Load Rating Reinforced Concrete Bridges without Plans: State-of-the-Practice

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Synopsis: In response to Federal Highway Administration requirements, several states are in the process of ensuring all bridges within their inventories are load rated. A challenging aspect of this effort is load rating reinforced concrete bridges that have no structural plans when there are thousands of such structures within a state inventory. To inform these efforts, the literature was reviewed to identify existing methodologies and a survey was distributed to engineers at state departments of transportation throughout the United States to understand how practicing engineers approach this problem. The survey responses show there are numerous bridges in the U.S. without plans; over 25000 bridges without plans are located in the 18 states that provided responses. Concrete structures comprise 70% of such bridges. To load rate concrete bridges without plans, most responding states report primarily using engineering judgement, which may include reference to performance under existing traffic, era-specific design traffic loads, assumed material properties and reinforcement quantities, or data collected using load tests or non-destructive evaluation. Several methodologies are described and advantages/limitations of each are discussed.

Keywords: load rating, concrete, bridge, bridge with unknown details, NDE

INTRODUCTION AND BACKGROUND

The Kansas Department of Transportation (KDOT) is in the process of load rating all bridges in the state inventory in response to a Federal Highway Administration (FHWA) mandate. The scope of the task includes all bridges on the Kansas Local System, a network of nearly 20000 structures owned and operated by counties, cities, and other local municipalities. Structures owned and operated by state and federal agencies are not part of the Kansas Local System. There are no existing design or as-built plans for many of these structures. There are approximately 6000 reinforced and prestressed concrete bridges in the Kansas Local System without plans, although some information about these structures is known, including condition, span length, number of spans/lanes, traffic loads, etc. Load rating concrete bridges without plans is difficult because of the lack of information on member dimensions, material properties, and the size and location of reinforcing bars and/or strands. Some effective and established methods for load rating these structures, such as static proof load testing, are impractical for implementation across the entire inventory. Furthermore, accurate load ratings are essential, as load ratings that are too conservative cause bridge owners and the public to incur large costs because of disruptions to freight transfer routes and bridge retrofits or replacement.

The survey described herein was conducted to 1) approximately quantify how many concrete bridges without plans in the United States are not load rated and 2) document which methodologies are used by state departments of transportation (DOTs) to load rate large numbers of in-service reinforced and prestressed concrete bridges without plans. The aim of this paper is to summarize survey responses and therefore to characterize the state of the practice of load rating concrete bridges without plans in the United States. Reference is also made to pertinent literature to contextualize survey responses. A more detailed review of the literature and survey responses is described by Lequesne and Collins [1].

AASHTO Manual for Bridge Evaluation requirements

The AASHTO Manual for Bridge Evaluation (MBE) [2] includes detailed procedures for load rating bridges with existing plans. The procedures are intended to account for *in-situ* conditions (e.g., material properties, boundary conditions, deterioration, etc.). The intended result is a load rating with a reliability similar to new bridges.

For concrete bridges where important information such as amount and detailing of reinforcement is not available, the MBE [2] gives guidance that is considerably less specific than that for bridges with plans. It states in Section 6.1 that load ratings are to be determined using standardized procedures implemented by bridge owners (i.e., state DOTs). It does not indicate which procedures are preferred, except in Section 6.4 where it states that "a physical inspection of the bridge by a qualified inspector and evaluation by a qualified engineer may be sufficient to establish an approximate load rating based on rational criteria. Load tests may be helpful in establishing the safe load capacity for such structures." Finally, the MBE indicates in Section 6.1.4 that "a concrete bridge with unknown details need not be posted for restricted loading if it has been carrying normal traffic for an appreciable period and shows no distress."

The MBE [2] is therefore relatively unspecific with regard to the extent to which existing bridges with unknown details should be investigated and which load rating methodologies are acceptable. Furthermore, the FHWA, which is the regulatory entity requiring that all existing bridges be load rated, has not provided clear guidance to bridge owners and engineers regarding which methodologies it considers acceptable. One engineer stated, in response to the survey described below, "It is unclear what [methodologies] FHWA has allowed and disallowed." The result in practice is that bridge owners, engineers, and FHWA representatives often have different expectations regarding the approach to load rating these structures and the extent to which existing structures should be investigated. The practice of load rating bridges without plans therefore varies considerably among states.

Description of survey

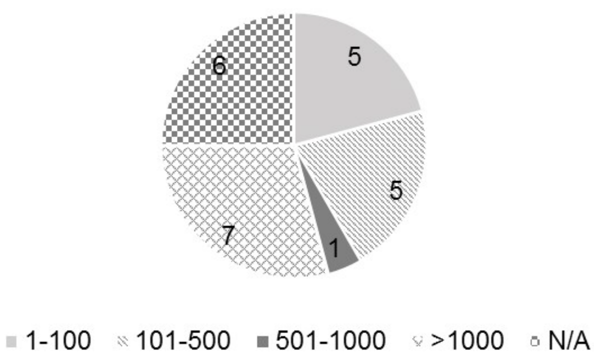
A survey was developed by the research team, with input from KDOT engineers, to gather information on the state-of-the-practice of load rating concrete bridges with no plans. The survey was divided into three sections, with the first simply gathering respondent contact information. The second section of the survey was designed to assess how states deal with the issue of rating concrete bridges with no plans, while the third and final section asked questions aimed at quantifying the scope of the issue within each state. The survey is shown in Appendix A of this paper.

