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► **To cite this version:**

Michael V. Gangone. Case Studies Illustrating the Effect of Weakened Load Transfer on Neutral Axis Measurements. Le Cam, Vincent and Mevel, Laurent and Schoefs, Franck. EWSHM - 7th European Workshop on Structural Health Monitoring, Jul 2014, Nantes, France. 2014. <hal-01020374>

HAL Id: hal-01020374

<https://hal.inria.fr/hal-01020374>

Submitted on 8 Jul 2014

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CASE STUDIES ILLUSTRATING THE EFFECT OF WEAKENED LOAD TRANSFER ON NEUTRAL AXIS MEASUREMENTS

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ABSTRACT

Experimental load rating, utilizing strain measurements obtained under controlled vehicle loading, allows for the structures capacity to be determined. This is particularly important for older bridges. However, deterioration can often hinder the load transferring capabilities of the bridge. This results in weaker signal strength at girders farthest from the applied loading. If this is not recognized the results from the load testing and subsequent load rating may prove erroneous. This paper discusses the accuracy of one particular parameter, the neutral axis of bending based on the ability of the structure to adequately distribute the load. Two separate multi-girder/stringer bridges at different periods of their service life were tested using a custom developed wireless sensor system under various loading scenarios. The neutral axis and load distribution factors were acquired using standard department of transportation practices. The results show the ineffectiveness of the deteriorated bridge to transfer the load to resulting in highly variable measures of the neutral axis at girders farthest from the loading. However, this variability was minimal in the newer bridge.

KEYWORDS : *Bridge, Load testing, wireless sensors, field evaluation*

INTRODUCTION

Highway bridges in the United States have faced heavy scrutiny over the past many years due to the large numbers that are deteriorated. Nearly 11 percent of the 607,380 in the United States are rated structurally deficient [1]. The American Society of Civil Engineers (ASCE) 2013 report card for America's infrastructure awarded bridges a "C+", a half letter grade higher than the 2009 grade. According to the report, the average age of a bridge in the US is 43 years and more than 30 percent are exceeding their 50 year design life [2]. As the necessary funds are not available to replace all critical bridges, engineers are required to find other methods to repair and assess these structures to assure they are fit for service.

Currently in the United States, a bridge is inspected once every two years. The inspection methods used are primarily visual based and can often be time consuming and subjective. To help improve the condition assessment and health monitoring process, many researchers around the globe are working on methods that utilize newly developed technology [3-5]. Various research has also shown the importance of experimental load rating for accurately predicting the true capacity [6-8]. With using any sensor system it is important to know what affect parameters like system noise has on the overall accuracy of the measurements.

1 EXPERIMENTAL LOAD RATING

Load rating and testing of bridges is a standard practice by state agencies around the country. The goals of a load test are to determine the capacity of the structure as well as evaluate the behavior of the structure under different loading conditions. Load testing can occur on any structure at any point during its life span. In fact, load testing on deteriorated structures is perhaps most common.

As a structure deteriorates, the capacity reduces and load distributions paths change. For this reason, the ability to determine the safe load carrying capacity is necessary to prevent structural failure. A major benefit to load testing a bridge is determining its service status. Bridge owners, whether state, federal or local, can potentially save the bridge and money in the process by not having to replace the structure.

Diagnostic load testing is a method where a predetermined load is applied to the structure and the effects to the members are measured. Diagnostic tests are affective in verifying assumptions made during the design. Such assumptions include impact factor and load distribution that are used in the load rating [9]. Additional factors such as unintended composite action, and end fixity contribute additional stiffness that may have not been accounted for in the design. This will aid in increasing the load rating. Ultimately the end result will provide a maximum safe load for the bridge, and a load will be posted.

