

# Bridge Load Rating Using Physical Testing

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## ABSTRACT

The problem of an aging and rapidly decaying infrastructure is an issue facing many agencies charged with maintaining a fully functioning transportation system. Numerous bridges of marginal condition must frequently be posted, resulting in detours with increased travel time and distances. However, when tested, these bridges often exhibit strength and stiffness characteristics beyond traditional codified parameters and beyond calculated rating procedures. The use of diagnostic load testing for the purpose of load rating has become an accepted practice for addressing these bridges by many public agencies. Commercial equipment and analytical tools, like the Bridge Diagnostics, Inc. (BDI) system, have simplified the process of testing, modeling, and rating bridges.

This paper presents a current effort at Iowa State University to evaluate and document the applicability, ease-of-use, and accuracy of a system for load rating of bridges through physical testing. To illustrate the use of the physical load testing, results from the load rating of one of seven bridges that were part of the current research are presented. A typical bridge was instrumented with 40 strain transducers and tested with known loads using the BDI system. Several finite element models of the bridge were then developed and calibrated based on the observed behavior and the field measured strain. Results from the calibrated model were then used to carry out load rating calculations which were then compared to traditional rating calculations. The resulting ratings showed a general increase over the traditional codified ratings. For the subject bridge, various configurations of strain gages were investigated with respect to general influence on modeling and rating accuracy. The results of this sensitivity study are also presented.

**Keywords: bridge testing—Load rating**

## **INTRODUCTION**

The 2001 Iowa National Bridge Inventory (NBI) Report indicated that of the 25,138 bridges in Iowa, 7,102 (29%) are either structurally deficient or functionally obsolete. While many of these bridges may be strengthened or rehabilitated, some simply need to be replaced. Before implementing one of these options, one should consider performing a diagnostic load test on the structure to more accurately assess its load carrying capacity. Frequently, diagnostic load tests reveal strength and serviceability characteristics that exceed the predicted codified parameters. Usually, the codified parameters are conservative when predicting the load distribution characteristics and the influence of other structural attributes; hence the predicted rating factors are often conservative. In cases where calculations show a structural deficiency, it may be very beneficial to apply a tool that utilizes a more accurate model that incorporates field-test data; at a minimum, this approach would result in more accurate load ratings and frequently results in increased rating factors. Bridge Diagnostics, Inc. (BDI) developed hardware and software that is specially designed for performing bridge-ratings based on data from physical testing. The hardware consists of pre-wired strain transducers, a data acquisition system, and other components. The software consists of three separate programs for visually evaluating test data, developing an analytical model, analyzing and calibrating the model, and performing load-rating calculations with the calibrated model.

## **BRIDGE TESTING SYSTEM**

The Structural Testing System (STS) is the field component of the testing system, and consists of four main elements: the BDI Intelliducers, the BDI STS Units, the BDI Autoclicker, and the BDI Power Unit. The main purpose of using the STS is to collect bridge behavior data. Specifically, collecting strain data as a truck with known dimensions and weight is driven over the bridge. It is common to position the truck in at least three different transverse positions: the outer wheel line placed at two feet from each curb and the truck centered on the bridge. Additional positions may also be included if needed. Typically, the truck will be driven in each lane twice to verify that the recorded strains are consistent.

The BDI Intelliducer, shown in Fig. 1, is the strain transducer used with the BDI system for measuring bridge response. Each Intelliducer measures 4.4 in. x 1.2 in. x 0.4 in., with either a 15-ft or 25-ft wire attached and has the ability to identify itself to the rest of the system with a unique number (i.e., 4696, 4788, etc.) that can be identified and recognized by the STS power unit (described subsequently). From this unique number, the system has the ability to calibrate and zero the gage using a pre-stored gage calibration factor. Intelliducers may be used on many different surfaces, including, but not limited to, steel, concrete (reinforced and pre-stressed), and timber. For gage placement on reinforced concrete structures, gage extensions should be implemented to increase the 3-inch gage length; the longer length enables surface strains to be averaged over a greater distance, thus reducing the effects of aggregate and cracks in the concrete.



