APPENDIX K: FLEET HEALTH MONITORING OF T-BEAM BRIDGES (PENNSYLVANIA, USA)

K.1. Introduction

It is well established that nation’s bridge population continues to age, and there are not enough funds for the rehabilitation and renewal of all existing bridges that are deemed as “deficient” due to posting. As rehabilitating and replacing “posted” bridges is deferred due to financial constraints, it has become even more important to be able to objectively evaluate the structural condition and safe load capacity of these deficient bridges. In the last decade there has been a great thrust for objective condition assessment, repair and renewal technologies, and non-destructive evaluation methods. However, it is unreasonable to expect that the time and resources required for an in-depth evaluation of every single one of more than 150,000 bridges deemed “structurally deficient of functionally obsolete” will be available (*Chase,2001*).

In this study, integrated applications of analytical, experimental and information technologies for reliable condition-assessment are presented for the health monitoring of large bridge populations in the context of “fleet monitoring.” A research study for re-qualification of 1,651 reinforced concrete T-beam bridges in Pennsylvania based on the fleet health monitoring concept is summarized in this example.

K.2. Description of the Bridges

Although a large number of Pennsylvania’s T-beam bridges are aged, deteriorated, and anticipated to be nearing the end of their service life, it is also expected that the actual load capacities and structural condition of these bridges may be much better than estimated due to the inherent desirable qualities of cast-in-place RC beam-slab

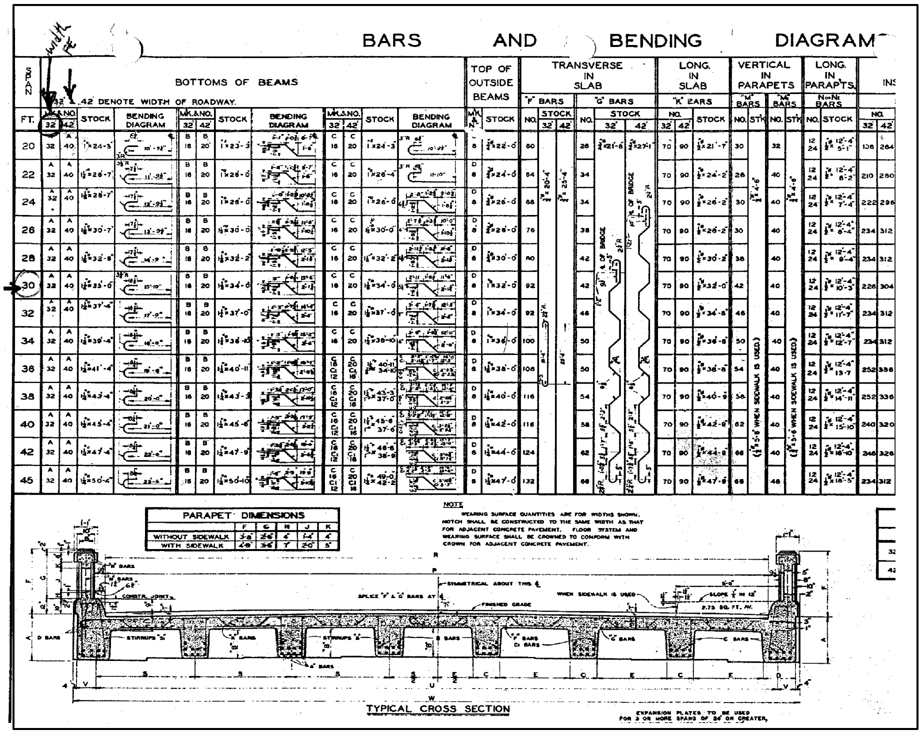

Figure 1: Standard design drawing sample

systems. If the mechanisms of additional safe capacity for T-beam bridges can be identified and the mechanisms that can be consistently relied on incorporated, it is possible to extend the service life of these bridges without compromising safety considerations.