Inventory and operating loading levels are the two classes of loads that are produced from load rating. Inventory loading corresponds to design stresses and current material conditions, such as deterioration and loss of section. A live load at this level can be applied to the existing structure for an indefinite period of time. Operating load level is “the maximum allowable live load the structure can withstand. Too much use at operating level reduce the service life of the structure” [10]. Operating loads could potentially lead the bridge to experience inelastic deformations, creating residual strains in the material. These residual strains would reduce the overall stiffness and load capacity of the structure. For these reasons, posting for maximum loading on a bridge is done using the inventory load. However, if a minimum load of three tons is not feasible, the bridge must be closed [9]. These regulations along with the load rating standards are governed by one federal agency.

American Society for State and Highway Transportation Officials (AASHTO) sets guidelines for design and load ratings of bridges [10]. H trucks of known weight are arranged in different loading patterns. The loads are considered static or semi-static as the trucks move at slow crawl speeds or are in a stand still position as measurements are taken. Strain transducers provide the information into the load capacity of the bridge. The locations for monitoring are dependent on the type of bridge being evaluated.

2 EXPERIMENTAL TESTING SETUP

2.1 Wireless Sensor System

Performance monitoring methods are critical in assessing the performance and condition of a structure. With the rising demand for technologies to improve the accuracy of structural evaluations, many institutions are devising ways to efficiently and effectively monitor the effects of different loading scenarios. A Wireless Sensor System (WSS) which includes a dual axis accelerometer, strain transducer, and a custom conditioning board has been developed in the Laboratory for Intelligent Infrastructure and Transportation Technologies (LIITT) at Clarkson University. An accelerometer and strain transducer connected to a single conditioning board that attaches to a mote, sending the signal wirelessly in packets to another mote connected to a CPU where the data is collected and processed by a custom software platform. The conditioning boards permit readings to be sampled at 1.0 kHz, and then digitally filtered. This provides for a more accurate description of the behaviour of the structure, in particular the dynamic response. For more information on the developed wireless system see Whelan and Janoyan [11].

2.2 Country Route 55 Bridge Test

The bridge instrumented is located in Brasher Falls, New York crossing the Deer River (figure 1a). The bridge was reconstructed in the summer of 2009 to replace a deteriorated open steel grating deck on steel girders. The replacement design incorporates 8- 19.96cm (7.75 in) thick glass FRP (GFRP) panels 2.4m (7.9 ft) in length by 7.27m (24 ft) wide which rest on 5 – W30x235 steel

girders spaced at 1.67m (5.5ft) on center. Steel girders are supported by elastomeric bearings and cast into the gravity abutments in an integral abutment design. Seven equally spaced MC 18x42.7 sections served as intermediate diaphragms between each girder. The bridge has a non-composite inventory rating of 75.1 metric ton (82.8 tons) for the HS46.0 truck and an operating rating of 124.9 metric ton (137.7 tons) for the HS76.5.

Eleven reusable strain transducers measured the quasi-static and dynamic response of the bridge. Sensor locations are shown in figure 1b. The strain transducers were distributed to measure the girder load distributions, neutral axis locations, and end fixity. The majority of the strain transducers were mounted along the centerline of the bottom flange in the longitudinal direction of the bridge. At the locations where the neutral axis is determined (girders 3 and 5), an additional gauge was placed on the top flange. All strain transducers were mounted with removable threaded tabs affixed to the girders with the manufacturer recommended adhesive. For additional information regarding this test see Gangone et al. [12].

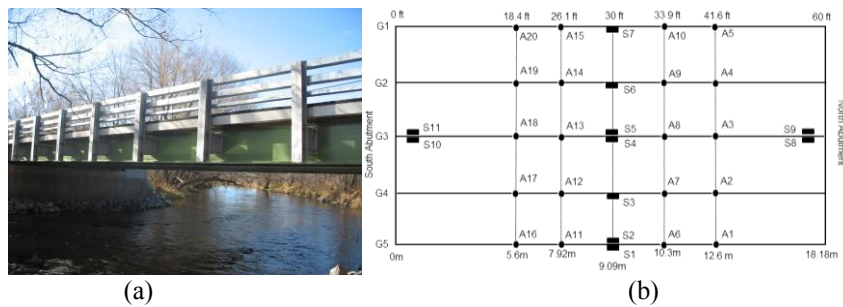


Figure 1: (a) CR55 Bridge Test Structure; (b) Instrumentation Setup (A : Accelerometer, S : Strain)