**FIGURE 1. A BDI Intelliducer in Use on Top of a Concrete Curb**

The BDI STS Unit transfers the data collected from the Intelliducers to the Power Unit (described subsequently). Each STS Unit is capable of collecting data from four Intelliducers and has the capability of storing 50,000 data points during a single test. At the conclusion of a test, the data are transferred to the Power Unit. The unit is equipped with six connection points, four transducer connections, a “line out” connection, and a “line in” connection. All of the connections are quick-lock, military-style. The “line out” transmits data to the Power Unit. The “line in” connection is designed to attach to other units in series and/or parallel through the use of Y-cables. This wiring configuration is a significant advantage over traditional transducer wiring in that only a single cable is connected to the Power Unit.

The Power Unit powers the Intelliducers and transmits commands to the system during the test. Each transducer requires a 5-volt excitation voltage that is provided by the Power Unit. The unit has the ability to operate under two different power sources: DC current from an automobile battery or AC current from a small portable generator or inverter.

The BDI Autoclicker measures and transmits the load vehicle position to the Power Unit through the use of an electronic eye and hand-held radio transmitters. A reflective strip placed on the load vehicle’s tire triggers the electronic eye. Thus, every wheel revolution creates a “click” in the data. These “clicks” are used to convert data collected in the time domain to the truck position domain.

The control functions of the system are performed by the STS software. The software is run in a Microsoft Windows environment on a laptop computer that is attached, via a parallel port, to the Power Unit. The system is relatively easy to use with pull down menus and large command buttons. The main software menu window contains most of the information that is critical to the load test. Items such as sample frequency, test length, and file output name are easily accessible in the main window. Other options specifically related to Intelliducers such as channel gain, initial offset, and filtering are located in the advanced options menu. Careful attention should be given to these settings to ensure proper data collection.

The BDI Software Package is the analytical modeling part of the testing system, and consists of three main components: WinGRF – data presentation, WinGEN - model generator, and WinSAC - structural analysis and correlation. All elements serve different purposes, but each is essential to the overall process. Each component has been developed such that data can be seamlessly moved from one application to another. These three components are described in detail in the following paragraphs.

WinGRF is used for graphical data presentation, and is the first step in the modeling process. With a known truck position plots can be viewed to observe bridge behavior information, such as

the presence of end restraint, non-symmetric behavior, etc as the truck crosses the bridge. Plots, such as neutral axis location, may also be constructed if the distance between a pair of top and bottom Intelliducers has been input in the program.

WinGEN is a finite element model generator developed specifically for bridge modeling. This application allows the user to create models using beam and shell elements. A 2-D model can be created using the WinGEN; however, it is also possible to create a 3-D model using a commercial drafting program, such as AutoCAD, which is then imported into WinGEN.

After a model has been created in WinGEN, the WinGEN output file is used in WinSAC. WinSAC performs analytical calculations and also constructs iterative analytical solutions by changing user defined optimization parameters within user defined boundaries. The resulting model, in the best way possible, represents the actual bridge behavior given user entered constraints. Typical variables chosen as optimization parameters are beam moments of inertia, modulus of elasticity of slabs, and rotational restraint at the supports. The user sets the appropriate boundaries, so that the final optimized variables are within reasonable values. Analytical accuracy is reported in terms of total error, percent error, percent scale error, and correlation coefficient.

## **TESTING OF BOONE COUNTY BRIDGE #11**

Boone County Bridge #11, located in northern Boone County, IA, is a non-composite, simple-span, steel-girder bridge with a timber deck and no skew carrying L Rd. over a small stream one mile North of 130th Street. Based on a cursory visual inspection and photographic documentation, all steel-girders except one appeared to be, with the exception of some light rust, in good condition. The girder on the far West side was bent at midspan (possibly hit by a large object during a flood). The timber deck is in good condition. A photograph of the underneath side of the bridge is illustrated in Fig. 2 This bridge has a span length of 38 ft – 10 in. from centerline to centerline of bearings with a roadway width of 17 ft and an overall width of 19 ft – 9 in. (one 12 ft traffic lane and two 2 ft – 6 in. shoulders).

