Examples of Damage Detection in Real-Life Settings Based on the Position of the Neutral Axis

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EXAMPLES OF DAMAGE DETECTION IN REAL-LIFE SETTINGS BASED ON THE POSITION OF THE NEUTRAL AXIS

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ABSTRACT

The objective of the research discussed in this paper is to create damage detection methods based on universal parameters that are applicable to a large number and large variety of structures. Such methods, if successful, streamline the data analysis across large bridge networks and provide a basis for bridge managers to reach efficient, effective, yet safe and sustainable maintenance decisions. The first step towards this goal is to identify an appropriate parameter and validate that it can be used to detect damage in real-life settings.

The centroid of stiffness is a universal parameter and its position in a cross-section can be evaluated for any load-carrying beam structure as the position of the neutral axis under conveniently chosen loads. Thus, a change in the position of the neutral axis within a cross-section can indicate change in the position of the centroid of stiffness, i.e., unusual structural behaviors. This research focuses on the neutral axis because of its universal applicability to beam-like structures and its direct correlation with unusual structural behaviors (e.g., damage).

In this paper two examples of successful damage detection in real-life settings using the neutral axis are presented. In both cases the neutral axis is evaluated with long-gauge fiber-optic strain sensors installed on the structure in a parallel topology. The results show that the neutral axis is sensitive to damage and can be used to detect cracking and delamination in real-life settings, even years after the damage occurred.

KEYWORDS : *Damage Detection, Neutral Axis, Beam-Like Structures, Long-Gauge Fiber-Optic Strain Sensors.*

INTRODUCTION

Structural Health Monitoring (SHM) is the process of continuously or periodically measuring structural parameters and the transformation of the collected data into information on real structural conditions. SHM is an emerging field within structural engineering, and even though monitoring technologies are commercially available, many bridge owners are reluctant to implement them. The main reason for this reluctance is the inefficiency of current monitoring methods (including monitoring strategies, data analysis methods, and cost limitations), which compromises the potential benefit.

The objective of the research discussed in this paper is to create damage detection methods based on universal parameters that are applicable to a large number and large variety of structures. Such methods, if successful, streamline the data analysis across large bridge networks and provide a basis for bridge managers to reach efficient, effective, yet safe and sustainable maintenance decisions. The first step towards this goal is to identify an appropriate parameter and validate that it can be used to detect damage in real-life settings.

In this paper two examples of successful damage detection in real-life settings using the neutral axis are presented. In both cases the neutral axis is evaluated with long-gauge fiber-optic strain sensors installed on the structure in a parallel topology. The two examples are the Streicker Bridge, a pedestrian bridge located on the Princeton University Campus, and a large-scale testing bridge model located on the Livingston Campus of Rutgers University. The former is a single-girder post-tensioned curved continuous concrete bridge that experienced early-age cracking, whereas the latter consists of a reinforced concrete slab supported on three steel stringers, with damage artificially applied to the concrete slab. Thus the structures represent two very different structural systems, even though they are both based on beams. The results show that the neutral axis is sensitive to damage and can be used to detect cracking and delamination in real-life settings, even years after the damage occurred.

1 NEUTRAL AXIS AS DAMAGE SENSITIVE FEATURE

The centroid of stiffness is a universal parameter and its position in a cross-section can be evaluated for any load-carrying beam structure as the position of the neutral axis under conveniently chosen loads. Thus, a change in the position of the neutral axis within a cross-section can indicate change in the position of the centroid of stiffness, i.e., unusual structural behaviors. This research focuses on the neutral axis because of its universal applicability to beam-like structures and its direct correlation with unusual structural behaviors (e.g., damage).

The neutral axis can be located with a minimum of two sensors in a cross-section. Under service conditions the structure is in the linear regime, and unless the shape of the cross-section is unusual, Bernoulli hypothesis is assumed to be valid. Thus, the strain distribution is assumed linear through the cross-section. The neutral axis is the location where there is zero strain, measured from an arbitrary point, for example the bottom of the cross-section. If only two strain measurements are available within the cross-section the line connecting them is unique, and so is its intercept. However, if more than two measurements within a cross-section exist then the best line can be found, for example by the method of least squares.