2.3 Bridge over Big Sucker Brook Test

The highway bridge investigated, located on RT345 in upstate New York consists of a 19.1 cm (7.5 in) thick reinforced concrete slab supported by three interior W33x152 and two W33x141 exterior steel girders (figure 2a). The bridge is a 3-span simply supported two-lane structure consisting of a 13.7 m (45 ft) simply supported span at an elevation of approximately 1.2 m (4 ft) from the waterline. The girders have a center-to-center spacing of 2.1 m (7 ft) and are supported by pin and rocker steel bearings. End and midspan intermediate diaphragms are constructed of C15x33.9 sections that are bolted to transverse plates welded to the girders. Prior to the scheduled closure for replacement, the structure serviced New York State Route 345 over Big Sucker Brook in the town of Waddington. Constructed in 1957, the bridge maintained a sufficiency rating of 61.2%, an operational rating of 44.5 metric tons, and an average daily traffic estimate of 1169 vehicles.

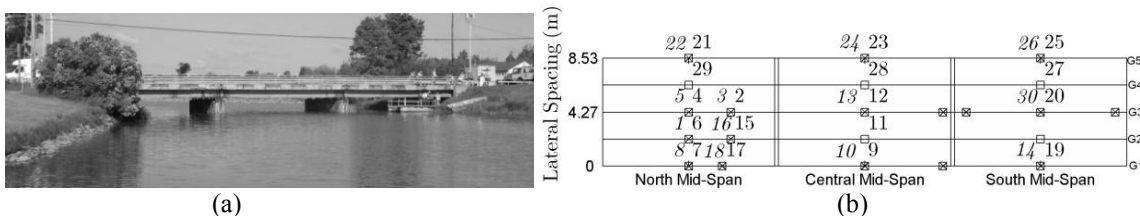


Figure 2: (a) RT345 Bridge over Big Sucker Brook Test Structure; (b) Instrumentation Layout

Wireless Bridge Diagnostic Incorporated (BDI) strain transducers were deployed for completion of a full scale load test on all three spans. BDI sensors were deployed primarily at the midspan of the steel girders for measuring NA, DF, and impact factor response for a flexural ASD load rating. The instrumentation layouts for both tests showing the strain gauges placed at the bottom and in some cases top flanges as well are presented in figure 2b. Locations which show two

numbers side by side (e.g. 4 and 5 of figure 2b) indicate that both the top and bottom flanges were instrumented at that location. It should be noted that while some sensors were placed at locations other than just the midspan, only the midspan measurements are used in the discussion of this paper. Additional information from this test can be found in Gangone et al. [13].

3 EXPERIMENTAL RESULTS

Both bridges were sectioned into three different lanes, east, west and center (figure 3). Calibrated testing vehicles were provided by the New York Department of Transportation (NYSDOT). Axle weights were known and their position on the bridge within each of the three lanes was pre-determined. The rear axle, the heavier of the two axles, was positioned at the midspan to excite the maximum strain response at each sensor location. From testing in each of the three lanes, each girder was excited to a high level of stress.

