a dedicated website to provide continuous feedback to bridge engineers on the state of the bridge in real-time.

General Project Description

Data acquired through instrumentation and controlled diagnostic testing was used to conceptualize the less-understood or unknown phenomena that influence bridge performance and to verify design assumptions and rating models. Service data was compared with the recorded construction stresses and measured material properties to determine their effect upon various observed phenomena such as deck cracking.

In particular, on-site instrumentation was used to collect a complete set of strain and temperature response data on and in the soil, the substructures (piles or footings, piers and abutments), and the superstructure components (deck and parapet concrete, girders, cross-braces) of the test specimen. Meanwhile, all the relevant atmospheric effects at the site were also monitored. Traffic loading was monitored by automatic weigh-in-motion (WIM) scales and video camera. In addition, a regimen of diagnostic testing was conducted in order to track the mechanical characteristics of the bridge.

Bridge flexibility was determined from intermittent modal tests. The associated flexibility model was used to accurately determine the bridge deflection profiles and magnitudes for various loading scenarios.

Bridge influence lines at critical locations were determined from intermittent crawl-speed truckload tests. The crawl-speed test allows separation of the influence of each truck axle by eliminating dynamic effects and accounting for linear superposition of the loads. The associated model was used to accurately determine the static stress induced by various loading scenarios, and to estimate the impact factor for live loads.
The modal and truckload test results were analyzed in order to corroborate each other as well as measurements obtained from continuous monitoring. The results were trended to assess the existence or onset of any structural damage or deterioration and to rate the current capacity and stiffness of the bridge for standard truck loading (e.g., HS20-44).

Using these results, together with the availability of dedicated on-site instrumentation, an “intelligent” monitor system was developed to track bridge structural condition and alert officials in case of any sudden changes in structural behavior. An architecture consisting of 2 PCs and a high speed data acquisition system was permanently installed and configured to run full-time monitoring of the traffic responses of the bridge. At the same time, the system also continually reviewed weigh-in-motion data. When a truck was detected by the WIM, one PC activated a camera to take a picture and recorded truck parameters from the WIM while the other PC captured the bridge's live load response from the data acquisition system. All of this information was then automatically fed into custom designed software to calculate AASHTO capacity ratings. This was done in real-time and automatically posted to the web 24/7. The system ran reliably for nearly two years and logged nearly 20,000 truck responses (www.uc.edu/ucii).

**Specific Results & Recommendations**

This project required advancements in state-of-knowledge in feasible and reliable bridge instrumentation, monitoring, and nondestructive evaluation technologies. Further, this improved methodology was implemented in the experimental evaluation of two stringer bridges in service.

Methods for calculating experimentally derived parameters (e.g., unit influence lines, distribution factors, inventory and operating rating factors, etc.) were established. For example, the HS20-44 truckload was virtually simulated in each lane by linear superposition of the experimentally derived influence lines, weighted by the specified axle weights. This allowed the live load to be calculated and then the bridges to be summarily rated by both the allowable stress and load factor approaches. The experimental results so obtained generally compared favorably with analytical expectations.

Several truckload tests conducted for HAM-42-0992 on August 5-7, 1997 at various speeds, temperatures, driving paths, and truckloads were reanalyzed in detail. The influence lines were found to peak at exactly the position of the gage, as predicted by the theory of an ideal beam. The simulated truck response from the influence line was proven equivalent with the actual crawl-speed and static truck responses.

Several truckload tests conducted for HAM-126-0881L in May and September of 1998 at various speeds, temperatures, driving paths, and truckloads were also reanalyzed in detail. In comparison with the results for HAM-42-0992, HAM-126-0881L showed significant vibration during and after the truck crossing. This is attributed to its lower natural frequency which allowed for greater interaction between the dynamic modes of the bridge and truck. The designed composite action in the middle span was found to be intact, but the end spans exhibited unintended, but partial, composite action with the concrete decking. The top flange strain response was nonzero but not equal in magnitude with the bottom flange strain response.

At higher speeds (i.e., > 60mph), the influence line and the dynamic modes become overlapped in the frequency domain, as predicted by the ideal beam theory. The actual truck responses were also distorted by the dynamic structural modes, but the error is bounded by typical experimental limitations. Hence, the influence lines derived by 50mph tests can still be shown to provide an accurate simulation of those derived at crawl speeds.