Forty-nine state DOTs (excluding KDOT) were contacted about load rating concrete bridges with no plans. Ultimately, engineers at 24 states returned the survey and engineers at two state DOTs provided information via email and/or phone but did not return the survey. Survey responses varied widely in terms of their level of detail. Except for references to publically available documents, presented results are not associated with respondents because some states asked that their responses remain anonymous. A detailed summary of survey results is described by Lequesne and Collins [1].

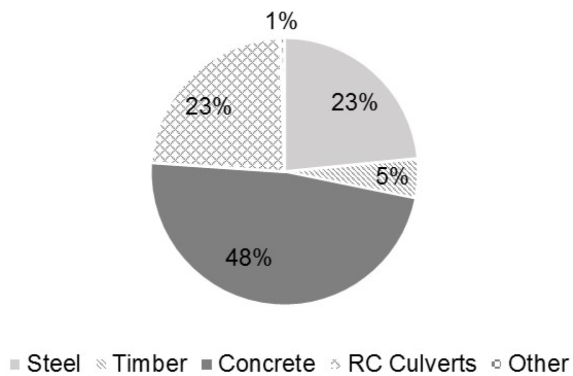
HOW MANY BRIDGES WITHOUT PLANS EXIST?

Respondents were asked for the number of bridges in their state for which there are no available plans, regardless of material. The 18 respondents (six survey respondents did not provide the number of bridges without plans in their state) reported over 25000 bridges with no plans. Extrapolation of these results implies the number of bridges without plans in the U.S. may be near 70000 if the responses are representative of other states.

The number of bridges without plans varies widely from state to state, with reported totals ranging from 7 to 6000. Figure 1(a) illustrates the range of responses, with reported statewide totals grouped into ranges of fewer than 100, 101 to 500, 501 to 1000, or more than 1000 bridges without plans. Seven of 18 states (39%) that responded to this question reported having more than 1000 bridges without plans in their inventory. States were also asked to indicate the number of bridges without plans made from various materials. As shown in Figure 1(b), the majority of bridges with no plans are concrete structures, representing 48% of responses, with reinforced concrete culverts representing an additional 23% of bridges without plans. The other bridges without plans are either steel (23%), timber (5%), or "other" (1%) structures.



(a) Number of bridges without plans



(b) Material-type of bridges without plans

Fig. 1—Scope of the problem for responding states

Across the nation, the scope of this problem is enormous. Concrete structures, including reinforced or prestressed concrete bridges and culverts, account for approximately 70% of the 25000 reported bridges without plans in the 18 states that provided responses to these questions. There are therefore tens of thousands of in-service concrete structures without plans in the U.S. While it is possible to determine an appropriate load rating for steel and timber structures after a detailed site investigation and testing of sampled materials, load rating reinforced concrete bridges without plans is less straightforward. Satisfying the FHWA mandate to load-rate all bridges is a large undertaking.

METHODOLOGIES FOR LOAD RATING CONCRETE BRIDGES WITHOUT PLANS

Survey respondents were asked which of five methodologies their state has used to load-rate concrete bridges with no plans. The five options were:

- Load testing,
- Destructive testing,
- Nondestructive testing,
- Rating based on known traffic loads and condition, and
- Engineering judgement.

It is evident that while some states have used load testing or other destructive or nondestructive testing approaches, the vast majority of concrete bridges without plans are rated based on engineering judgement and/or known traffic loads, which may overlap depending on the details of the procedure. The percentage of respondents who selected each methodology is shown in Figure 2. In the following sections, these and other methodologies are discussed. Reference is made to the literature and survey responses, as appropriate.