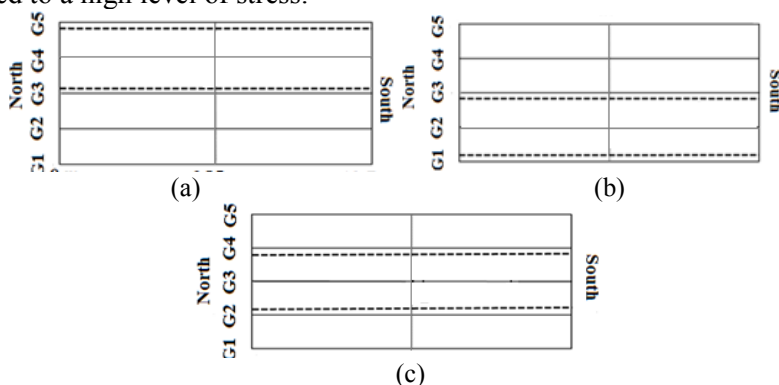


Figure 3: Testing lanes (a) east, (b) west, (c) center

3.1 Neutral Axis and Distribution Factor Response

The neutral axis of bending is an important parameter relating to the flexural stiffness and capacity levels at critical locations of the superstructure. A rise or fall in its value could indicate, among other things, loss of composite action and section loss within the girder or slab, or a higher level of composite action not accounted for in design. The neutral axis was monitored at the midspan of the center girder and at least one exterior girder. The mounted positioning of the strain transducers on the top and bottom flange of the girder is shown in figure 4. The neutral axis was then calculated assuming a linear strain profile along the depth of the section.

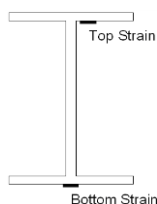


Figure 4: Positioning of the strain transducers for monitoring neutral axis location

Transverse load DFs are a measure of the load transfer through the structure. As a means of safety, the load is typically shed to other bridge elements as to not overstress the primary load carrying member. For this to occur, the load is transferred transversely within the structure through the bridge deck and diaphragms. The distribution factors presented in this paper result from the midspan strains monitored at the bottom flange. The strain at each girder (ϵ_i) is divided by the total strain at the midspan from all girders to get the individual girder distribution factor (DF_i) as seen in equation (1). This analysis was performed for each girder under testing in each of the three designated lanes.

$$DF_i = \frac{\varepsilon_i}{\sum \varepsilon_i} \quad (1)$$

Since between 2 and 4 tests were completed in each of the three designated lanes the standard deviation of the measurements for each monitored girder is presented. The following data will look to compare the standard deviation of the neutral axis measurements with the distribution factor for the beam. It would be expected that the higher the loading to the beam, the greater the resolution of the strain measurement, providing greater accuracy in the data.

Country Route 55 Bridge

This bridge was monitored within one year of construction. There were no visible signs of deterioration that would normally hinder the load shedding capabilities. Figure 5 illustrates the load shedding characteristics based on the test vehicle positioned in each of the three lanes. The results in figure 5a are as expected with girders 4 and 5 receiving a majority of the load demand then shedding to the remaining girders. West and center lane load cases (figures 5 b,c respectively) seem to show similar findings. The findings also suggest good repeatability in the data as the distribution factors appear to be nearly identical for both load tests particularly for loading in the east and center lanes.