Approximately 2,600 RC T-beam bridges were constructed in PA mostly between 1900's and 1960's by using a standard set of design drawings where the structural details and element dimensions depended on the span length and width of the bridge as shown Figure 1. Because these T-beam bridges share geometry and design details, materials and similar cast-in-place construction, and since monolithic cast-in-place RC beam-slab behavior is known to be excellent (*Al-Mahaid et al, 2000*; *Song et al, 2002*) the T-beam bridge population was an excellent candidate for a fleet-type-evaluation. A representative R.C. T-beam bridge is shown in Figure 2.

Figure 2: Representative reinforced concrete T-beam bridge

K.3. Statistical Sampling of T-beam Bridges

The first stage in evaluating the bridges is to understand the characteristics of the entire population (*Catbas et al, 2002*). In order to determine the parameters that should govern the statistical sampling, the writers hypothesized that the load capacity rating is a function of a number of statistically independent "nominal structural" and "as-is condition" parameters as given below.

Load Capacity Rating= f (Nominal Structural Parameters + Condition Parameters)

The nominal structural parameters included those related to specified materials, geometry, detailing, substructure and boundary conditions. The majority of the T-beam bridges were constructed in the 1930s using a standard set of drawings. In the standard design drawings, the structural details and element dimensions are dependent on the span length and width of the bridges. For example, when a bridge with certain plan geometry is selected, the beam sizes, reinforcement and all other details are automatically established. This "mechanistic" dependency greatly reduces the number of independent structural parameters.

The possible condition parameters for the statistical sampling included age, location, climate, maintenance history, deterioration, damage, condition rating, construction quality and district engineers' input. The challenge was in identifying which of these parameters were dependent on others, and which impacted the actual load carrying capacity of a bridge. Different parameters were analyzed by manipulating the inventory records by the help of GIS software ArcVIEW (2001). Statistics, histograms, population characteristics and geographic distribution within the state of Pennsylvania were evaluated.

It was hypothesized that the small number of condition parameters and the nominal structural parameters will govern the actual capacity rating for the 1,651 bridges, provided that undesirable brittle failure modes due to any deterioration of the superstructure or any deficiencies due to the substructures are eliminated. The nominal structural parameters could be reduced to just the span and skew, as width was found "statistically" dependent on span within the population, and the remaining proportions and detailing were dependent on span and skew. The condition parameters included the location (based on climate, truck-traffic and population density, the State was divided into North and South partitions), age, current condition rating and direct input from District Engineers, especially regarding those bridges they were most concerned about. As a result of the analysis, a sample set of 60 bridges that statistically represent the state's entire population of 1,651 single span T-beam bridges was identified (Figure 3). The remainder of the population either lacked data or were multi-span bridges that could not be considered as members of the same "fleet."