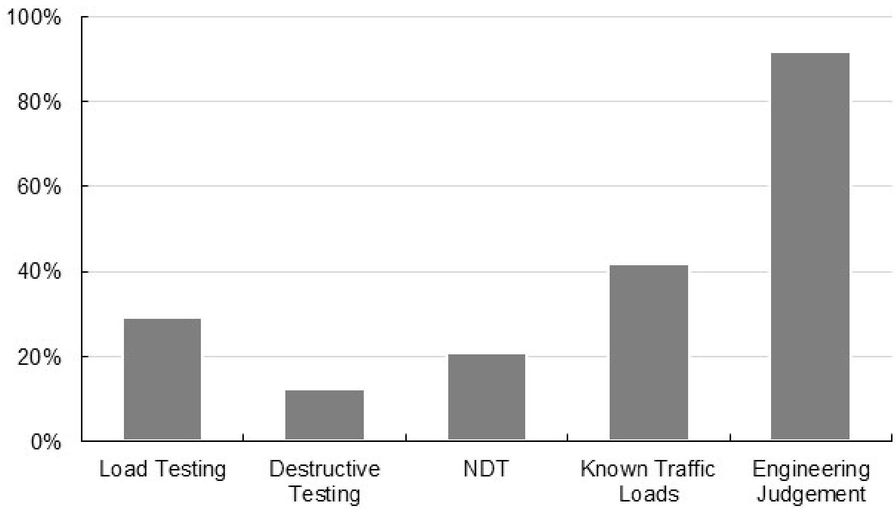


Fig. 2—Respondent approaches to load-rating concrete bridges with no plans

Rating based on bridge age and traffic loads

Several states assign load ratings based on engineering judgement, with or without supporting calculations. Regardless of whether it is explicit, such ratings rely on the assumption that a bridge that has been in service for years and remains in good condition is able to remain in service under similar conditions and traffic loads. In effect, the time-in-service is treated as a proof load test. Although there is a sound basis for this approach, as discussed below, there are some limitations. Unless additional physical testing, simulation, or reliability studies are undertaken, this approach should not be used as the sole basis for establishing a load rating when a bridge:

- Is being evaluated for an expected increase in traffic loads,
- Has fatigue-susceptible details, or
- Has evidence of critical deterioration.

Because most prestressed and reinforced concrete bridges do not fail in a manner related to fatigue, this approach is applicable to most concrete bridges without plans.

There is a sound basis for use of bridge condition surveys and knowledge of existing traffic loads to support bridge assessments. Reliability studies have shown that when bridge age and existing traffic loads are considered, the calculated annual reliability of an in-service structure significantly increases [3, 4]. In other words, whatever the annual reliability of the bridge was when it started carrying current traffic loads, its annual reliability at the time of reevaluation is larger if it remains in good condition. Wang et al. [4] explain, "surviving a service load history that is stochastic in nature provides evidence of structural reliability that may be comparable to what might be learned from a proof load test." Wang et al. also provide a brief example of how time-in-service affects the calculated reliability and probability of failure of a well-maintained concrete T-beam bridge. In their example, they show that the probability of failure decreases from approximately 0.006 at the time of construction to 0.001 after 50 years of service. The improvements in reliability occur because the distribution assumed for the bridge resistance (e.g., shear, flexure, etc.) can be truncated after accounting for the adequate behavior of the structure under traffic loads. To establish a load rating based on acceptable service under existing traffic loads, traffic data can be assumed based on published data [5] or measured near the structure using weigh-in-motion measurement technology.

Similar reliability methods can be used for detailed evaluation of an individual structure [6, 7] when additional information about the structure is available, including condition assessment, structural layout, boundary conditions, dimensions, material properties, and reinforcement amounts and detailing. This can be advantageous because it prevents overly conservative ratings that can be very costly. Such methods have been standardized in the Danish guideline titled "Reliability Based Classification of the Load Carrying Capacity of Existing Bridges" [8, 9]. However, the effort involved makes these reliability-based assessment approaches practical only for special structures.

Rating based on assigned rating factors

Several DOTs have established simplified procedures for assigning both inventory and operating rating factors without supporting calculations. In many cases, these states reference the MBE [2], which states, "a concrete bridge with unknown details need not be posted for restricted loading if it has been carrying normal traffic for an appreciable period." Inherent in this method is a reliance on bridge age and performance under traffic loads and a recognition that the annual reliability is currently larger than it was when the structure was first built [4].

In several states, it is policy to only allow this method to be applied to structures with a condition rating of 5 or better, where ratings of less than 5 indicate poor, serious, or critical condition. In some cases, state procedures provide little guidance beyond referencing engineering judgement for load rating bridges with condition ratings less than 5, while other states require some form of mandatory testing (e.g., nondestructive evaluation, destructive testing, load testing, etc.). Other DOTs employ a sliding scale, whereby load rating factors are diminished based on condition ratings. This method either directly applies rating factors based on condition or provides a condition reduction factor to be used in assigning load ratings. In some instances these scales only applying to certain structure types, while in others the rating factors apply to all concrete bridges with no plans. An example of assigned load factor rating (LFR) design load rating factors based on condition assessment is shown in Table 1. Table 2 shows example condition factors used in Oregon for rating national bridge inventory (NBI) items 59 or 60, which are the superstructure and substructure, respectively.

Table 1—Example of rating factors and load postings based on condition [10]

Condition Rating	LFR Design Load Rating Factors		Load Postings (tons)		
	Inventory	Operating	Single Unit	3 or 4 Axle Combinations	5 or More Axle Combinations
Good to Excellent - No signs of structural deterioration or distress.	1.00	1.66	No Posting Required		
Fair - Initial evidence of structural deterioration or distress. (No restrictions required)	0.75	1.25	No Posting Required		
Poor - Some structural deterioration or distress. (Legal Loads Only restriction)	0.60	1.00	No Posting Required		
Serious - Advance structural deterioration or distress evident. (Load posting required)	0.39	0.65	15	20	25
	0.21	0.35	8	12	14
Critical - Sever structural deterioration or distress evident.	0.13	0.22	5		

Table 2 – Condition factors used by the Oregon DOT for incorporating bridge condition in load ratings [11]

NBI Item 59 (or 60), Superstructure (or Substructure) Condition Rating	Condition Factor
5 "Fair Condition" or better	1.00
4 "Poor Condition"	0.50
3 "Serious Condition"	0.25
2 "Critical Condition"	0.12

As described previously, acceptable performance of a bridge under known traffic loads over time is a reasonable basis for establishing load ratings. This approach provides better evidence that existing reinforcement details in a particular structure are adequate for sustaining current loads than methods based on assumptions or comparisons with other structures. This approach is also cost effective, particularly for structures in fair or better condition.