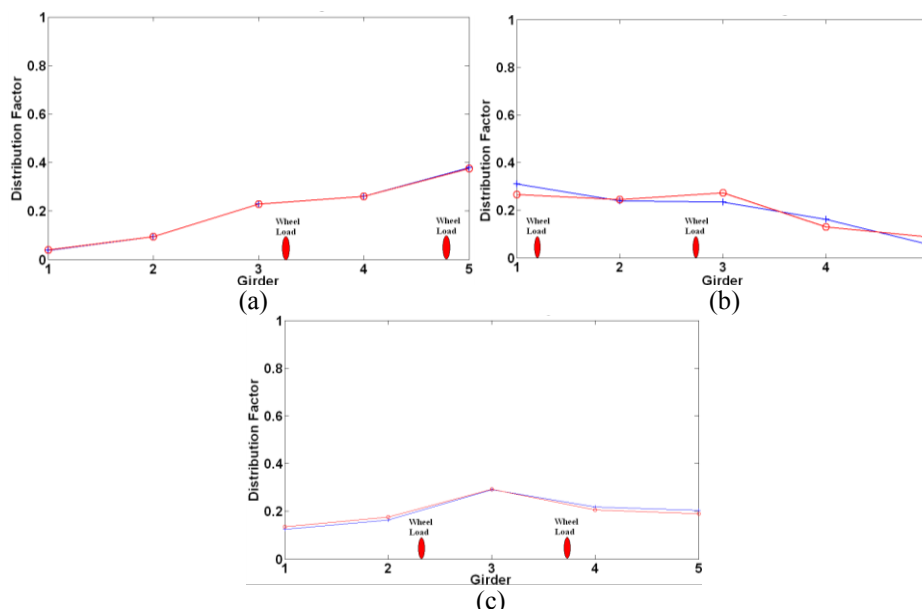


Figure 5: Distribution factors at the midspan of CR55 Bridge based on; (a) loading in the east lane; (b) loading in the west lane; (c) load in the center lane

Four load tests were performed in each of the three testing lanes. Figure 6 compares the average distribution factor for the girder with the standard deviation of the neutral axis (NA) measurements. Girder 3 represents the center girder and girder 5 is the eastern most girders. The data for this bridge indicates that there are very small standard deviations among the neutral axis measurements. In addition, the distribution factors were large enough that the strains were able to be acquired with high enough resolution to get greater precision for each case. For this bridge, the load shed thoroughly from girder-to-girder no matter the position of the vehicle. Part of the precision of this measurement is due to the bridge deck material. Glass FRP deck panels do not produce the composite action that is seen between a reinforced concrete deck and steel girder. Therefore, the neutral axis lies near mid-depth of the girder providing high strains at both flanges. These high strains give greater resolution of the strain measurements.

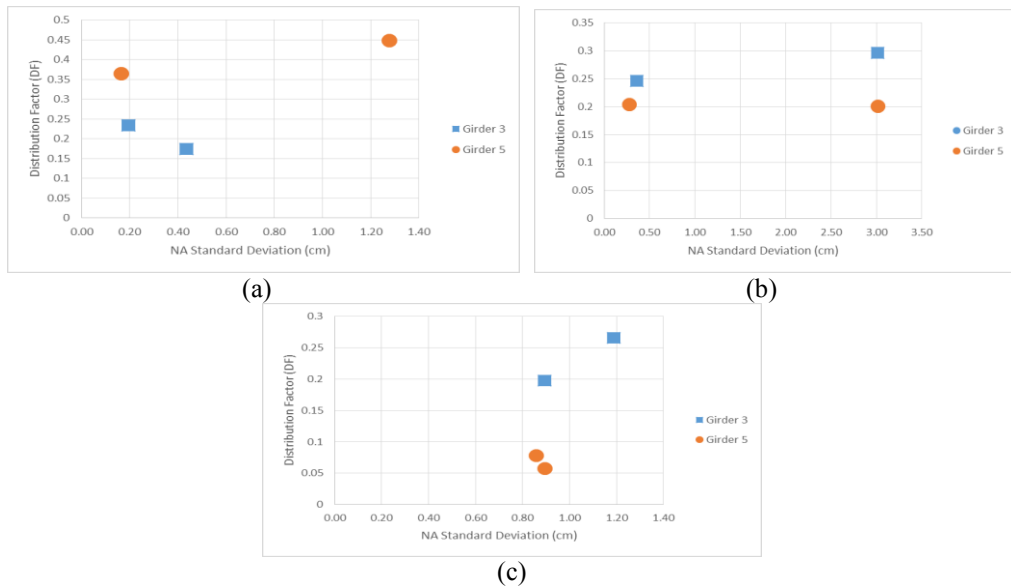


Figure 6: Standard deviation in of the neutral axis measurements based on the load distribution factor of the beam of the CR55 Bridge; (a) East lane load test; (b) Center lane load test; (c) West lane load test