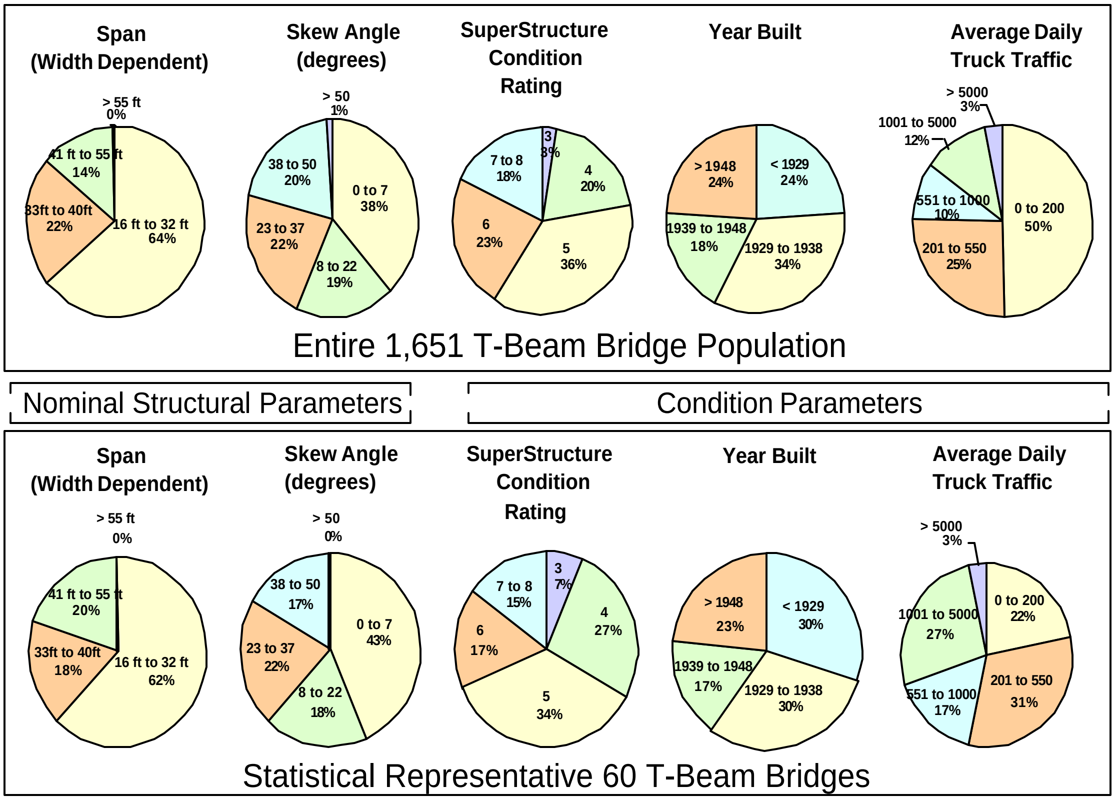

Figure 3: Characterization of the single span T-beam bridge population

The sample population also represents the entire population in terms of their distribution within the state. The entire population and the sample 60 bridges are shown in Figure 4.

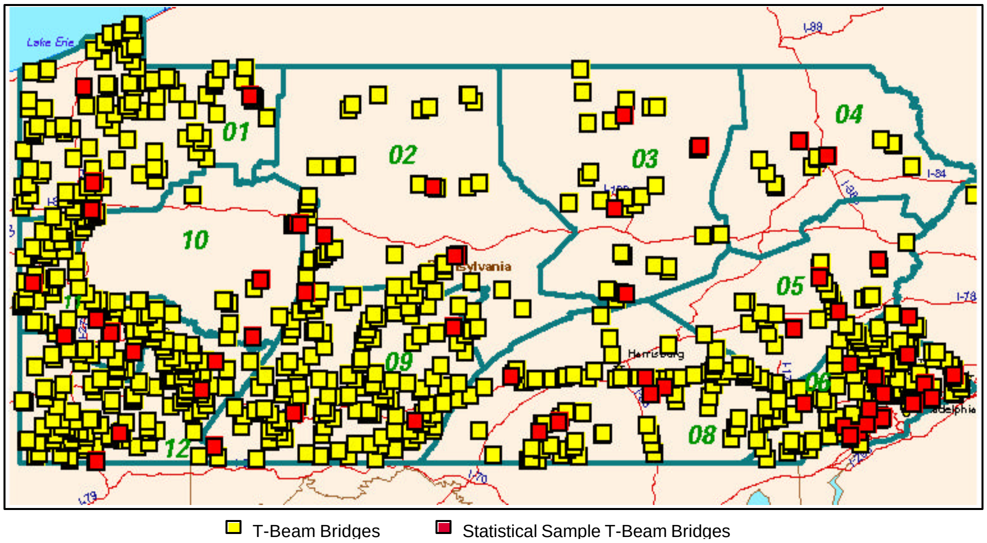

Figure 4: Distribution of entire the population and statistical sample of 60 bridges

K.4. Analytical Initiative

K.4.1. Bridge Characterization

The field inspections and structural testing of sample bridges from the T-beam bridge population provided invaluable insight into the as-is conditions of the bridges. Using the original design drawings and also by conceptualizing the geometry and boundary conditions, microscopic finite element models that simulated the exact spatial geometry and detailing of these bridges were constructed.

K.5. Finite Element Modeling

The finite element libraries of modern general-purpose structural analysis software, such as SAP 2000, offer various options for 3D FE modeling of a T-beam bridge. 3D solid and 3D frame elements were selected to construct a geometric replica analytical model, representing each concrete or reinforcing steel material point in the bridge with a corresponding material point on a one-to-one basis in the analytical model.