For structures assigned condition ratings less than 5, the authors find it reasonable to assign rating factors correlated with bridge condition rating to bridges without plans. However, the basis for development of the factors shown in

Table 1 and Table 2 is unknown. Development of such factors should be done systematically and in a manner consistent with condition factors applied to bridges with plans.

This approach may be both appropriate and cost-effective for many structures without plans, but there are limitations. This approach does not provide evidence that can be easily extrapolated beyond normal traffic loads. For bridges being evaluated for overweight vehicles or changes in traffic loads, as well as for damaged bridges (e.g., due to impact), additional evidence may be required to support engineering decisions.

Rating based on historic design loads

Although inherent in the previous method, the use of historic design live loads can be used directly in calculations to determine rating factors. Some DOTs have implemented this method by tabulating historic live load moments and/or capacities based on span length, while others simply present historic live loads to be used in calculations. Other DOTs state historic design live loads should be used as part of an engineering judgement rating process, with little procedural guidance provided for doing so. An example of era-specific design live loads is shown in Table 3.

Table 3—Era-specific design live loads specified by the Washington DOT for use in load rating bridges [12]

Design Truck Designation	Design Load in Tons	Design Era
H-10	10	Early 1900 - Mid 1920s
H-15	15	Mid 1920s - Mid 1960s
H-20	20	Mid 1910s - 1920s
HS-15	27	Mid 1940s - Late 1960s
HS-20	36	Mid 1940s - Early 2000s

One way to implement this method systematically is to require that load ratings be assigned using operating capacity tables derived using historic design loads. Several states use this approach, but one state in particular has developed capacity tables based on results from parametric analyses conducted using historic design live loads (like those shown in Table 3) applied to groupings of similar structures. Although similar in form to those published by other state DOTs, it is unclear whether other tables were developed with a similar study.

The majority of states employing historic design live loads specify that this method is suited for structures showing little to no signs of distress. Little guidance is typically given for how to apply these procedures to bridges with condition ratings below fair. Oregon DOT procedures state that ratings should be lowered for "condition ratings that involve advanced deterioration," using condition factors shown in Table 2.

This methodology is expected to result in conservative assessments of the load-carrying capacity of bridges that continue to perform well in-service. The conservatism occurs because traffic loads have generally increased over time and the conservatism of new designs has generally decreased as engineers adopted increasingly refined design approaches. It seems appropriate for states that adopt this method to make some allowance, as some do, for engineering judgement to be used to avoid costly over-conservatism.

Rating based on association with similar bridges with known load ratings

Although few states do so, load ratings can be assigned to bridges without plans based on knowledge of other bridges in the owner's inventory or the NBI maintained by the FHWA [13]. In practice, this approach has been adopted by some engineers who know with some certainty that standard bridge plans were used throughout the state for design of bridges constructed within known periods. Under these circumstances, a qualified engineer establishes the load rating for one bridge that has detailed information available about design loads, structural configuration and proportions, reinforcement, and material properties. Engineers then assign the same load rating to all similar bridges within the inventory that were built around the same time and have similar condition ratings.

Some researchers have endeavored to adapt this approach so it can be applied more broadly. Catbas et al. [14] proposed using assessments of a statistically representative sample of bridges to make assessment and management decisions about larger populations of bridges. Their study focused on a population of 1650 reinforced concrete T-beam bridges in Pennsylvania. An analysis of the database indicated the load resisting mechanisms and critical failure modes of the bridges were governed by two independent variables, span length and skew, as long as unusual conditions such as foundation problems were ruled out by inspections. A small but representative sample of bridges was then randomly sampled from the larger population. Catbas et al. showed that findings from detailed assessments of the representative sample of bridges could be applied to the entire population with high enough confidence to inform resource allocation decisions by the bridge owner. Using this probabilistic approach to establish bridge load ratings was not discussed. It is important to note that the T-beam bridges considered in this study were believed to all be designed using similar procedures.

There have since been attempts to use a similar approach to develop load ratings based on large populations of bridges that were not designed using the same plans or procedures [15, 16, 17]. The researchers proposed using analytical procedures including multivariate regression, advanced neural networks, and machine learning to examine populations of bridges like the NBI [13], identify bridge characteristics that correlate with established load ratings, and produce estimates of load ratings for bridges that do not have plans. The results showed there is potential for this approach as a screening tool used to prioritize allocation of resources to potentially vulnerable bridges within an inventory.

There are, however, limitations. Although populations of bridge structures share many attributes, each structure is unique and can have unique vulnerabilities that are not common among bridges in the NBI [13]. This issue is highlighted by Foden and Van Brunt [18], wherein nominally identical slab bridges were found to have substantially different rotational fixity at supports that affected the relative strengths of the structures. Furthermore, it is difficult for the average engineer to dedicate the time required to fully understand the advanced analytical tools adopted in these studies. Engineers are therefore at the mercy of the models and not well positioned to apply judgement. It is the opinion of the authors that this type of approach may be a valuable screening tool but should not be used to assign load ratings – particularly to bridges with unusual details, construction defects, or other relatively unique features.