RT 345 Bridge

This bridge was monitored at the end of its service life. Significant deterioration relating to corrosion in the steel girders and bearings and concrete bridge deck cracking were noticed. As a result, it was expected that the load shedding capabilities would be reduced. Figure 7 illustrates the load shedding characteristics of the north span based on the test vehicle positioned in each of the three lanes. Only results from the north span are shown due to paper length restrictions. The results in figure 7a are as expected with girders 4 and 5 receiving a majority of the load demand then shedding to the remaining girders. In figure 7b girder 2 does not have the spike that girder 4 had in the east lane case (figure 7a). This could suggest that girder 2 has lost some load stiffness due to the deterioration and as a result the neighboring girders are carrying higher loads. In both cases the girder farthest from the loading experiences very low stress levels. For the center lane case, the load has shed to girder 4 more so than girder 3. This could suggest that girder 4 is less deteriorated than the remaining members.

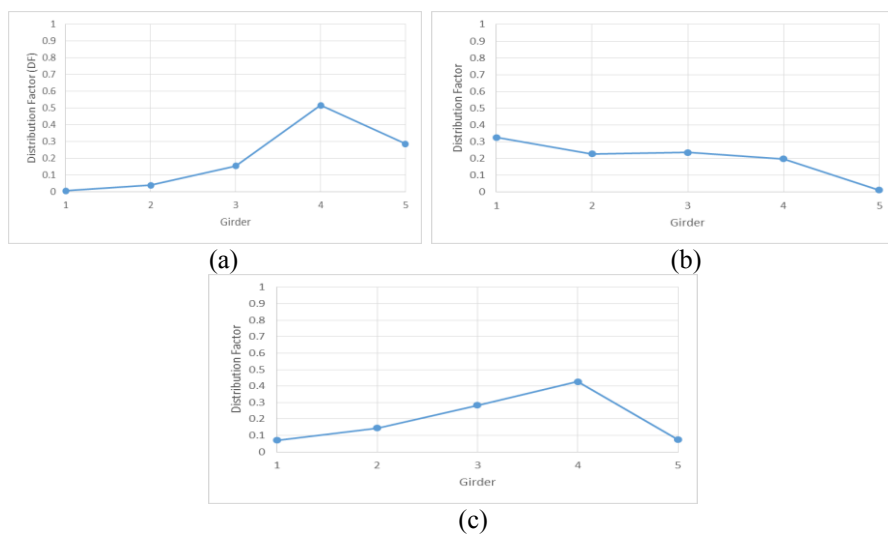


Figure 7: Distribution factors at the midspan of RT345 Bridge based on; (a) loading in the east lane; (b) loading in the west lane; (c) load in the center lane

Two load tests were repeated on each of the three lanes during testing. The neutral axis was computed for each case. The standard deviation is noticed to be very high for girder 1 (which is on the far west side of the bridge) when the vehicle is in the east lane (figure 8b). Similarly, when the test vehicle is in the west lane, girder 5 shows a large standard deviation in the neutral axis (figure 8a). In the case of center lane loading, the neutral axis in girder 1 also was shown to have a high standard deviation. Much of this can be seen from the distribution factors in figure 7. When the distribution factor is low, less strain is recorded by the sensor and the system noise levels become dominate. This bridge differs from the previous structure in that it uses a reinforced concrete bridge deck. This typically results in much greater composite action between the deck and girder. As a result, the neutral axis is typically near the top flange and therefore produces very low top flange strain readings. With a low strain level recorded at the bottom flange it is expected that the top flange would be even lower. The result is a heavy influence of system noise in the measurement leading to low precision in the neutral axis readings.

