Design and Implementation of Load Cell Bearings to Measure Dead and Live Load Effects in an Aged Long Span Bridge

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ABSTRACT: In the spring of 2010, the expansion bearings of the Burlington-Bristol Bridge were replaced due to a poor condition rating (that caused the bridge to be classified as structurally deficient). The replacement of these bearings represented a unique opportunity to configure the new bearings to monitor the dead load and live load actions as well as their variation with environmental conditions. Towards that end, a series of trial designs were developed with various bearing types, load cell configurations, etc. These candidate designs were then evaluated through a series of finite element analyses and a single design was selected. To validate the selected design, a prototype was developed and tested in the laboratory under various axial forces, unidirectional and bidirectional moments, and shear forces. Once validated, 14 “smart bearings” were fabricated and installed on the Burlington-Bristol Bridge. To verify their proper operation, a series of load tests were carried out following installation. This paper and presentation will detail the development and validation activities for the “smart bearings” as well as the results from the first few months of long-term monitoring. In addition, non-technical challenges associated with developing appropriate design and performance specifications for the bearings will be discussed.

1. INTRODUCTION
In evaluating structures for their levels of safety, current methods are heavily reliant on load rating techniques. Varying state Department of Transportation’s each have their own specific guidelines as to the general method used or even the more detailed loading configuration to be used within the general methods. Irrespective of the methodology used, each follows the same general form of calculating a rating factor:

\[(F_C*\text{Capacity} – F_{DL}*\text{Dead Load}) / F_{LL}*\text{Live Load},\]

where \(F_C\), \(F_{DL}\) and \(F_{LL}\) are factors to be applied to capacity, dead load and live load, respectively. The methodologies enforce different analysis techniques by varying how the factors amplify or decrease the effects of its respective component. For example, the Allowable Stress Factor calculation reduces the capacity by a factor of 0.55 and does not amplify live or dead load effects, leaving their respective multiplication factors at 1.0. In contrast, a Load and Resistance Factor Rating (LRFR) method reduces the capacity by a factor of 0.9 and amplifies the dead and live load actions by a factor of 1.3. These differences in load rating methods, as well as the uncertainty in the complex structural analyses required to generate the live and dead load reactions, more specifically for long span structures, can lead to a significant variance in the load ratings of critical members. This has put bridge owners in a difficult position, as they are sometimes left with varying rating factors based on the calculation used and has generated motivation for an experimental method to more accurately estimate the real dead and live load effects on a structure over time.

As part of a large research effort into load rating methods of aged long span structures, Drexel University has designed and is currently testing Load Cell Bridge Bearings, which will be able to measure and transmit in real time the axial and bidirectional moment forces applied to multiple elastomeric bearing assemblies throughout an aged multi-span steel truss structure (Figure 1). In
conjunction with other methods which will provide the in-situ stresses of critical members, typical daily and weekly traffic responses as well as strain response due to seasonal effects, the Load Cell Bearings will provide crucial information regarding force paths, seating forces, vehicle weights and seasonal changes in bearing forces.

The incorporation of load cell sensing technology into a bearing replacement project for this structure required great planning and design to provide a system capable of accurately performing over the full lifetime of the bearing. The planning and design required the collaboration of various sensor vendors, bearing manufacturers and engineering firms, as well as Drexel University research staff.

The critical design milestones were identified as:
- Bearing Location
- Bearing Design and Finite Element Verification
- Component and Assemblage Verification
- Instrumentation Infrastructure
- Data Acquisition Design

Bearing Location
The locations of the load cell bearings (Figure 2) were carefully considered so that the maximum amount of useful information could be obtained from the structure regarding its performance. Since all expansion bearings were being replaced (Figure 3), it was decided that each of the new expansion bearings would have smart technology incorporated into the design. It was also decided to select one set of fixed bearings for replacement, allowing for the capability of one span to have all bearings measuring the reaction force. The full instrumentation of one span not only provides the researchers with the full dead load reactions, but also serves as a means of weighing the traffic load crossing the structure at any given time. This fully instrumented span will provide valuable data to be incorporated into the other monitoring systems installed on the structure. The remaining spans with smart technology incorporated into their expansion bearings will provide information as to how the structures are responding to temperature variation, live load effects and variation of dead load forces over time.