The finite element model constructed for such a "typical" bridge is illustrated in (Figure 5). This particular model features 151,011 degrees of freedom, employing 31,060 solid elements and 12,161 frame elements. Both longitudinal and transverse steel reinforcing bars were modeled on a one-to-one basis using frame elements and connected to the solid elements simulating perfect bond. The parapets and end diaphragms were modeled in detail. The restraints due to the dowels between the superstructure and abutment were modeled by defining "pin and roller" supports at the center nodes on the interface.

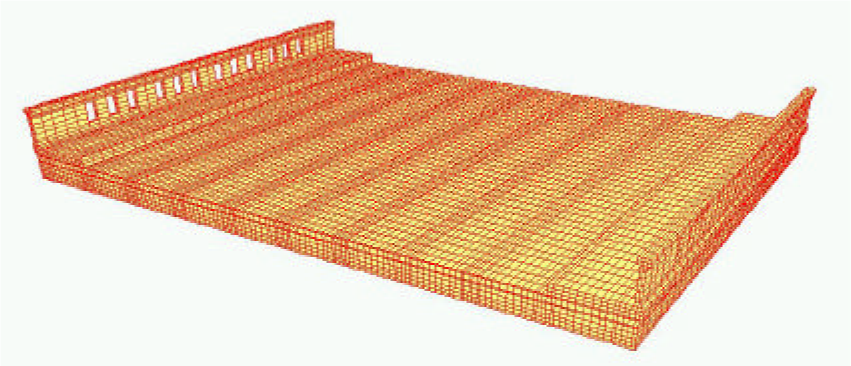

Figure 5: Finite element model of a T-beam bridge

K.6. Test Procedures

K.6.1. Field Inspection and Local NDE Applications

Rigorous field inspection, material tests, documentation and analysis were designed for the sample bridge population. Before visiting the bridges, any documents related to the bridges were collected. In addition, inputs from the District Engineers were solicited regarding any bridges they are concerned about. During the field visits, the location of the bridge was confirmed with respect to the National Bridge Inventory and latitude-longitude information was verified using GPS. Geometrics measurements and detailed pictures of the bridges are taken for documentation of the as-is condition. Cores were extracted to determine the material properties and condition of the concrete. The material properties were subsequently used when the finite element models were updated. To complement concrete coring, rebound hammer measurements were collected at different locations to map the material characteristics of the bridge.

Normal weathering and aging of the concrete is expected, however, any deterioration due to chemical attack is considered as significant. Another important objective was the inspection of the abutments and the superstructure-abutment interfaces for any visible settlement, scour, displacement or spalls. Regions close to the abutment were inspected to determine indications or susceptibility to shear distress. The secondary elements, such as diaphragm beams at the boundaries and reinforced concrete parapets, are inspected and evaluated since these elements also contribute to the structural behavior, although they are not explicitly considered in the design and load rating. In addition, petrographic analyses of concrete did not indicate chemical deterioration such as alkali-silica reaction.

K.6.2. Impact Testing

Impact test were conducted on each bridge to determine its dynamic properties. Since dynamic properties are a function of the mass, stiffness and damping of the bridges, it is possible to compare the dynamic properties of similar bridges to asses the condition. For a simple dynamic test to obtain the first few modal frequencies, data from only one or two accelerometer data may be enough under dynamic excitation such as traffic. However, in order to obtain the scaled mode shapes and the flexibility matrix of the bridge, a finer sensor array with known excitation is needed. Frequency, damping, mode shapes as well as modal flexibility of the bridge are generated from the data. The test results were used to calibrate the finite element models of the bridge. In particular, dynamic test data were used to verify or update the mass and stiffness distribution and the fixity at the boundary conditions.