Bridges should only be assigned ratings based on association with similar structures when there is a high level of confidence that similar details were used in construction and after careful inspection to rule out anomalous features. Aside from that purpose, there is potential for using associations among bridges as a screening tool to prioritize investigation of bridges without plans.

Rating based on assumed or measured structural properties

Some state procedures require load rating calculations even when as-built and/or design plans do not exist for concrete bridges. In these instances, engineers are required to use either assumed or measured material and structural properties. Measured properties can include field measurements of structural geometry, non-destructive testing to determine reinforcing bar/strand size and location, and/or destructive testing to determine concrete properties. Assumed properties used in load rating include era-specific concrete strengths as well as steel quantities based on ideally reinforced sections. These assumed or measured properties are then used in load rating calculations or in conjunction with one of the other approaches presented.

Numerous nondestructive evaluation (NDE) methods exist for concrete structures [19]. Committee 228 at the American Concrete Institute authored a report [19] that provides a thorough review of NDE methods, including discussions of advantages and limitations. Relatively few NDE methods provide a consistent and accurate means of identifying the size, location, and detailing of reinforcement. Visual inspections, which are essential for determining bridge condition ratings, can provide information about reinforcement location and size when concrete spalling has exposed reinforcement. However, most structures fortunately have too little spalling for this to provide a sufficient basis for structural calculations. Covermeters provide reasonably good information about bar spacing and can be used to estimate bar sizes. Ground penetrating radar can also be used to locate reinforcement, but identifying bar sizes is usually not possible. Furthermore, these methods do not easily identify reinforcement placed below other reinforcement (i.e., in layers). Another useful method is radiography, although the cost and safety concerns prohibit widespread use. Nevertheless, only 20% of responding states indicated they occasionally use NDE as a basis for load ratings, and of those, most do so only when no other options are available. Examples of required NDE include one state that requires field measurements make use of “a measuring tape, a caliper, and a pachometer.” When using field measurements as the basis for load rating evaluation, another state specifies the use of “concrete coring, pachometer or steel coupon sampling if deemed necessary.”

Several approaches are used in practice when assuming properties of concrete bridges with no plans. One state has developed procedures based on an assumed ideally reinforced concrete section. Assuming a concrete compressive strength of 2500 psi (17 MPa) and a reinforcing steel yield stress of 33 or 40 ksi (230 or 280 MPa), depending on the era of construction, tables have been produced that provide an estimated steel area and flexural strength as a function of member depth. These values are used in the load rating process. Another approach recommended by a few state DOTs is to produce calculations for each structure that incorporate era-based concrete and steel material properties. This approach, however, requires some knowledge or estimate of reinforcing bar area and spacing.

It may be necessary to use assumed material and structural properties as the basis for load ratings in some limited circumstances. For instance, this approach may be appropriate if a bridge is being evaluated for a permit load or change in use (i.e., increased traffic loads) and load tests (described below) are not feasible. However, this approach has important limitations the engineer should keep in mind. For instance, while assumed material properties may be justifiable, it can be difficult to make verifiable assumptions about reinforcement amounts and detailing because each structure is unique and may have unique flaws. Knowledge of standard reinforcement details in use at the time of construction is not evidence the contractor and engineer made no mistakes or omissions of reinforcement in construction of a given structure. It is for this reason that the authors recommend comparisons against similar structures be used primarily as a population-screening tool (as described previously). Furthermore, use of NDE to verify assumptions is challenging in many cases, as all inspection technologies available for identifying reinforcement details have limitations on their application or utility. It may therefore be more prudent to use shear and flexural demands induced by known traffic loads that the bridge has adequately supported as a basis for estimating reinforcement amounts, or, more simply, assign load ratings as a direct function of known traffic loads.

Rating based on measurements taken when bridge is under load

Section 8 of the MBE [2] summarizes approved static and dynamic non-destructive load testing procedures. Static load testing procedures are sub-categorized into proof or diagnostic load tests. Static proof load tests may be used to establish load ratings for bridges without plans, among other applications. Static diagnostic load tests, as embodied in the MBE, cannot be used to determine load ratings for bridges without plans. However, they do have other applications that are discussed below. Dynamic loading procedures are sub-categorized into weigh-in-motion, dynamic response, and vibration tests. None of these can be used to establish load ratings for bridges without plans, although there are efforts to develop methods for doing so.

Use of load tests in practice—No state that responded to the survey requires load testing of all concrete bridges with no plans as part of the load rating process. However, approximately 30% of respondents have used load testing for some bridges (Figure 2), usually when deemed necessary due to on-site conditions. One respondent recommends load testing when bridges are structurally deficient or where posting is required due to overly conservative rating approaches. Another respondent state requires that a minimum of three bridges be load tested annually. Two other states officially indicate that load testing is an appropriate method for load rating concrete bridges with unknown details, but no specific guidance is given for conducting such testing and other methods are also permitted. Proof load tests are costly given the costs associated with lane closures, mobilization of equipment, instrumentation, etc. The authors believe that states are correct to reserve load testing for special circumstances, including for bridges that are structurally deficient, damaged, or severely deteriorated, as well as when evaluating a bridge for overweight vehicles.