The timber deck consists of a 4-in. thick wood plank system with a 6-in. gravel overlay without structural connection to the girders. The superstructure is comprised of eight girders and four lines of diaphragms bolted to the girders. The substructure consists of expansion bearings and timber backwalls. The exterior beams and the six interior beams are the same size and are spaced on 2 ft – 6 3/8 in. centers. As shown in Fig. 3b, four of the eight girders were instrumented near the abutments, at midspan, and at quarterspan near the North abutment and two of the remaining four girders were instrumented near the North abutment and at midspan. Each instrumented sections had an Intelliducer installed on the bottom surface of the top and bottom flanges as previously described such that a total of 40 Intelliducers were installed at 20 locations.

A loaded tandem-axle dump truck with a total weight of 49.58 k was used in the tests. Data were collected for three truck paths with two runs conducted for each path. Path Y1 was oriented such that the driver's side wheel line was 8 ft – 11 in. from the far East girder (with the outer wheel line placed 2 ft from the centerline of the East girder), and Path Y2 positioned the truck approximately over the center of the bridge with the driver's side wheel line 11 ft – 11 in. from the East girder. Finally, Path Y3 was oriented with the driver's side wheel line 15 ft – 8 in. from the East girder (the outer wheel line was placed 2 ft from the West girder). Truck path information is summarized in Fig. 3.



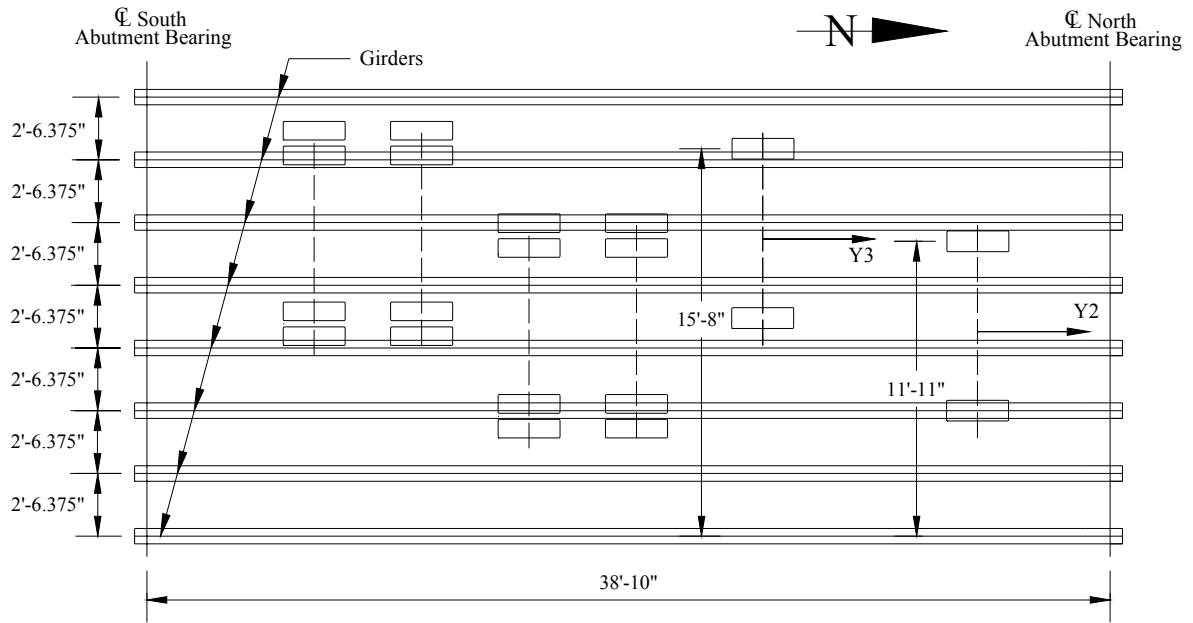
**FIGURE 2. Photograph of Bridge Superstructure**

The experimental data showed that compression was induced in the top flange and tension occurred in the bottom flange near the abutment. This indicates that this bridge has minimal end restraint. The location of the neutral axis was found to be approximately at mid depth of all sections; hence, non-composite action could be verified.