Figure 6: Impact testing of a T-beam bridge

For the ipmcact tests, PCB 393C accelerometers which have a frequency band between 0.025 Hz and 800 Hz. were used. The excitation was provided by an instrumented hammer. From the preliminary analyses and the tests, the frequency band of interest for the single span T-beam bridges in this population was found to be within 10 Hz to 70 Hz. In general, 12-15 accelerometers were distributed on the deck. Figure 6 shows an impact test at a T-beam bridge. Modal flexibility coefficients, which are structural signatures with very conceptual physical meaning, were also computed at the measurement locations. The flexibility coefficients were then compared with results obtained using a falling weight deflectometer for the input source. Modal frequencies for four test bridges are shown in Table 1.

Table 1: Test bridge geometry and modal frequencies

Bridge Road Name	Span Length (ft)	Skew	Modal Frequencies (Hz)		
			Mode 1	Mode 2	Mode 3
Manoa	32	15	16.62	19.77	23.75
Swan	26	0	22.36	41.38	55.40
Buchanan Valley	34	0	16.29	21.34	47.39
SR 2026	40	45	21.10	32.81	47.11

K.6.3. Controlled Truck Load Test

Controlled load test were conducted at the representative test bridges to obtain responses under known truck loads. The test truck axels were weighed before the test with scales and the trucks were positioned at pre-determined locations. In addition, one truck was crawled on the bridge in each lane to generate influence lines for the bridge. Displacement sensors, weldable strain gages and clip gages for concrete strains were used during each load test. Figure 7 illustrates a sample instrumentation plan with sensor locations and a case utilizing two trucks.

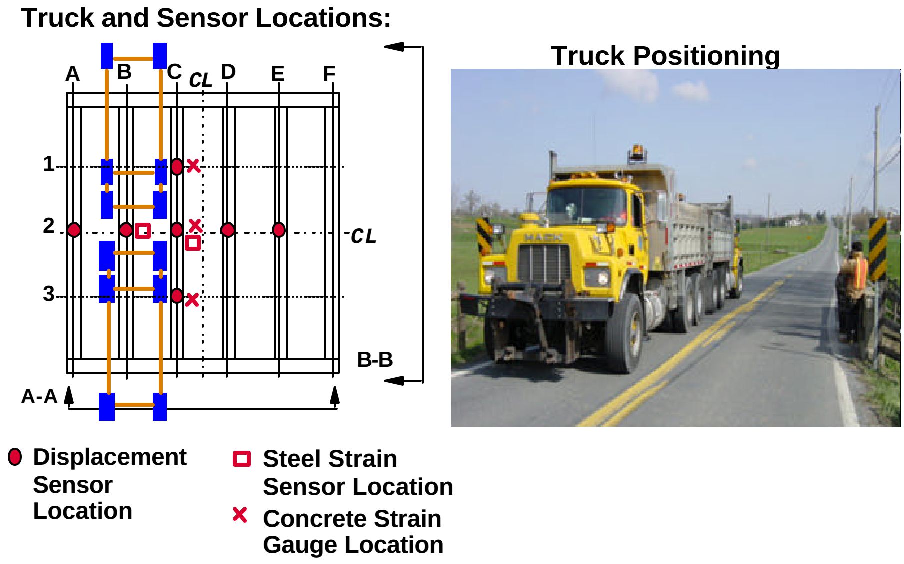

Figure 7: Sample instrumentation plan and truck loading

The steel reinforcing bar stress responses at critical locations were determined and compared to the yield stress. Similarly, concrete stresses under different loading conditions were evaluated. The deflection profile along a beam line and along a transverse line were obtained and compared with the L/800 AASHTO serviceability limit. In addition to evaluating critical locations, the test data were used to validate the local behavior of the analytical models and to generate a baseline for future tests. A summary of the test results is provided in Table 2.

Table 2: Load test summary from the test bridges

Bridge Road Name	Truck Load Applied[a] (Kip)	Max. Deflection (in)	L/800 (in)	Max. Rebar Stress (psi)	Max. Concrete Stress (psi)
Manoa	106	0.032	0.040	1237	222
Swan	98	0.015	0.032	886	120
Buchanan Valley	80	0.024	0.042	841	234
SR 2026	109	0.016	0.050	504	120

K.6.4. Falling Weight Deflectometer (FWD) Testing

Falling weight deflectometer (FWD) testing was being investigated as a practical test method to generate flexibility coefficients at the measurement locations. FWD has been used for pavement testing and the test set-up is optimized so that it is pulled by a van which also houses a personal computer that runs the test and data acquisition (Figure 8). The weight of the FWD may be increased and the weight may be dropped from different elevations to achieve the necessary peak loads. The concept of the FWD for generating the flexibility coefficients is analogous to the impact test, however, higher load levels can be achieved. The writers are investigating the suitability of the FWD system, which is designed for pavement testing as a practical tool for bridge testing.