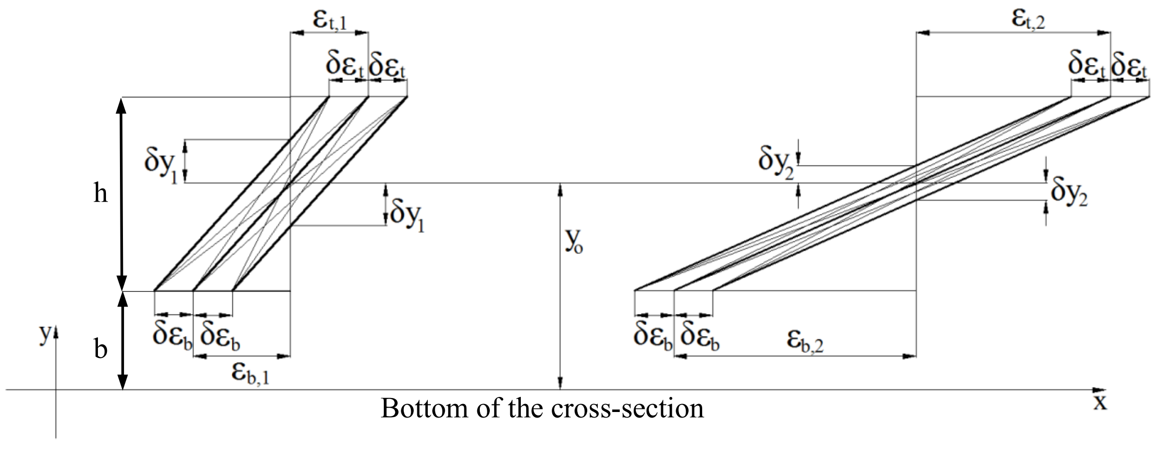

Figure 1: The magnitude of the strain measurement influences the uncertainty of the location of the neutral axis; the larger the strain magnitude the smaller the uncertainty. Figure modified from [1].

Equation 1 shows the location of the neutral axis, y_o, in uniaxial bending, using two strain measurements, one at the bottom, ε_b, and one at the top, ε_t, with the distance, h, between the sensors. The neutral axis is measured from the bottom of the cross-section, where b is the distance from the bottom of the cross-section to the bottom sensor (see Figure 1 for notation).

$$y_o = \frac{\varepsilon_b h}{\varepsilon_b - \varepsilon_t} + b \tag{1}$$

The uncertainty in the location of the neutral axis, δy_o, depends on the magnitude of the strain [1] shown in Equation 2:

$$\delta y_o = \frac{1+|c|}{(1-c)^2}\frac{1}{|\varepsilon_b|}h\delta\varepsilon \tag{2}$$

where $c = \varepsilon_t / \varepsilon_b$ and $\delta\varepsilon$ is the uncertainty in the mechanical strain measurement. This dependency of the uncertainty on the strain magnitude is illustrated in Figure 1. On the left the strain magnitudes are low and the uncertainty is high whereas on the right a larger strain value results in lower uncertainty. It is therefore preferable, in order to decrease the uncertainty of the evaluation of the location of the neutral axis, to measure large strains. Examples of how the magnitude of the strain affects the evaluation of the position of the neutral axis are provided in the following sections.

Theoretically, the neutral axis coincides with the centroid of stiffness of a given cross-section and it is constant for a constant load pattern. However, field observations on real, healthy structures show that the location of the neutral axis varies [1]. This variation can be due to a variety of reasons, a few of them are long-term effects such as nonlinear thermal gradients and rheological effects, the dynamic nature of the loading, and changing load patterns. The position of neutral axis was determined in real structures using static or quasi-static testing (e.g., [2-3]), and dynamic monitoring (e.g.,[4-5]). In all these studies variations in the location of the neutral axis were confirmed in non-damaged structures. Thus, using a deterministic approach, where one value is considered representative for the cross-section, is not accurate and a probabilistic approach has been developed (more information in the litereature Sigurdardottir & Glisic, 2013).

