Comparison of Historical In-Service Monitoring Data for Improved Maintenance and Management of Typical Bridges

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Abstract. An In-Service Bridge Monitoring System (ISBMS) has been developed and implemented for gathering quantitative strain data from typical bridges, due to site-specific traffic. The ISBMS has been used to monitor 15 different bridges in Delaware, multiple times, over a period of five years. By comparing data sets collected at different times, changes in the bridge response, due to damage or deterioration could potentially be detected. Because visual comparison is subjective, a method for quantitatively comparing two data sets from the same bridge has been developed: this can be used as a low level health monitoring tool. Results of comparisons from different seasons on the same bridge did not indicate any seasonal variations in the data. In-service load rating factors were also computed and found, in most cases, to be higher than the corresponding theoretical rating factors.

1. Introduction

Periodic in-service monitoring of typical bridges is a practical and cost-effective approach to health monitoring of the majority of bridges in an owner's inventory. It is unlikely that the day will come when simple grade crossing bridges are designed and built with permanent structural health monitoring systems. However, periodic in-service monitoring can be effectively used to gather quantitative data on these types of bridges. By gathering such data at different intervals of time, during the life of the bridge, a quantitative historical record can be constructed that shows how the bridge deteriorates over time. Research has been ongoing at the University of Delaware to develop, test, and implement, simple technologies for gathering such data on ordinary bridges [1-3]

A small, battery operated In-Service Bridge Monitoring System (ISBMS) has been used to monitor the strain induced in typical bridges due to site specific traffic. During a typical data collection trial, which usually lasts between 2 and 3 weeks, the system continuously collects the peak strain "events" induced in a key girder. The system operates by recording data continuously at 200 samples/sec. When the strain exceeds a user specified threshold (usually set to between 25 and 75 microstrain) the system captures and stores the peak strain of the time history, and saves it, along with the date and time the event was triggered to memory. When downloaded the data includes a table of the peak strains from each event and the data and time that they occurred. A photograph of the ISBMS mounted to a girder is shown in Figure 1. The data can be used to calculate a load-rating based on the in-service data, for fatigue evaluation, and ultimately for damage assessment of the bridge.

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The ISBMS has been deployed on 15 different bridges in Delaware dating back to September, 2006. Eleven of the bridges have been monitored twice, with at least two years in between trials. Two of the bridges have been monitored three different times. Tests have also been conducted on the same bridge at different times of the year, to determine if there are any variations in the data due to the seasonal changes. By comparing data sets from different trials, several years apart, one should be able to infer either qualitatively or quantitatively if the bridge has deteriorated, or if traffic has changed. Before this can be done, however, a method for comparing datasets and determining when they are different, has to be developed.

Figure 1. ISBMS mounted on girder

Presented in the paper are the results of a recent study to collect and compare datasets collected at different times on the 15 bridges. To compare two datasets collected at different times on the same bridge, a quantitative method is needed for deciding when the datasets are similar, and when they are not. Three different parameters were used to characterize the datasets and compare the results from different trials. Thresholds were determined to denote when a change is significant. In-service load ratings factors were also calculated for the 15 bridges and compared to the AASHTO predicted rating factors. Moving forward, the system and the data can be used for the long term maintenance and management of a state's bridge inventory.

2. Description of the Bridges and Bridge Monitoring

The ISBMS was deployed on a total of 15 bridges in Delaware over the past six years. A number of criteria were used to select the bridges to be monitored, including: (1) ease of access, (2) proximity to the University of Delaware, (3) must have a steel superstructure, (4) relatively high Average Daily Truck Traffic (ADTT), and (5) are not over railways or large bodies of water. All of these criteria were adopted to minimize the support required for maintenance of traffic to deploy and retrieve the ISBMS. All but one of the bridges were monitored at least twice over the six year period. One bridge was monitored just once, in 2006, and has not been monitored again because of the poor quality of the data retrieved because of the low ADTT. Table 1 summarizes the details of the 14 bridges that were monitored at least twice between 2006 and 2011.