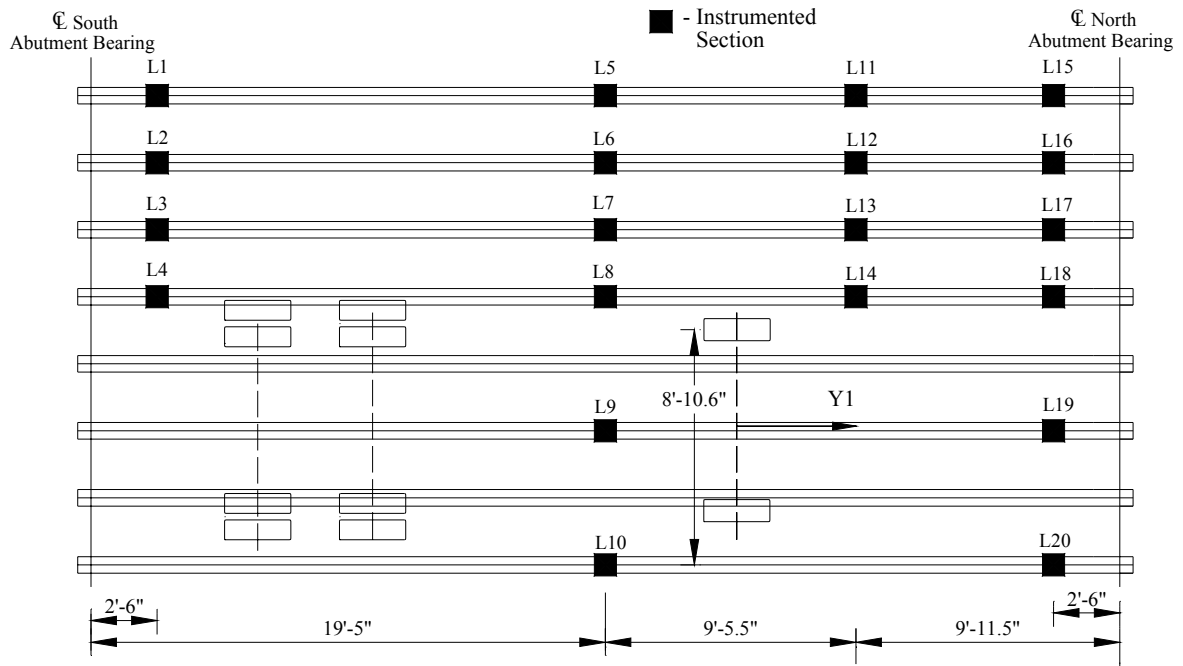
Based on the initial review of the data briefly discussed in the previous paragraph, an analytical model (Model 1) was created using one element between each girder in the transverse direction and twelve elements in the longitudinal direction. Although the experimental data indicate insignificant end restraint, rotational springs were included for all girders at the centerline of the abutment bearings to verify this behavior. As a result of the experimental data indicating that all girders behave non-compositely, the girders in the analytical model were created as one uniform, non-composite section along the length of the bridge.

Table 1 summarizes the optimized parameter results for Model 1 using only the Intelliducers at midspan (L5-L10) and near the North abutment (L15-L20). These results indicate that all optimized parameters (excluding the springs) compare very well with the initially selected parameters. An example of the accuracy of the model is shown graphically in Fig. 4. All results compare well (e.g., less than 2% error with a correlation coefficient of 0.99).

The rating model was created using the optimized model (Model 1) with the appropriate rating trucks and dead load on the structure. Dead load applied to the structure included the self-weight of the steel girders, a 4-in. thick timber deck, a 6 in. x 15 in. wood curb applied on the exterior girders, a weight of 25 lb/ft distributed uniformly over both exterior girders to take into account the steel rail on top of the wood curb, a uniform load distributed over the interior beams to take into account the dead load of the diaphragms, and an additional 6-in. deep gravel overlay on top of the timber deck.