Static proof load tests—The MBE [2] states that bridges without plans are potential candidates and beneficiaries of static proof load testing. Perhaps no other method for establishing a load rating results in higher confidence in the assigned rating. Furthermore, detailed knowledge of the bridge is not required when conducting a static proof load test.

A static proof load test consists of incrementally applying a static load to a bridge while closely monitoring the structure for signs of distress or non-linear behavior (see Saraf et al. [20] for an example). The imposed load must exceed, by some margin, the live load the bridge is expected to carry. The load rating for the bridge is determined from the proof load after accounting for the impact factor, live load factor, and other features such as non-redundancy of the bridge design, observed deterioration, extent of knowledge of the bridge condition and reinforcement, and observations during testing. Slightly different analysis procedures are recommended when static proof load tests are used for permit load decisions.

There is considerable evidence that deterministic methods for establishing load ratings based on proof load tests, embodied in the MBE [2], tend to be conservative. Several researchers have argued [4, 21, 22, 23, 24] there is a need to migrate to more reliability-based methods, which would tend to produce a more controlled level of conservatism. Reliability theory can also be used to determine an appropriate proof load magnitude based on age, condition, and actual traffic loads that will result in a load rating with the desired reliability [22, 25]. Regardless, these reliability-based methods continue to need research and standardization before they can be broadly implemented.

Static diagnostic load tests—Static diagnostic load tests described in the MBE [2] are used to validate or refine models of a bridge created based on known information about the structure. These are not used as a basis for load rating bridges without plans. The imposed loads tend to be less than the rated capacity of the structure, although the closer the applied load is to the unfactored gross rating, the more certain it is that the bridge can sustain factored loads. To conduct a static diagnostic load test according to the MBE, the prescribed load is positioned on the structure and then measurements of deformation are recorded. These measurements may include changes in strain, deflection, or rotation that occur in response to application of the load. Typically, multiple tests with the load positioned in different locations are required to maximize load effects on critical bridge components. Recorded data are then compared against the results of engineering calculations for that structure under the prescribed load. If, for instance, the measured strains are less than estimated, the load rating determined analytically may be increased as a function of the ratio between estimated and measured strains using prescribed procedures. This increase must account for the magnitude of the applied load, observations during testing, and the linearity of the measured response.

Static diagnostic load tests can be expensive, as they can require extensive instrumentation, mobilization of loading trucks, and diversion of traffic. Furthermore, engineers must be cautious when using models based on measurements taken under relatively small loads to determine load ratings because the behavior of a structure under small loads does not necessarily represent its behavior at its rated capacity [26]. This is because some mechanisms such as support stiffness and degree of composite action do not necessarily scale up like other mechanisms. Nevertheless, static diagnostic load tests have been used in many circumstances. These include for the purpose of establishing bridge load ratings when plans exist [21, 27, 28, 29], assessing damaged and deteriorated structures [30], and examining a structure prior to permitting for superloads [31].

Static diagnostic load tests conducted in accordance with the MBE [2] are not readily applicable to the problem of bridges without plans because they are generally used when detailed information about the structure is known. There have been some efforts by researchers to apply this method to bridges without plans by using measurements of deformations to estimate the amount of flexural reinforcement in structural members [32, 33]. However, these methods have inherent limitations, as they require the engineer to accurately assess the distribution of cracking throughout the span, extent of load sharing between members, extent of composite action, concrete creep strains, stiffness of supports, etc.

Dynamic load tests—Three types of dynamic data collection or testing are described in the MBE [2]. These methods may provide useful information about traffic loads and *in-situ* bridge behavior.

The first is weigh-in-motion testing, wherein sensors are used to collect traffic data. These data may include vehicle arrivals, axle loads, gross loads, axle configurations, and vehicle speed. These data can be paired with dynamic data collection to assess features of the bridge response or used to inform load rating decisions based on existing traffic loads (MBE Section 3.1). Data from this type of testing may be an improvement over generic traffic load data derived such that they are applicable to a broad population of bridges (such as that provided by Cattan and Mohammadi [15]).

Dynamic response tests are also described in the MBE [2]. In these tests, either normal traffic or controlled test vehicles crossing the bridge at speed are used to excite the bridge. Data are typically collected using strain gauges, although there is evidence that accelerometers can also be used [34]. Data collected under dynamic excitation are compared against data collected under static loading. These comparisons can be used to obtain estimates of the dynamic load allowance of an existing bridge. Data collected from dynamic response tests can also provide evidence of the live-load stress ranges experienced by bridge components. These results are insufficient to determine a load rating, but they can inform load rating and fatigue evaluation calculations.