Figure 8: Falling weight deflectometer (FWD) test

Flexibility coefficients derived from the FWD test are compared with the flexibility coefficients computed from the load test and the impact tests in Table 3. It is seen that there is a very high correlation between the three independent test methods for the Manoa Bridge. The other test results are also agree with each other reasonably well. More research is needed before this technology can be implemented. Some of the issues that need further research are different span lengths, pavement conditions, loading levels etc.

K.7. Purpose and Expected Outcomes From Health Monitoring

To restructure the problem of bridge condition assessment to a manageable size, the fleet-monitoring strategy that serves owners of airplane and truck fleets offers great promise. For example, airplane fleet owners take advantage of common symptoms and in-depth inspections of just a few members of a fleet and extrapolate these to the condition of large populations of similar vehicles that share a common use-history and age. It should also be noted that the concept of statistical sampling of large bridge populations has been implemented by other

Table 3: Modal flexibility coefficients from 3 different tests

	Flexibility Coefficients (in/kip x 10^{-3})		
Bridge Road Name	Load Test	Impact Test	FWD
Manoa	0.462	0.479	0.444
Swan	0.409	0.415	0.525
Buchanan Valley	0.459	-	0.493
SR 2026	0.402	-	-

researchers: Livingston and Amde (2000) investigated the causes of micro-cracking and additional deterioration in concrete due to formation of mineral ettringite by analyzing bridge populations (*Livingston and Amde, 2000*). In another study, Madanat et al (1996) developed statistical models of infrastructure facility deterioration by including the presence of persistent facility-specific but unobserved factors such as construction quality. They then extended the model to investigate the presence of state dependence to develop a model for bridge-deck deterioration. The data used for this study consisted of 5,700 state-owned bridges in Indiana and the condition ratings of these bridges were included in the analysis (*Madanat et al, 1997*).

Integrated applications of analytical, experimental and information technologies for reliable condition-assessment and then health monitoring of large bridge populations in the context of "fleet monitoring" offer promise in managing large populations. Fleet health monitoring, along with the various technologies can be employed as a complement, would provide objectivity to the current practice yielding better operation and maintenance management of large population of structures with similar geometric and condition parameters. The writers anticipate that the fleet monitoring concept can be implemented on other recurring infrastructure components such as transmission towers (*Catbas et al, 2002*).

K.8. Overview of Findings

The fleet strategy requires a determination of the nominal and as-is condition parameters that govern the load capacity of a "family" or "fleet" of bridges. The results of the study reported here, involving in-depth inspections of 27 bridges, in-depth structural testing and analysis of 4 bridges and analyses of an additional 10 representative bridges, it is possible to increase the load rating of the 1,651 single-span T-beam bridges between 6%-40%, even when using a very conservative approach. This investigation revealed that load rating of T-beam bridges by field-calibrated finite element models led to rating factors that exceeded the corresponding factors obtained by BAR7 analysis by at least two and a half times, and in some cases by as much as five times.

The bridge management consequences of the conclusions reached in this study are not insignificant. Currently, nearly half of the population of T-beam bridges are, or soon will be posted. The financial impact of deferring the replacement of the posted bridges for five years is substantial. Furthermore, it is possible to make more definitive estimates of the true capacity of T-beam bridges or quantify the impacts of additional mechanisms of conservatism that may permit increasing the current load rating values even more than twice as observed from the field-calibrated models of the test bridges. By inspecting and analyzing larger statistical samples, conducting nonlinear finite element analyses, and by controlled testing of analyzing decommissioned samples from the fleet to damage and destruction, it will be possible to obtain a much closer estimate of the true load capacity of the T-beam bridge fleet.