All of the bridges are constructed of rolled, wide-flange steel members. The ISBMS strain transducer was placed longitudinally at mid-span on the girder specified in the table on the bottom of the bottom flange. Every effort was made to locate the sensor on the girder that would experience the highest strains, i.e., underneath the right travel lane. Data collection on each bridge lasted, on average, 14 days. Some trials were shorter because the system memory filled and the unit automatically shut down; some were longer. Presented in Table 2 is the list of when each bridge was monitored, for how long, and how many events were collected. One can see that the number of events varied from a low of 62 in 13 days on bridge 1-234, to highs of 5943 (the storage capacity of the ISBMS) for several of the bridges.

3. In-service Data

One of the challenges in setting up the ISBMS is to set the trigger threshold correctly so that a large number of events will be captured before the battery drains, but not so many are

collected that the memory fills before the desired monitoring period ends (usually at least 14 days). The trigger level may vary depending on the traffic on the bridge, condition of the bridge, etc. Presented in Table 3 is the strain threshold assigned for each bridge, the number of events collected, and the maximum strain recorded. The number of events recorded ranged from a low of 807 to a high of 5943. The maximum strain recorded ranged from a low of 77 με to a high of 422 με.

The in-service data can be displayed in timeline and histogram plots. The timeline chronologically plots the peak strains that exceeded the trigger threshold. The histogram plots the number of events recorded for particular microstrain bins. An example timeline plot, for bridge 1-826N, is shown in Figure 2(a.) and the corresponding histogram for the data is shown in Figure 2(b.).

Table 1. General bridge information and gauge locations

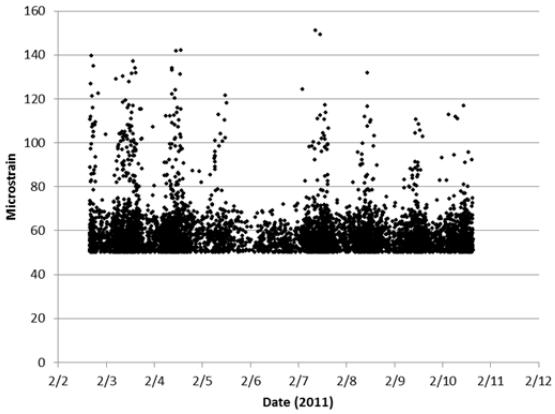
Bridge Number	**Year Built**	**ADT**	**Percent Trucks**	**Number of Spans**	**Number of Girders**	**Span Tested**	**Span Length**	**Girder Tested**	**Prev. Monitor**
1-781	1967	25,420	12	3	6	1	32'-0"	10	✓
1-728	1958	3,670	12	3	5	1	35'-3"	3	✓
1-704	1962	60,884	4	3	12	3	25'-1 ¾"	6	✓
1-826 S	1972	38,521	4	3	7	3	70'-0"	4	
1-262 S	1981	28,756	9	5	7	1	90'-0"	3	✓
1-826 N	1972	31,963	4	3	7	3	70'-0"	4	✓
1-911 S	2003	19,190	12	1	6	1	65'-0"	3	✓
1-821 N	1975	39,148	12	4	9	3	76'-7 5/8"	5	✓
1-791	1966	18,624	12	3	6	1	35'-0"	3	✓
2-918 N	1992	20,949	12	1	6	1	65'-0"	10	✓
2-920 N	1992	15,352	12	1	6	1	65'-0"	11	
1-907 S	2003	2,528	7	1	5	1	81'-0"	3	
1-394 S	1964	12,825	12	3	5	2	62'-0"	2	✓
1-149	1989	17,546	7	1	11	1	80'-0"	8	✓

Table 2. Bridge monitoring periods (2006-2011)