2 DETECTING EARLY-AGE CRACK IN CURVED CONTINUOUS GIRDER

Streicker Bridge is a pedestrian bridge on the Princeton University Campus. It has four approach ramps, called legs, and a main span which crosses the Washington Road. Streicker Bridge has been transformed into an on-site laboratory. Approximately 100 long-gauge (60cm) Fiber Bragg-Grating (FBG) sensors were installed in the concrete deck during construction. The monitoring system has been logging data every 5 minutes since construction, with intermissions. The southeast leg is used as an example in this paper; it is shown in Figure 2. It is a post-tensioned, curved continuous concrete girder supported by slender steel columns. Nine cross-sections along the length of the southeast leg are instrumented with parallel sensors. That is, with two sensors in each monitored cross-section, one at the top and one at the bottom, close to the vertical axis of symmetry. In this paper the focus is on location P11, see Figure 2.

Figure 2: Left: Load test, the bridge was loaded with four golf carts. Right: Location P11 is above a support.

The concrete was poured in early November 2009, and the bridge was post-tensioned a week later followed by the removal of the formwork. The removal of the formwork after post-tensioning can be regarded as a load test where the weight of the structure is uniformly applied. This event was used to calculate the location of the neutral axis at all instrumented cross-sections along the length of the southeast leg. The advantage of using the form removal as a test is that the strains are relatively high and therefore the uncertainties are low, as discussed earlier. It was concluded that the neutral axis was located lower in the cross-section than theoretically expected.

The reason is a reduced effective width of the cross-section due to its particular shape, similar to T-beam behavior (more information can be found in the literature [1]). Thus the healthy location of the neutral axis is at 350mm from the bottom of the cross-section.

A load test of the southeast leg was performed in March 2011, see Figure 2. Four golf-carts with passengers were placed sequentially at midspan of the longest span in the southeast leg, i.e. the load was gradually increased and then gradually decreased by driving the carts onto and off the structure one by one. The results for location P11 are shown in Figure 3. In the first two load steps the strain magnitude is low and therefore the uncertainty is high. The same is true for the last two load steps. A stable value of ~300 mm is achieved when all the golf carts are on the midspan simultaneously (load steps 3-6). Thus, the neutral axis was found to be approximately 50 mm below the expected position.

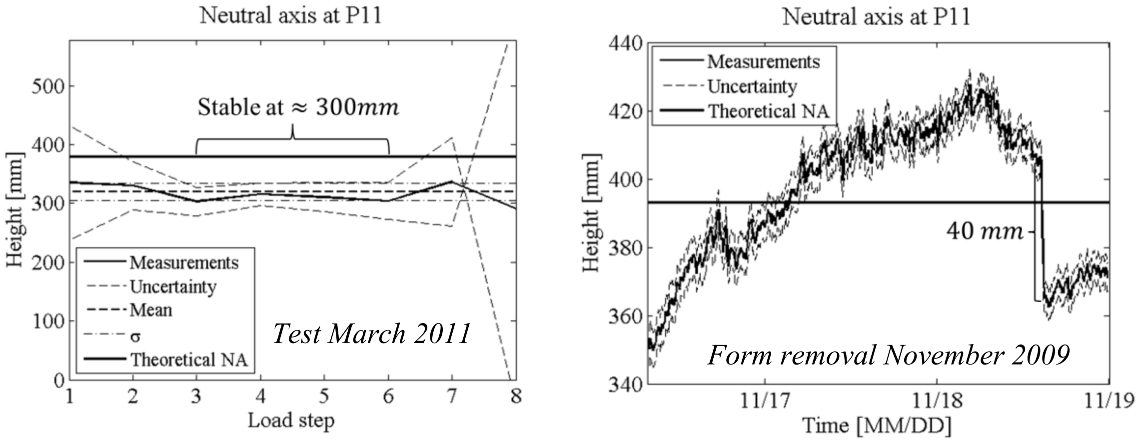

Figure 3: Left: Neutral axis location during static testing with golf carts. Right: Neutral axis location after form removal. Both figures are modified from [1].

The reason for the lower neutral axis location can be found three days after the form removal, see Figure 3. The figure shows the neutral axis as a function of time right after the form removal. The variation in the neutral axis location is caused by nonlinear thermal gradients through the cross-section (more discussion provided in [1]). However, at first the neutral axis is at 350 mm, which is the expected healthy location. Approximately three days later a crack forms at location P11 and therefore causes the neutral axis to move down.