1.1 Background
The bridge to be instrumented with the Load Cell Bearings is an eighty year old steel truss structure with a vertical lift span capable of providing vertical clearances of up to 138 feet for ship passage. The bridge is a critical link in the surrounding transportation network between several large metropolitan areas and serves an Average Daily Traffic (ADT) demand of 25,000. The structure has had minor rehabilitations over its lifetime, mostly limited to deck reconstruction and floor system repair and strengthening. The structure was classified as being structurally deficient, partly due to its poor functional obsolescence score influenced by the narrow travel lanes and lack of shoulders as well as a poor substructure rating due to the presence of the original bearings which have lost their functionality over time. The bridge has since improved its sufficiency rating upon completing abutment repairs, however the need to replace the expansion bearings is still essential. In an effort to further raise the structural deficiency rating, the engineer of record called for a design of new bearings for the structure to replace all existing expansion bearings. At this time, Drexel University suggested incorporating sensing technology to enhance the functionality of the bearings as well as to provide critical response measurements of the structure due to traffic loading and seasonal effects. The bridge owner realized the great importance in learning this type of information from its structures and agreed to incorporate the Load Cell Bearing technology into the design to replace the expansion bearings.

2. LOAD CELL BEARING DESIGN AND PLANNING

Figure 1: Long span steel truss bridge to be instrumented with Smart Bearings

Figure 2: Instrumentation plan of smart bearings
Bearing Design and Finite Element Verification
The most important requirement in the design process of the load cell bearings is that the sensing technology could not compromise the structural integrity of the bearing or detract from its core functionality. With this in mind, an initial set of requirements was put together by Drexel University staff stating the basic performance specifications of the sensors used with respect to both the sensing functionality as well as its functionality as a structural component within the bearing assembly.

2.1 Bearing Requirements
The load cell bearings are being installed on two main span types on the structure, each with their own capacity requirements of the bearing. The expansion bearings of the 200 ft tower spans require an axial force capacity of approximately 400 kips, while the expansion bearings of the 125 ft truss approach spans require an axial force capacity of 200 kips. The bearing design consists of reinforced neoprene vulcanized to steel plates which are rigidly attached to the structure and the pier. The only difference between the tower and truss span bearings is the height of the reinforced neoprene section, to allow for higher capacity and higher range of anticipated deflection.

2.2 Sensor Requirements
In order to provide accurate measurements of force over long periods of time, high capacity-low profile load cells were specified as the sensor technology to be incorporated into the bearing. To ensure that the load cells are not experiencing drift over their service life, vibrating wire sensors are to be installed in parallel with the load cells.

Specifications were supplied to a load cell vendor chosen by the project contractor and a load cell was selected. The load cell vendor and Drexel University then worked together to provide a pattern of these load cells within the assembly to most efficiently transfer all of the bearing forces. This required constructing a geometric model of the bearing assembly (Figure 4) as well as multiple finite element models of the various design iterations to ensure that the capacity of the bearing is sufficient for the design loads specified. The geometric model consisted of seven major load cell bearing components. These components were modeled accurately to ensure that all space requirements were met.