(a) Overall bridge dimensions and truck paths Y2 and Y3.



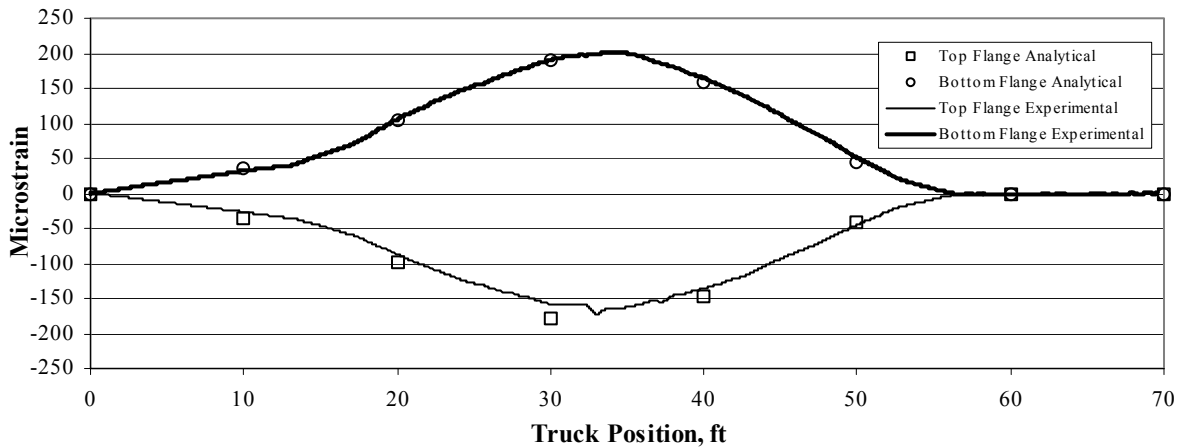
(b) Truck path Y1 and gage locations.

**FIGURE 3. Overall Dimensions, Gage Locations, and Truck paths**

**TABLE 1. Adjustable Parameters for Model 1**

Section	Property	Units	Initial	Optimized
Girder	$I_y$	$\text{in}^4$	1,230	1,255
Timber deck	E	ksi	1,000	845
Spring (rotational)	$K_y$	in-k/rad	0	29,210 <sup>a</sup>

<sup>a</sup> Corresponds to approximately 8 % fixity.



**FIGURE 4. Typical Strain Plots for Path Y3 at Location L5 using Model 1**

Individual member capacities were calculated following appropriate AASHTO Standard Specifications. Ratings obtained using the LFD Method (by applying AASHTO Standard Specifications) and by using the BDI Software are presented in Table 2. Table 3 summarizes the percent difference in inventory ratings between the LFD Method and the BDI Method (note: a positive percent difference indicates that the BDI Software rating value is greater than the LFD Method rating value). The critical rating condition is for flexure at the interior girder (0.92 by the LFD Method and 1.31 by the BDI Method for a difference of 42 %). It should be pointed out that lane loadings were also investigated in accordance with AASHTO Standard Specifications and were determined to not be critical.