Vibration tests are the last type of dynamic test described in the MBE [2]. These tests are used to determine dynamic characteristics of the structure such as frequencies of vibration, mode shapes, and damping. While normal traffic loads might be useable as a means of exciting the structure, it is also common to use portable shakers, sudden release of applied deflections, and other means of exciting the structure. Accelerometers are typically used to collect data during these tests, although some forms of non-contact data collection may be useful. For instance, high-definition video footage of the structure can sometimes be used to collect data about frequencies of vibration and mode shapes.

When conducted as described in the MBE [2], none of these dynamic tests provide information that can be readily converted into a load rating for a bridge without plans. However, each dynamic test may provide information that is useful to an engineer tasked with establishing a load rating for a bridge without plans. For example, information about traffic loads, dynamic load allowance, or dynamic stress ranges may be used to reduce some of the uncertainties associated with the necessary assumptions made in such an evaluation.

There have also been attempts by researchers to extrapolate from data collected during dynamic tests to establish load ratings for concrete bridges without plans. For instance, methods have been proposed for estimating reinforcement area based on modal properties determined from dynamic tests [35]. This approach has numerous inherent limitations, including that it requires the engineer to accurately assess the *in-situ* stiffness of supports, the extent and distribution of cracking throughout the structure, the shear stiffness of structural members, the extent of load sharing between structural members, the extent of composite action, effects of degradation and concrete creep, temperature [36], and other factors. There have been recent attempts to overcome these limitations by combining data collected from numerous tests conducted on a single structure without plans [37]. The approach requires the use of:

- NDT to determine structural member dimensions and concrete material properties (compressive strength and stiffness),
- Static diagnostic load tests to determine deflections and strains under load, which are then used to infer reinforcement quantities, and
- Dynamic vibration testing used to determine modal properties of the structure.

Results from these tests are then used to refine finite element models with the help of advanced analytical tools such as artificial neural networks and other optimization approaches. Bagheri et al. [37] were able to establish load ratings without access to bridge plans that closely matched the rating assigned to the structure by engineers with access to the bridge plans. However, this approach is expensive and clearly requires expert knowledge of instrumentation, field testing, finite element modeling, and mathematical optimization tools. Further development is necessary to streamline this approach before it can be implemented widely.

SUMMARY AND RECOMMENDATIONS

- There are a large number of concrete bridges in the U.S. without design or as-built drawings necessary for determining load ratings using conventional procedures. Within the 18 states that provided survey responses, there were reportedly 25000 bridges without plans, 70% of which are reinforced or prestressed concrete bridges or culverts.
- Numerous methods are used in practice or proposed for use in the literature. Prominent methods for assigning load ratings to bridges without plans are summarized in Table 4.
- Most bridge owners (90%) choose to use engineering judgement to load-rate concrete bridges without plans. When put into practice, this often means systematically assigning inventory and operating factors based on the observed condition of the structure. Because acceptable performance under traffic loads over many years is robust evidence of structural adequacy, this approach is cost-effective, consistent with MBE requirements, and supported (in concept) by the literature. This approach is not, however, conducive to assigning load ratings that exceed the usual traffic loads (e.g., evaluation for superloads).
- Some bridge owners use era-specific design traffic loads to load-rate structures. This approach is likely conservative, sometimes very much so. Some states that use this approach make an allowance for engineering judgement to reduce the over conservatism that can result from this approach, eliminating excessive posting.
- Some states use either load testing or NDE methods as part of the load rating process, but these approaches are commonly reserved for special cases where other methods are not applicable. While researchers have proposed methods for using dynamic load tests as the basis for load rating structures without plans, they need further refinement. Static proof load tests are currently the only load tests permitted or recommended for load rating concrete bridges without plans.
- Association with similar structures of a similar vintage and condition can be a useful screening tool for structures. However, because each structure is unique and may therefore have unique anomalies, this approach should not generally be used to determine structure-specific load ratings.
- Some states make assumptions about material and structural properties in the process of assigning load ratings. While it is generally accepted that conservative era-specific assumptions can be made for concrete and steel strengths, the authors do not recommend making assumptions about steel quantities and detailing.

Although such assumptions may facilitate detailed calculations, they cannot identify structure-specific anomalies or construction defects.

Table 4—Methodologies for Load Rating Bridges without Plans

Ratings based on…	Applicability/Utility	Advantages	Disadvantages
Bridge age, condition, and known traffic loads	Useful for load-rating a bridge for continued operation under existing loads.	Low cost method of obtaining a load rating substantiated by bridge condition and performance.	Not appropriate for evaluating structures for loads larger than traffic loads (e.g., superloads), severely damaged structures, or structures with fatigue-prone details.
Historic design loads	Useful when design loads can be determined with confidence.	Low cost and generally conservative.	Requires judgement to account for over conservatism or less than good condition assessments.
Association with similar structures	Useful for screening large populations of similar structures for vulnerabilities.	Can identify common vulnerabilities among populations of structures.	Should not be used for assigning load ratings to individual structures because similar structures can differ in important ways not visible to inspectors.
Assumed and measured properties	Measured properties can be used to refine calculations and models. Assumed properties should be used with caution. Assumed material properties are more justifiable than assumed reinforcement quantities.	Measured properties can result in more accurate calculated load ratings. Assumed material properties can expedite structural evaluations.	Measured properties can be expensive to obtain. Many engineers lack confidence in results obtained using NDE techniques. Assumed structural properties (e.g., reinforcement ratio) can result in unconservative load ratings.
Static proof load tests	Most useful for damaged bridges, bridges undergoing changes in use, or unique structures of high importance.	Most robust method for obtaining information about bridge capacity.	Too expensive for widespread use across large inventories.
Static diagnostic load tests	Used to calibrate and refine existing models of a structure.	Can lead to improved modelling accuracy.	Requires detailed knowledge of the structure. Static diagnostic tests should not be used to estimate important unknowns such as reinforcement quantity.
Dynamic load tests	Useful for quantifying ambient traffic loads, dynamic live load stress ranges, and modal properties of a bridge.	Can help define unknown quantities and improve modelling accuracy.	Requires detailed knowledge of the structure. Dynamic load tests should not be used to estimate important unknowns such as reinforcement quantity.