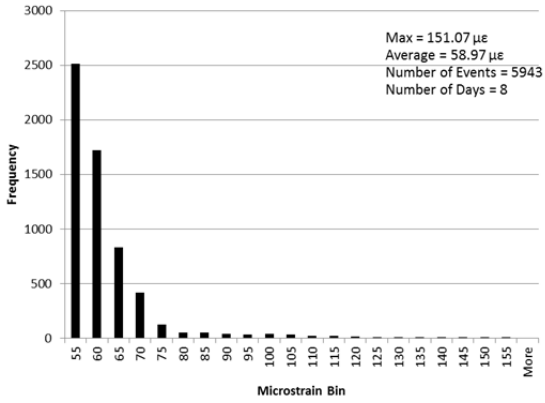
Bridge Number	1st Monitor			2nd Monitor			3rd Monitor		
	Start Date	Days	Events	Start Date	Days	Events	Start Date	Days	Events
1-791	9/26/2006	14	2,889	10/1/2010	14.5	1,430			
1-149	3/21/2006	14	1,892	3/31/2011	13	5,943			
1-826 N	5/01/2006	15	4,204	5/21/2010	5	5,936	2/2/2011	8	5,943
1-234	8/16/2006	13	62						
1-262 S	6/06/2006	14	754	6/10/2010	14	2,983			
1-704	8/30/2006	13	1,543	3/9/2010	10	1,616			
2-918 N	10/24/2007	14	1,576	10/20/2010	14	3,752			
1-911 S	6/07/2007	5	5,937	7/9/2010	6	5,943	11/17/2010	15	3,836
1-781	9/17/2007	13	3,027	11/17/2009	21	5,328			
1-821 N	7/31/2007	6	5,937	7/22/2010	5	5,943			
1-728	12/04/2007	17	1,145	12/10/2009	9	1,059			
1-394 S	8/23/2007	20	1,275	3/7/2011	24	3,141			
1-826 S	6/24/2010	5	5,283						
2-920 N	11/03/2010	14	5,943						
1-907 S	12/02/2010	14	1,176						

Table 3. Summary of collected in-service data (2009-2011)

Bridge Number	Number of Days	Threshold (με)	Number of Events	Maximum Event (με)
1-781	21	35	3,889	120.66
1-728	9	25	807	77.08
1-704	10	55	843	106.68
1-826 S	5	40	5,163	223.76
1-262 S	14	35	1,294	123.26
1-826 N	5	40	5,283	139.53
1-911 S	6	55	5,100	187.66
1-821 N	5	65	4,697	308.32
1-791	15	35	1,430	104.56
2-918 N	14	45	3,752	163.84
2-920 N	14	45	5,943	181.11
1-911 S	15	70	3,836	186.64
1-907 S	14	70	1,176	422.15
1-826 N	8	50	5,943	151.07
1-394 S	24	35	3,141	135.70
1-149	13	45	5,943	134.38



(a.) Timeline plot (dots represent recorded events)



(b.) Histogram

Figure 2. Bridge 1-826N (2011)

4. Data Comparison

In-service strain data collected on a bridge provides a quantitative "picture" of how the bridge is responding to the site specific traffic. Data sets that are collected at different times, whether they are a few weeks, months or years apart, can be compared: two similar data sets would suggest that the condition of the bridge, as well as the traffic, has not changed. Dissimilar data sets suggest that the bridge has changed in some way (i.e., has deteriorated or been damaged), or that traffic has changed. However, there will always be inherent variability in the data that shows up as a difference between the data sets. One way to compare data sets is to do a visual comparison of the normalized histograms using similar bin size. This process, however, is subjective and does not lend itself well to rapid or automated comparison. Therefore, a method for quantitatively comparing two data sets is needed. When comparing two data sets, two key questions must be answered: How can the

differences between the data sets be quantified and are the differences significant enough to suggest a change in the bridge condition or traffic?

Several parameters were explored for quantitatively comparing two data sets. These include: (1) Area Difference (AD), (2) Square Root Sum of Squares of Differences (SRSSD), and (3) Effective Strain Difference (ESD). Area Difference is the difference in the areas under two normalized histograms. The SRSSD is calculated by summing the square of the difference in frequency for every bin size, and taking the square root of the sum. The ESD is equal to

$$ESD = \bar{\varepsilon}_2 - \bar{\varepsilon}_1 \tag{1}$$

in which $\bar{\varepsilon}_j$ is the effective strain for a given data set, which is given by

$$ESD_j = \left[\sum \left(\frac{n_i}{N} \varepsilon_i^3 \right) \right]^{1/3} \tag{2}$$

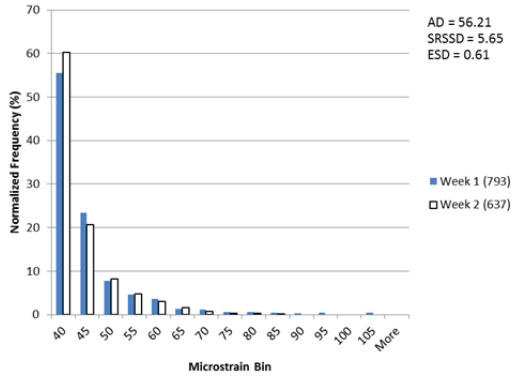
in which n_i is the count of bin *i*, N is the total number of events, and ε_i is the bin strain.