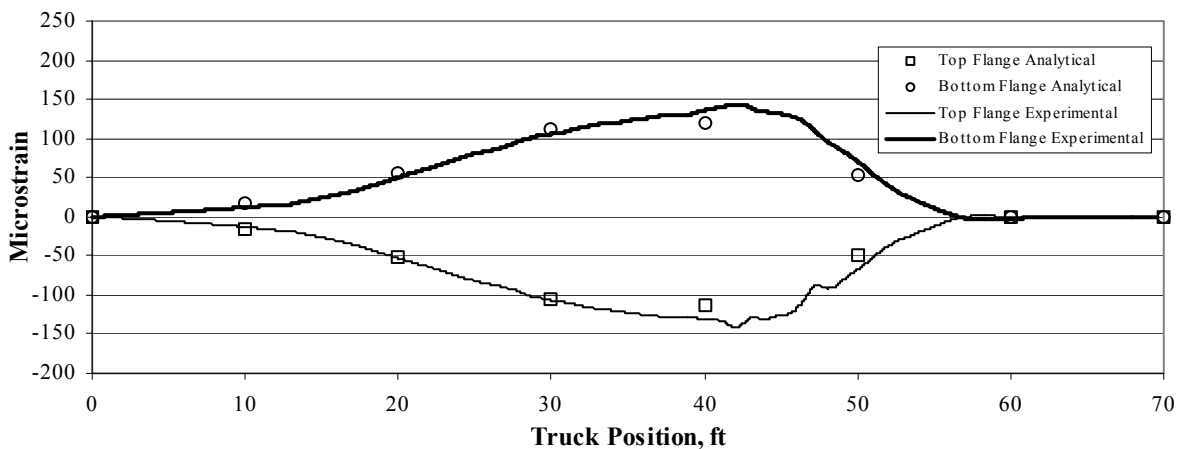
**TABLE 2. Rating Factors by the LFD and BDI Methods**

Section	HS-20				H-20				Type-3			
	Flexure		Shear		Flexure		Shear		Flexure		Shear	
	Inv.	Ope.	Inv.	Ope.	Inv.	Ope.	Inv.	Ope.	Inv.	Ope.	Inv.	Ope.
<b>LFD Method</b>												
Interior Girders	0.92	1.53	3.94	6.57	1.16	1.94	5.76	9.62	1.17	1.95	5.32	8.87
Exterior Girders	1.00	1.67	4.22	7.04	1.27	2.12	6.41	10.70	1.27	2.13	5.91	9.87
<b>BDI Method</b>												
	1.31	2.18	4.78	7.97	1.58	2.64	6.09	10.16	1.75	2.92	6.63	11.06
	1.54	2.57	7.61	12.70	1.97	3.29	11.56	19.29	1.99	3.33	10.37	17.31

**TABLE 3. Percent Difference in Inventory Ratings between LFD Method and BDI Software**

Section	HS-20		H-20		Type-3	
	Flexure	Shear	Flexure	Shear	Flexure	Shear
Interior Girders	42.4	21.3	36.2	5.7	49.6	24.6
Exterior Girders	54.0	80.3	55.1	80.3	56.7	75.5

As previously described, Intelliducers used in the testing were located near the abutments, at midspan and at the quarter-span near one end. However, only the Intelliducers located at midspan and near the North abutment were included in the optimization process. After the optimized model was developed (based on the limited number of gages), the bridge was analyzed to predict the behavior at the locations not used in the optimization process. The purpose of this was to verify that it is possible to predict strains at locations where no gages are attached. It was found that the predicted strains (example shown in Fig.5) correlate very well with the experimental strains. The model accuracy with all gages included had an error of only 2.1%.



**FIGURE 5. Typical Strain Plots for Path Y3 at Location L13 Using Model 1**



## **DISCUSSION AND CONCLUSIONS**

The field testing of Boone County Bridge #11 answered many questions about the structure. The girders were found to act non-compositely and that there was very little fixity at the abutments. In addition, it was found that there was very little edge stiffening present. A review of the rating factors revealed that the critical rating factor was 42% higher when determined using the BDI method.

Commercial systems, such as the BDI system, have been found to be effective tools to implement the testing, modeling, and rating of existing bridges. With an aging and rapidly decaying bridge inventory, the effective management of marginal condition structures is becoming a pressing issue. Diagnostic load testing for the purpose of load rating is the only currently available technique for determining accurate load carrying characteristics. Most bridges exhibit strength that exceeds that which traditional calculations predict and results in more accurate and increased load rating. Identification of the “reserve” strength often delays when bridges must be rehabilitated or replaced which results in significant long-term cost savings. While it is recognized that developing load ratings through diagnostic testing costs more than load ratings by traditional hand calculations, the long-term savings resulting from extending a bridge’s useful life may offset these costs.

## **ACKNOWLEDGMENTS**

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