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APPENDIX A: SURVEY OF STATE DEPARTMENTS OF TRANSPORTATION

Rating Methodologies for Concrete Bridges without Plans

Survey for Departments of Transportation

Thank you for your participation in this survey designed to gather information on the rating of concrete bridges without plans. This information may be included in a final report to the Kansas Department of Transportation and/or subsequent publications. However, other than documenting participation, no identifying information will be associated in published documents with your specific responses.

This survey has three parts. The first gathers contact information for our internal purposes (this information will not be shared outside the research team). The second section is aimed at gathering information about how your state/locality deals with the issue of rating concrete bridges with no plans. The final section is designed to quantify the scope of this issue in your state or locality. As applicable, please provide all requested information and return to the University of Kansas (rlequesne@ku.edu or william.collins@ku.edu) by July 31, 2018.

1: Contact Information

1.1 State/Locality:

1.2 Contact Information:

Name:

Address:

Telephone:

Email:

2: Methods for Rating Concrete Bridges with No Plans:

2.1 What approaches has your state taken to load-rate concrete bridges with no plans? Please select all that apply, and indicate most prominent methods. If relevant, please attach additional details on how your preferred method(s) are used, and in what circumstances.

Load testing

Destructive testing (please specify/see 2.6)

Nondestructive testing (please specify/see 2.6)

Rate based on known traffic loads and condition

Use of 'engineering judgement' (please specify)

2.2 Does your state have a formalized process for rating concrete bridges with no plans?

Yes ☐ No ☐

2.2 If you responded 'Yes' to 2.2 please provide an overview of this process. Please attach any pertinent documentation with your survey responses

2.3 Does your state publish its own bridge evaluation manual?

Yes ☐ No ☐

2.4 If you responded 'Yes' to 2.3, is the rating process for concrete bridges with no plans addressed in this manual? Please attach (or provide links to) any applicable material with your survey responses.

Yes ☐ No ☐

2.5 Does your approach to rating concrete bridges with no plans follow the procedures recommended in the Manual for Bridge Evaluation (MBE)?

Yes ☐ No ☐

2.6 Do you use any specific technologies to aid in the process of rating concrete bridges with no plans?

Yes ☐ No ☐

2.7 If you responded 'Yes' to 2.6, what specific technologies have you used, and what information has this provided? How is this information used in the load rating process?

2.8 Please provide any additional information related to your methods for rating concrete bridges you feel would be beneficial for us as we look into this issue.

2.9 Please list any relevant documentation you have attached to this survey to supplement your responses.

3: Quantifying Scope of this Issue:

3.1 How many bridges exist in your state for which you have no plans?:

3.2 Provide the quantity of no-plan bridges in each of the following categories:

Rolled steel girders:

Built-up (welded/riveted/ bolted) steel plate girders:

Railroad flatcar structures:

Other steel structures:

Timber structures:

Reinforced concrete girders:

Prestressed concrete girders:

Reinforced concrete culverts:

Reinforced concrete slabs:

Other concrete structures (please specify):

Other concrete structures (please specify):

Other (please specify):

3.3. Are all of these bridges currently load rated? If no, are they in the process of being load rated?

3.4. Are Special Haul Vehicle postings currently required for any rated bridges in your state? If so, explain the sign(s) you are using for posting and if they are used in conjunction with any MUTCD signs such as R12-1 or R12-5.

3.5 In your state, who is responsible for rating bridges owned by counties/localities?:

3.6 Has your state ever been required to develop a Plan of Corrective Action for bridge load rating?

Yes ☐ No ☐

3.7 If you responded 'Yes' to 3.6, did this include bridges for which you had no plans?

Yes ☐ No ☐

3.8 Has your FHWA Division Bridge Engineer approved or disallowed specific methods for load rating bridges with no plans?

Yes ☐ No ☐

3.9 If you responded 'Yes' to question 3.8, what methods were approved? What methods were disallowed?

3.10 Has your FHWA Division Bridge Engineer ever requested additional information regarding the rating of bridges with no plans?

Yes ☐ No ☐

3.11 If you responded 'Yes' to question 3.10, what additional information was required? How did you approach this situation?

3.12 Please provide any additional information you feel would be beneficial for us as we look into this issue.

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