To determine when a change in one of these parameters would indicate a significant change due to deterioration or a change in traffic, the normal variability in the parameters for when there is no damage or change in traffic must be determined. To do this the AD, SRSSD, and ESD were computed for two different weeks of the same data set, assuming in this case that there was no change due to deterioration or traffic. The parameters were calculated for 13 different data sets collected between 2009 and 2011, from 11 different bridges. For these data sets the AD ranged from 28.4 to 383.9, SRSSD ranged from 3.01 to 41.1, and ESD ranged from 0.07 to 17.8. Using these data, threshold values were determined for each parameter based on the method of outlier determination [4]. Values that fall above the threshold would be considered "outliers", indicating that something was causing the data to be outside of the normal range of variability. The threshold values for each parameter were determined to be: AD_{TH}=230, $SRSSD_{TH}$=18.5, and ESD_{TH}=28.5.

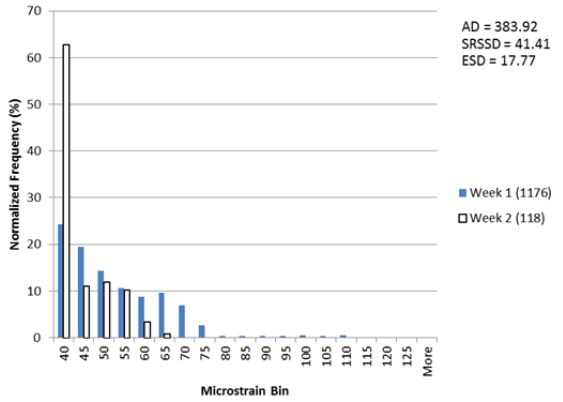
Presented in Figure 3 are sample histograms from week-to-week comparisons for two of the bridges. Figure 3(a.) shows the histograms for two different weeks from bridge 1-791. The histograms are nearly identical, and the three parameters (AD=56.21, SRSSD=5.65, and ESD=0.61) all fall well below the threshold values. Thus the quantitative comparison confirms what can be seen very easily by comparison of the histograms.

Figure 3(b.) shows the week-to-week comparison for bridge 1-262S in which the data from the two weeks is very different. All three parameter values are greater than the respective threshold value (AD=383.92, SRSSD=41.41, and ESD=17.77), thus, the quantitative comparison confirms what the visual comparison of the histograms show. One reason for the major difference in the parameter values is the number of events collected in the two weeks: 1176 in week one versus 118 in week two. The exact cause for the difference was unknown, but could have been due to some temporary change in the traffic over the bridge that the authors were not aware of, since no damage to the bridge was reported during the trial.

Having established threshold values for the three parameters, comparisons were next made between data sets collected during different times, in many cases two or more years apart. Comparisons were made on nine different bridges: data sets from the same bridge that were collected at very different times of the year were excluded so that any possible difference due to seasonal variations would not bias the results. Visual comparisons of the normalized histograms from the two different datasets from the nine bridges showed visual differences in six of the nine cases. The AD, SRSSD, and ESD were calculated for every comparison. In none of the cases did the ESD value exceed the threshold of 28.5 to indicate that the datasets were different. This suggests that the ESD is not a good parameter for comparing data sets. In five cases the SRSSD indicated a