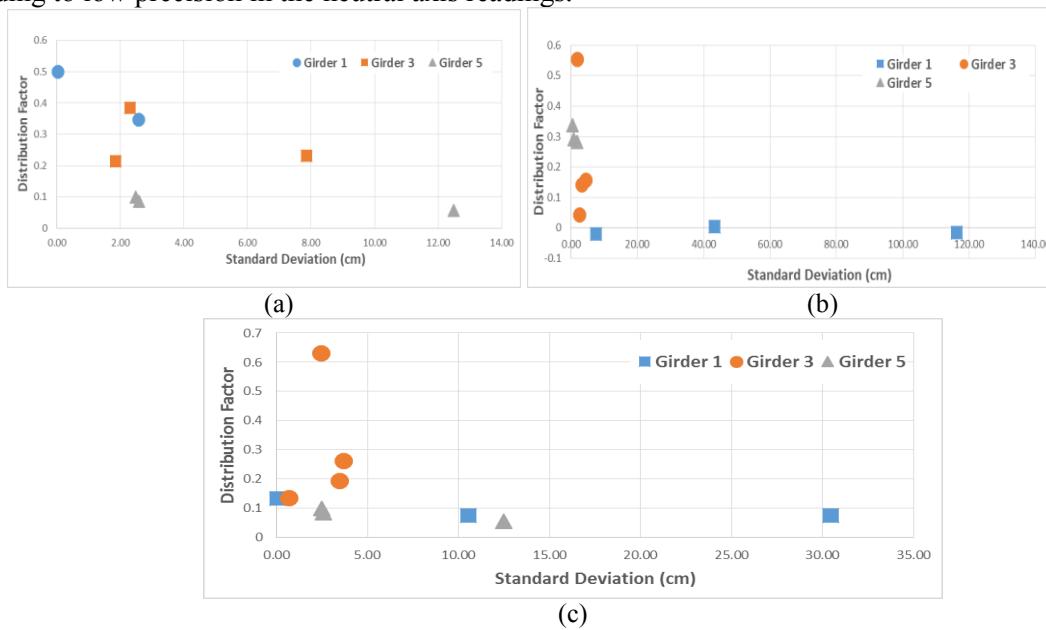


Figure 8: Standard deviation in of the neutral axis measurements based on the load distribution factor of the beam for the RT 345 Bridge (a) West lane load test; (b) East lane load test; (c) Center lane load test

CONCLUSION

Two highway bridges at different points in their service life were tested in New York State. One structure was monitored within one year of construction while the other was at the end of its service life. While both fall into the general category of a multi-girder/stringer bridge, one bridge employed a glass FRP panel deck and the other was a traditional reinforced concrete deck. The bridges were sectioned into three separate lanes for loading. Multiple load tests were performed in each lane to test the repeatability of the measurements. The standard deviation of the neutral axis measurements indicated less precision in the measurement the farther the vehicle was positioned from the instrumented girder. In other words, when the test vehicle was in the east lane, the exterior girder on the far west side of the bridge had very poor precision. The girder on the east side of the bridge however showed good precision. The same was noticed for loading in the west lane and the far east fascia girder. This was especially the case for the bridge that was most deteriorated and at the end of its service life.

The load shedding abilities of the bridge were noticed to be weaker for the bridge with the greatest deterioration. This deterioration prevented most of the load from transferring to the farthest girder resulting in lower resolution in the measurement. The reinforced concrete deck also

generated a composite action that put the neutral axis near or in the top flange. As a result, a much smaller strain was recorded in the top flange in comparison to the bottom. This created an even lower resolution of the measurement with the high amount of system noise in the reading. The result was low precision in the neutral axis location. The newer structure with a glass FRP panel deck had much lower standard deviation in the neutral axis measurements for each instrumented girder. This is the result of the strong load transfer mechanisms within the superstructure combined with the less significant composite action between the steel girder and panel. This allowed for higher strain readings in both the bottom and top flanges creating greater resolution in the measurement and therefore greater precision in the neutral axis location.

Overall, this testing showed the effect that bridge deterioration can have on the load shedding capabilities and in turn the precision in the neutral axis measurement. This measurement is important for monitoring during load testing where the testing results are eventually converted into a load rating. Positioning of the testing vehicle is important to maximize the strain response of each girder to get the most precise load testing measurements.

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