In summary, the neutral axis location was found to be lower at location P11. The reason was a crack that occurred shortly after the form removal. The neutral axis location was found during the 2011 tests and thus lower stiffness at this location was confirmed. This is an example of damage detection in a real life setting; the robustness of the method is displayed through the fact that the neutral axis was used to detect loss of stiffness long after the event occured.

3 DETECTING DELAMINATION IN MULTI-STRINGER STRUCTURE

The ANDERS (Automated NonDestructive Evaluation & Rehabilitation System) project is led by Rutgers University with the aim to develop NDE technologies that enable early detection of defects in bridge decks [6]. As part of ANDERS a scale-model bridge was constructed with a reinforced concrete slab supported on three steel stringers and damage artificially applied to the concrete deck. The research presented here is not a part of the ANDERS project; however the ANDERS team allowed the authors to install sensors on the structure and perform monitoring.

Long-gauge (50 cm) FBG sensors were installed both on the steel stringers and embedded in the concrete. In each monitored cross-section there are four parallel sensors, at the top and bottom steel stringer flange and attached to the top and bottom reinforcement in the concrete.

Location A has a horizontal plastic sheet installed to create artificial delamination in the concrete, see Figure 4. Location F does not have any artificial damage and is considered healthy.

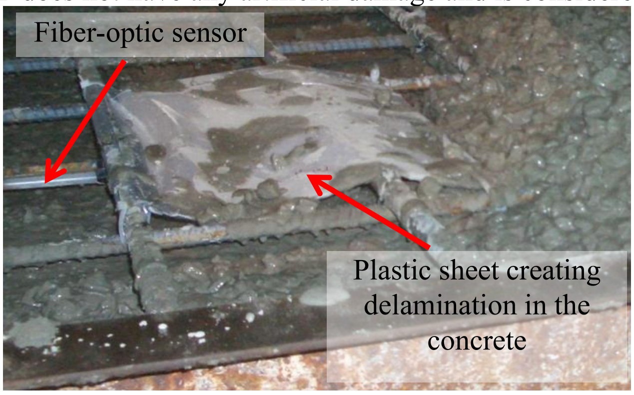

Figure 4: Location A, artificial damage is created in the concrete by placing a plastic sheet in the concrete. The FBG sensor is located under the delamination. (The plastic sheet is 26x31cm and covers ~50% of the length of the sensor).

The structure was constructed at Jersey Precast in Hamilton, NJ. The steel stringers were resting on the floor during pouring of the concrete. Seven days later the model bridge was lifted onto supports in order to remove the formwork. This lifting was registered by the monitoring system, and the strains measured by the four sensors in cross-section F are shown in Figure 5. The neutral axis location, as calculated with the strains measured on the steel flanges, is also shown in Figure 5. Two major conclusions can be drawn from this figure; 1) the neutral axis varies in a healthy cross-section with the mean close to the expected neutral axis location, 2) the magnitude of the strain does have an effect on the dispersion of the neutral axis values, confirming that the uncertainty decreases as the strain magnitudes increase.