2.3 Final Design and FE Verification
The final design of the load cell assembly was achieved after multiple design iterations and verification. The load cell pattern accepted (Figure 5) consist of five load cells symmetrically spaced between two steel plates. The load cells are configured in a way to provide shear resistance within the bearing assembly without compromising the ability of the load cells to measure the total axial force.
In examining the geometric model, Drexel University staff wanted to ensure that the stresses within the plate were within acceptable limits; however these responses could not be calculated intuitively. A three dimensional finite element model (Figure 6) was constructed using ABAQUS to verify that the design of the load cell spacing and installation procedures were sufficient to withstand the service loads the bearing is expected to see. The full anticipated design load was applied to the portion of the model which reflected the actual in situ connection. The reinforced neoprene was modeled using alternating layers of steel material and a linear material which had properties as realistic as possible to neoprene. Even though rubber is not linear in nature, it was modeled this way to reduce the time required for model analysis.

The load cells were modeled in geometric replication to their exterior dimensions. The interior structure of the load cell is proprietary, limiting the ability to accurately model the exact sensing configuration. The three dimensional model allows for exact geometric representation of all components within the bearing assembly, including the spherical contact surfaces of the load cells and the shear interfaces on the masonry plate and bottom plate. The model utilized quadratic elements of both hexagonal and tetrahedral types, depending on the geometry of the component in which they were modeling. The analysis of the final design showed that von Mises stresses within the top base plate (Figure 7) were satisfactory between the load cell locations. It is also noteworthy that the contact stresses at the location of the load cells were high; however this is expected considering the spherical nature of the load cell button. The button will plastically deform the plate as it indents into the steel, ensuring ideal contact conditions for the load cell. Upon completion of the finite element modeling of the bearing assembly, the five load cell configuration was approved pending further full-scale laboratory testing.

3. COMPONENT AND ASSEMBLAGE VERIFICATION

As required in the specifications, the load cell vendor supplied Drexel University with a sample of the 100 kip capacity load cells to be used in the bearing assembly. A series of tests was performed on the load cell using a Model FX-400 Forney compression machine, with an inbuilt load cell measuring up to 400,000 lbs ± 0.5% FS (calibrated on April 8, 2009).

Testing comprised:
- Cyclic concentric loading at: (1) 10,000 lbs increments up to full range (100,000 lbs), and (2) 1000 lbs increments at 50,000 ± 5000 lbs
- Cyclic eccentric loading at 5000 lbs increments up to 50,000 lbs
• Cyclic loading of the load cell inclined at 10°. Loading consisted of 5000 lbs increments up to 50,000 lbs.

The eccentric load scenario was used to verify that the load cell will function with satisfactory results under cases where the load is not applied directly in the center of the load cell button. This could happen due to manufacturer error in machining the shear interfaces of the plates. The inclined load scenario simulated the forces the load cell will experience in the assembly. Each load cell will transfer the shear force in the bearing to the masonry plate affixed to the pier, so it must be able to measure axial force accurately under shear loading.

At each load increment, the vendor load cell and the Forney load cell readings were recorded and plotted against each other (Figure 8). The test results showed that the vendor load cell read to within ±2.5% of the Forney load cell for all performed tests. Given that the Forney load cell is only accurate to within 2000 lbs, these results indicate that the vendor load cell will read with sufficient precision. On the basis of the test results thus far, the load cell was approved and the manufacturer was told to proceed with production of the full bearing assembly for further verification.

Figure 8: Results from eccentric load test of vendor load cell

The full assemblage testing program consisted of multiple setups designed to simulate expected forces and reactions within the bearing to prove that the load cell assembly will perform to specifications. The first setup consisted of loading the bearing in a concentric axial manner to test the full capacity capabilities of the assembly (Figure 1). This setup required the use of two hydraulic actuators so that the full design force of 400 kips could be applied. The load was transmitted to the bearing through a stiff steel beam placed at the center of the bearing parallel to the direction in which the truss gusset plates of the truss will be connected.

The next testing setup included a specially designed load plate which rotated the bearing 10° about its East-West axis. In this manner, it was possible to load the bearing in shear as well as axial compression so that the rigidity of the load cell assembly under shear loading could be studied (Figure 2).