Modal tests for HAM-126-0881L from 1997 and 2002 were compared. The frequencies for the various modes decreased in 2002, relative to 1997. Further, some of the higher modes changed shape and/or ordinal position between tests. It is clear that the structure has become
more flexible with time; displacement under BGCI (Bridge Girder Condition Index) has doubled in 5 years. This is a very large increase in a short amount of time (i.e., relative to the bridge lifespan of 50 years) and the change is global, affecting all girders equally. It is possible that the integral nature of the abutment has been weakened, which would lead to lower mode frequencies. If it is found that these areas later exhibit maintenance problems, new design details or construction practices should be considered.

Truck load testing of HAM-126-0881L from 1998 and 2002 was also compared. For the both tests, the maximum stress occurred in the middle span on the middle girder at the bottom flange. The response in the south lane was reduced in 2002, leading to a higher rating. Whereas the east span was almost non-composite in 1998, the west span still showed considerable unintended composite action in both tests. The pier response was significantly reduced in 2002, compared to 1997 results; especially with regards to the top flange response.

Although partial composite action is clearly present in the measured data from the diagnostic load test, it is not clear whether this additional strength for the section will actually exist at the allowable stress. Most certainly, the unintended composite action would not remain at the ultimate or plastic moment of the limit state approach. The Structure Rating chapter of the ODOT Bridge Design Manual indicates that the “members shall be analyzed as to the intended method of design”. In this research, the ODOT specification was met and a reduced load rating was also determined for any section with unintended composite action based in part upon the NCHRP Manual for Bridge Rating Through Load Testing.

The continuous and automated, web-based monitoring system not only realized the full potential of today’s latest internet technologies to put forth a state-of-the-art and user-friendly display of monitored parameters on the web, but also helped in building-up a sizeable database of such parameters which can be later studied to come up with an even more efficient system of monitoring. Such a monitoring system eradicates any user input at the remote structure under observation and its automated and comprehensive results can be obtained over the internet in the comfort of one’s home or office, thus making it the first of its kind, both in academe or industry.

The refined algorithms for rating calculations using highway traffic with the automated system was established to have an accuracy approaching those of controlled truckload experiments. An efficient archive section was built that tracks the performance of the bridge. This archive gives an insight into the behavior of the bridge for the past day, week, month, etc.

Implementation Potential

The research has collected data and documented a number of previously unknown causative effects on bridge response and behavior. This knowledge can be cultivated to help optimize future bridge designs as well as bridge maintenance (including load-rating). We expect the data from this research to impact the AASHTO design and evaluation provisions pertaining to stringer bridges.

In addition, comprehensive measurements (both traffic and environmental) collected on one structure over an extended period of time has resulted in a unique database. This baseline information will provide a valuable and rational evaluation tool for bridge behavior.

The lessons learned regarding instrumentation, data acquisition and long-term monitoring have led to a rigorous and scientific evaluation of the reliability of existing sensors and data acquisition hardware and software for monitoring incremental and absolute long-term response. These will pave the way for future instrumented health-monitoring applications. Issues related to full-structure sensor arrays and intelligent structures will be explored as a significant benefit.

Valuable knowledge regarding the reliability and feasibility of various nondestructive evaluation technologies has been generated leading to more practical field test tools to aid bridge engineers.

The global NDE methodology explored in this research, based upon the structural identification concept and employing modal testing, truckload testing and instrumented monitoring as its principal experimental tools, showed great promise and revealed a number of interesting insights into stringer bridge behavior. The derived parameters (e.g., modal flexibility, unit influence lines, etc.) helped to establish relationships between various physical properties of the structure and also served as a baseline for future tracking its condition. Methods for calculating experimentally derived parameters (e.g., unit influence lines, distribution factors, inventory and operating rating factors, etc.) were established and then automated by custom software implemented by a dedicated real-time monitor.

Finally, the HAM-126-0881L bridge itself has been established as a fully operating intelligent structure. The remote monitoring capability developed at this site will serve as the basis for future remote monitoring bridge projects and efforts.