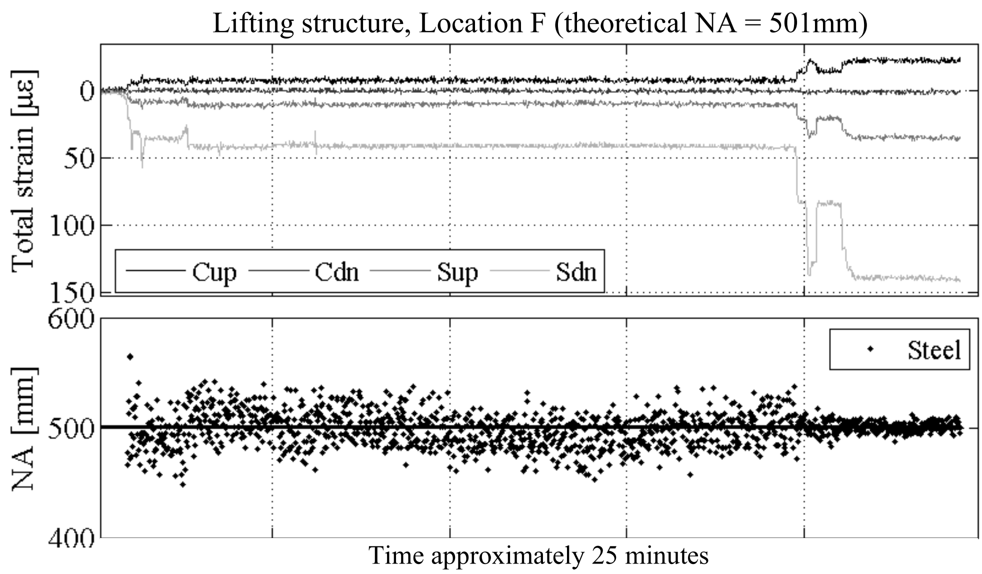

Figure 5. Strain at location F during the lifting from the floor onto supports. Cup is sensor at concrete up, Cdn is sensor at concrete down, Sup is sensor on the upper steel flange, and Sdn is sensor on the lower steel flange. The neutral axis location measured from the bottom of the cross-section as measured by the steel sensors.

The location of the neutral axis was calculated from the lifting data using three different sensor combinations; first using the steel sensors (Figure 5), then the concrete sensors, and lastly all four sensors. The results are presented in Table 1. At the healthy location F all combinations of sensors are close to the theoretical value (501 mm) and this cross-section is concluded to be healthy. However, at location A, which has a delamination in the concrete deck, the results between different sensor combinations are not consistent. These results show that the neutral axis is sensitive to damage and it can be used to detect delamination in concrete decks. The sensors located on the steel flanges are the most sensitive to the damage whereas the concrete sensors are less affected. This conclusion is important for monitoring existing structures since it is not necessary to embed the sensors in the concrete to detect damage in the deck. Further research is ongoing to understand the behavior at the damaged locations.

Table 1: Location of the neutral axis for locations A and F calculated with three sensor combinations. The values are provided in millimeters from the bottom of the cross-section. The theoretical value is provided in parenthesis.

Location (Theor.)	**Sensor comb.**	**During lifting**	**After lifting**	**Location (Theor.)**	**Sensor comb.**	**During lifting**	**After lifting**
F (501)	steel	497	500	A (514)	steel	556	541
	concrete	501	500		concret e	517	521
	all	497	502		all	506	514

CONCLUSIONS

The centroid of stiffness is a universal parameter and its position in a cross-section can be evaluated for any load-carrying beam structure as the position of the neutral axis under conveniently chosen loads. Thus, a change in the position of the neutral axis within a cross-section can indicate change in the position of the centroid of stiffness, i.e., unusual structural behaviors. This research focuses on the neutral axis because of its universal applicability to beam-like structures and its direct correlation with unusual structural behaviors (e.g., damage).

In this paper two examples of successful damage detection in real-life settings using the neutral axis are presented. In both cases the neutral axis is evaluated with long-gauge fiber-optic strain sensors installed on the structure in a parallel topology.

In Streicker Bridge, a pedestrian bridge on the Princeton University Campus, the effects of an early-age crack were detected during a load test of the bridge. The damage was detected as a lower neutral axis at that cross-section. These results also show that the neutral axis can be used to detect loss of stiffness long after the event occurs. This is very significant, especially for monitoring of existing infrastructure, where it may be difficult to establish a healthy baseline.

Data from the multi-stringer structure allowed for analysis with different combinations of sensors. For the healthy cross-section all sensor combinations provided similar results, and the neutral axis was found at the location where it was theoretically expected. However, the location where damage had been artificially placed in the concrete deck showed inconsistent results between the different sensor combinations. This discrepancy indicates that the location is damaged. It was concluded that the sensors installed on the steel flanges were most sensitive to the damage and it is therefore recommended, if budget or accessibility issues prohibit installing four sensors in each cross-section that the sensors are installed on the steel stringer. These results are important because they show that it is feasible to use the neutral axis as a damage sensitive feature, even in existing structures since the sensors do not have to be embedded in the concrete deck.

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