Figure 9: Shear loading configuration

Overall, the accuracy of the load cell bearing assembly within the load cell’s measurement range limits was satisfactory. As a means of presenting the comparison of the measured response versus the applied load, the two data sets are plotted against each other. The closer the slope of the best fit line for this relationship is to 1, the higher the overall correlation of the measured load compared to the applied load. In this case the slope is 1.008, showing the high degree of accuracy supplied by
the load cell bearing assembly over the range of forces applied.

Instrumentation Infrastructure

The expected lifetime of the Smart Bearing system is at least fifty years. The long lifetime expected of these bearings requires instrumentation cables to be durable and resistant to effects of extreme weather and roadway conditions. In conjunction with the engineer of record for the bridge, a network of instrumentation cables protected by hard conduit was designed provided with weather-proof military style connectors for each load cell and vibrating wire sensor. This rugged instrumentation infrastructure will minimize the amount of maintenance needed throughout the lifetime of the bearings by eliminating damage to cables from future construction, environmental conditions and contamination from wildlife living on the structure. Each load cell requires a six-wire instrumentation cable run from the load cell location to the data acquisition site and likewise, each vibrating wire strain sensor requires a four-wire instrumentation cable run from the bearing location to the data acquisition site.

4. DATA ACQUISITION DESIGN

The total network of load cell bearing assembly requires a data acquisition system which can measure seventy load cells and fifty-six vibrating wire strain gages. In order to reduce cable lengths across the length of the bridge, the total network was divided into two sub-networks: the northern approach network and the southern approach network. The northern approach network consists of a CR5000 data acquisition system capable of measuring fifty load cells and forty vibrating wire strain sensors. The southern approach network also consists of a CR5000 data acquisition system capable of measuring twenty load cells and sixteen vibrating wire sensors. The load cells and the vibrating wire sensors are both measured utilizing multiplexers, greatly minimizing the cost of the total data acquisition system. The high speed multiplexer allows twenty-five load cells to be measured at 30Hz per channel. The vibrating wire sensors will be sampled at a much lower frequency as they are only utilized for ensuring long term stability of the load cell system. The total number of channels required on the Campbell Scientific CR5000 for the northern approach network is five, leaving fifteen more channels free for future monitoring equipment. The data acquisition system will be installed within a weather-proof NEMA certified enclosure, provided with connections for each sensor coming into the location.

Data will be recorded and stored remotely using a fiber optic network cable installed along the length of the bridge. This will allow Drexel University staff to synchronize the multiple data loggers used for the load cell bearing system as well as other currently installed monitoring systems, providing a comprehensive monitoring network which can be accessed from any location with an internet connection.

5. CONCLUSION AND FUTURE WORK

In evaluating structures for their levels of safety, current methods are heavily reliant on load rating techniques. Varying state Department of Transportation’s each have their own specific guidelines as to the global method used or even the more detailed loading configuration to be used within the general methods. These differences in load rating methods, as well as the uncertainty in the complex structural analyses required to generate the live and dead load reactions, more specifically for long span structures, can lead to a significant variance in the load ratings of critical members. This has put bridge owners in a difficult position, as they have to consider methods which generate poor ratings even though other methods have satisfactory ratings and has generated motivation for an experimental method to more accurately understand the real dead and live load effects on a structure over time.

As part of a large research effort into load rating methods of aged long span structures, Drexel University has designed and is currently testing Load Cell Bridge Bearings, which will be able to transmit in real time the axial and bi-directional moment forces measured by multiple elastomeric bearing assemblies throughout an aged multi-span steel truss structure. In conjunction with other methods which will provide the in-situ stresses of
critical members, typical daily and weekly traffic responses as well as strain response due to seasonal effects, the Smart Bearings will provide crucial information regarding force paths, seating forces, vehicle weights and seasonal changes in bearing forces.

In this presentation, a design for monitoring bearing reaction forces will be discussed as well as the current status of the project. The presentation will also include the preliminary results from the installation of the bearings on the bridge.