(a.) Bridge 1-791 week-to-week comparison

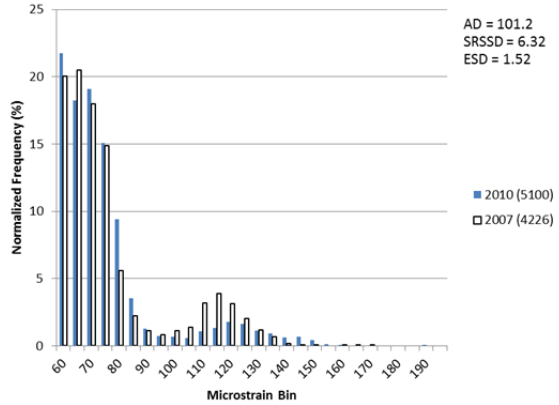


(b.) Bridge 1-262S week-to-week comparison

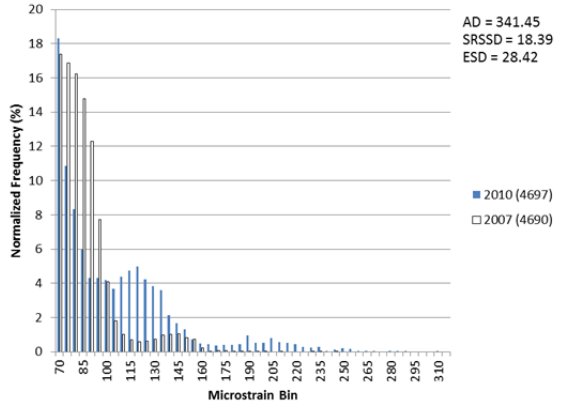
Figure 3. Sample week-to-week comparisons

difference, and in four cases the AD indicated a difference. In three cases both the AD and SRSSD indicated a difference. Used together, the AD and SRSSD parameters captured all six data sets that showed differences based on visual comparison of the histograms.

To illustrate, Figure 4(a.) shows the histograms from bridge 1-911S from 2007 and 2010. The histograms are nearly identical and all three parameters for the data sets fall below their respective thresholds (AD=101.2, SRSSD=6.32, and ESD=1.52). By comparison, the histograms shown in Figure 4(b.) for bridge 1-821N from the same years are very different. The AD (AD=341.45) for this comparison is well above the threshold of 230, and the SRSSD and ESD, while technically are below their thresholds, are very close to their respective threshold values (SRSSD=18.39, ESD=28.42). The difference between the data sets for bridge 1-821N are most likely due to the fact that the bridge underwent major repairs between the time the datasets were collected, specifically, all of the bearings on the bridge were replaced.



(a.) Bridge 1-911S comparison of 2007 and 2010 data sets



(b.) Bridge 1-821N comparison of 2007 and 2010 data sets

Figure 4. Sample comparisons from different years

To see if there is any effect of temperature or seasonal variations on the measured data, data sets recorded on the same bridge during different times of the year were compared. Again, parameter threshold values defined in the week-to-week comparisons were implemented for comparisons. Six different datasets on four different bridges were available to study the effect of seasonal variations. In each case one data set was collected during colder months (November through March) and another data set was collected during warmer months (May through August). The AD, SRSSD, and ESD were calculated for all comparisons. In only one instance did one of the parameters, SRSSD, indicate that there was a difference. Visual comparisons of the histograms did not show any clear trend or

indication that there were seasonal differences: four of the six could be characterized as very similar and the remaining two could be characterized as showing some minor differences. While this was a limited comparison, the results do not support the idea that there are large differences due to seasonal variations in the data.

The results of this study demonstrate that the AD and SRSSD parameters are reasonably reliable methods for quantifying the differences in two data sets collected at different times. The threshold values of 230 and 18.5 seem to be good indicators of when the data sets do differ. The ESD parameter did not work as well as the other two in signalling when a difference is present. The data collected thus far from different seasons does not suggest that there are large differences because of seasonal variations, which means that data sets from different seasons can also be compared.

With the parameters and thresholds established, it is now possible to compare data sets collected at different times on the same bridge and use the result as a low level heath monitoring tool. If the AD and/or SRSSD between two data sets are greater than the normal threshold, this could be an indication that the bridge has been damaged, or has deteriorated since the last data collection trial. When this happens it could trigger a more detailed hands-on inspection of the bridge. The one caveat, of course, is that the change could also be due to a change in traffic volume (ADTT) or traffic pattern. Therefore, it is imperative that accurate records of the traffic conditions during the monitoring period be maintained along with the ISBMS data.

5. In-Service Load Rating

The data collected by the ISBMS can also be used to calculate an In-Service load Rating Factor (ISRF). The record of events recorded over the nominal two week period is the record of actual live load stresses induced in the girder. Using the absolute maximum strain recorded during the trial, the ISRF can easily be determined by proportioning the theoretically calculated rating factor by the theoretical factored live load moment (or stress) in the girder divided by the measured live load moment (or stress). A similar procedure can be used to calculate the ISRF for return periods in the future (e.g., two, fifty, or seventy-five years), except that the maximum likely strain for the specified period must first be estimated.

The 50-year in-service rating factors were calculated for all bridges for the AASHTO HS20 vehicle. The rating factors were calculated using the AASHTO procedure using the program BRASS. The ISRF was calculated using the strain projection procedure. A comparison of the values is shown in Figure 5. Shown in the figure are the ISRF's from this study, shown by the blue bars, and also from a previous study at the University of Delaware (Rakowski, 2008) shown by the white bars, for the bridges that were monitored in years past. In all but one instance the ISRF is greater than the theoretically derived rating factor. In some cases it is many times larger. This shows the conservative nature of the theoretically derived rating factor and the benefit that can be derived from the in-service data.

6. Conclusions

An In-Service Bridge Monitoring System has been developed and implemented for gathering quantitative strain data from typical bridges, due to site-specific traffic. The ISBMS has been used to monitor 15 different bridges in Delaware, multiple times, over a period of five years. The ISBMS data provides a "picture" of how the bridge is responding

to the traffic at any given time. By comparing data sets collected at different times, changes in the bridge response, due to damage or deterioration could potentially be detected.

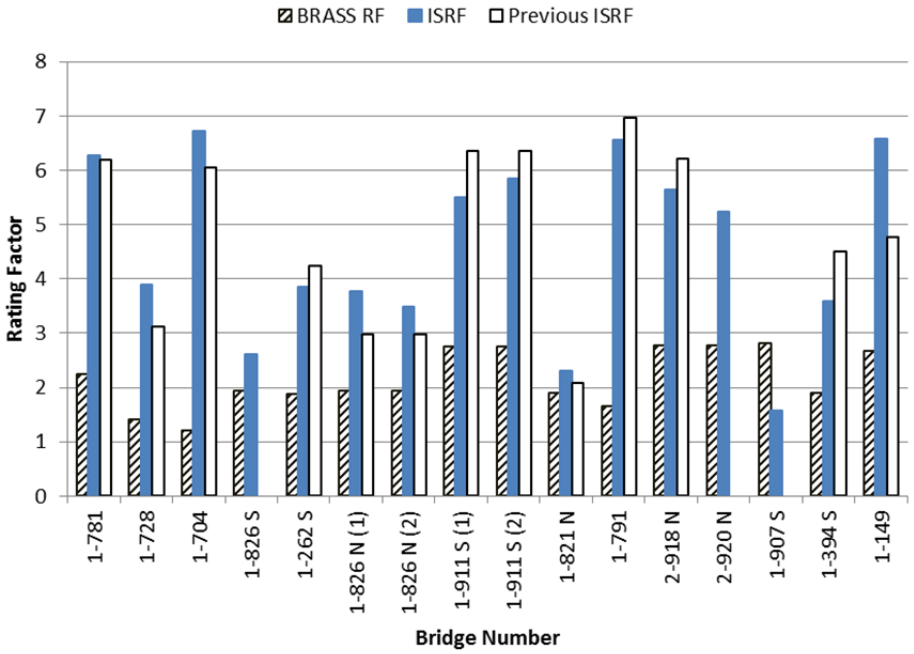


Figure 5. 50-year HS20 rating factor comparison plot [1]

Because visual comparison is subjective, a method for quantitatively comparing two data sets from the same bridge has been developed. The AD, SRSSD, and ESD parameters were calculated and tested. The normal variability of the data was established and a threshold value\ for each of the three was determined that would signal that a data set is significantly different from a previous one. The threshold values for the AD and SRSSD are 230 and 18.5, respectively. These two parameters seemed to do the best job of identifying when there was a significant change in the data sets. Results of comparisons from different seasons on the same bridge did not indicate any seasonal variations in the data. In-service load rating factors were also computed and found, in most cases, to be higher than the corresponding theoretical rating factors.

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