Finite Element Verification of the Method of Neutral Axis for Damage Detection in Composite Beam Structures

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Key words: Structural health monitoring, composite beam, finite element analysis, neutral axis, fiber optics, long-gauge strain sensors, damage detection.

Abstract

The neutral axis in a loaded beam structure is the curve in the cross-section that experiences zero strain. With the absence of axial effects, the healthy location of the neutral axis can be predicted using the position of centroid of stiffness of the beam cross-section. Change in position of the neutral axis can indicate the change in position of centroid, and thus, can be used for damage detection purposes. In this paper, a finite element based analysis was used to verify the method of neutral axis for damage detection in a multi-girder concrete-steel composite test structure with known minute damage. Long-gauge fiber-optic strain and temperature sensors were installed on the test structure at two locations of damage and one healthy baseline location prior to the pouring of the concrete slab. A finite element model was developed and validated using strain measurements for static loading events, and used to predict the healthy neutral axis position at each monitored location. Results show that the finite element prediction of healthy neutral axis location matches very well with actual sensor measurements at the healthy baseline location. An upward shift of the neutral axis is noticed at damaged locations, which was also an observation from previous research. While the change of the position of the neutral axis at damaged locations is confirmation of the damage detection capabilities of the method, further research is needed to explain the physical cause of the detected upward shift of the neutral axis.

1 INTRODUCTION

In a typical beam-like structure, the neutral axis is the curve in the cross-section that experiences zero strain. The neutral axis method is a strain-based structural monitoring method that uses the movement of the neutral axis as an indication of structural condition. In a composite beam structure, the position of the neutral axis can be associated with geometric and material stiffness properties of the structure [1]. According to literature, downward movement of the neutral axis in a composite beam structure can be used as an indication of damage in the concrete slab [1]. With the assumption of linear theory, the neutral axis position can be calculated with as few as two strain values in the cross-section of a structure monitored by strain sensors with parallel topology [2]. Previous research efforts have confirmed a strong correlation between neutral axis position and structural conditions through laboratory experiments and controlled tests on composite structures with significant damage [3][4]. However, the ability of neutral axis to detect small, early-stage damage in structures in uncontrolled environmental settings has not been comprehensively studied. At the current research stage, the authors believe that more in-depth studies on the movement of neutral axis in composite structures with minute damage would close this research gap, and facilitate a more thorough understanding toward the method of neutral axis for damage detection and condition assessment for composite structures.

This paper discusses the application of the neutral axis method on the monitoring data of a model beam structure. The test structure is a multi-girder composite scale model bridge with a span of 30 ft. The structure consists of a reinforced concrete deck and three wide-flange steel I girders. Minute artificial damage was incorporated into the concrete slab at two girder locations by inserting paper-sized plastic sheets. The test structure is monitored by three sets of strain and temperature sensors at a baseline location and two locations of minute damage. The approximate positions of strain sensors, as well as the sizes and locations of the minute artificial damage are shown below in Figure 1.

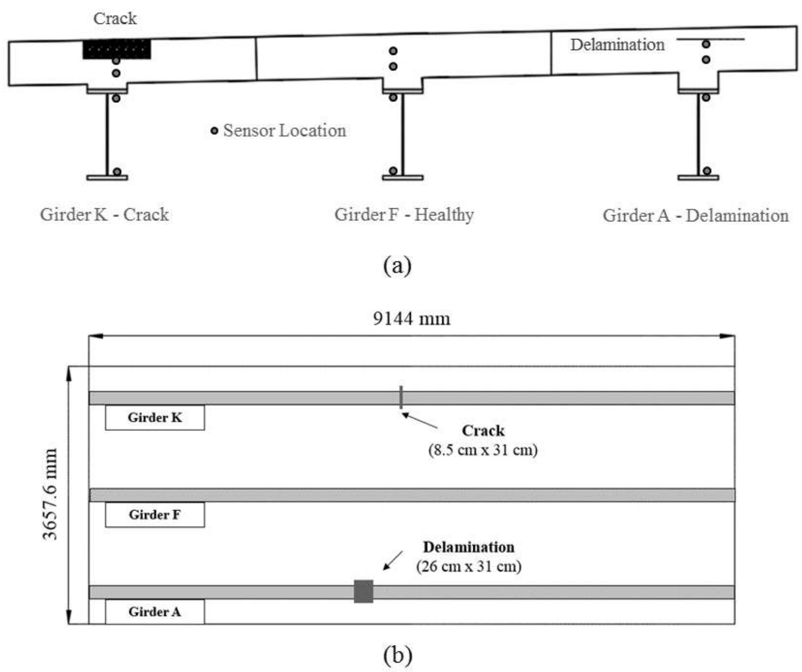

Figure 1: Test structure cross-section and plan.

The test structure was monitored through a set of loading events, which began seven days after the casting of the concrete slab. In the following sections, the neutral axis position of the structure will be analyzed for two static loading events, and finite element analysis will be used to predict the healthy neutral axis position. In a typical composite structure, minute damage in the concrete slab causes the neutral axis to move downwards. However, the monitoring data of the test structure indicates upward movement of the neutral axis in the presence of damage. Finite element simulation suggest early-age shrinkage of the concrete slab as a partial cause of the unexpected behavior.

2 METHODOLOGY

Strain data from the first monitoring session of the test structure was used for the neutral axis analysis. Temperature sensor readings were used for thermal compensation of the strain measurements. Two static loading events were identified based on the evolution of elastic strain over time, as illustrated in Figure 2. Load case 1 occurred when the structure was lifted at two intermediate jacking points, and load case 2 took place when the structure was placed on temporary wooden supports.

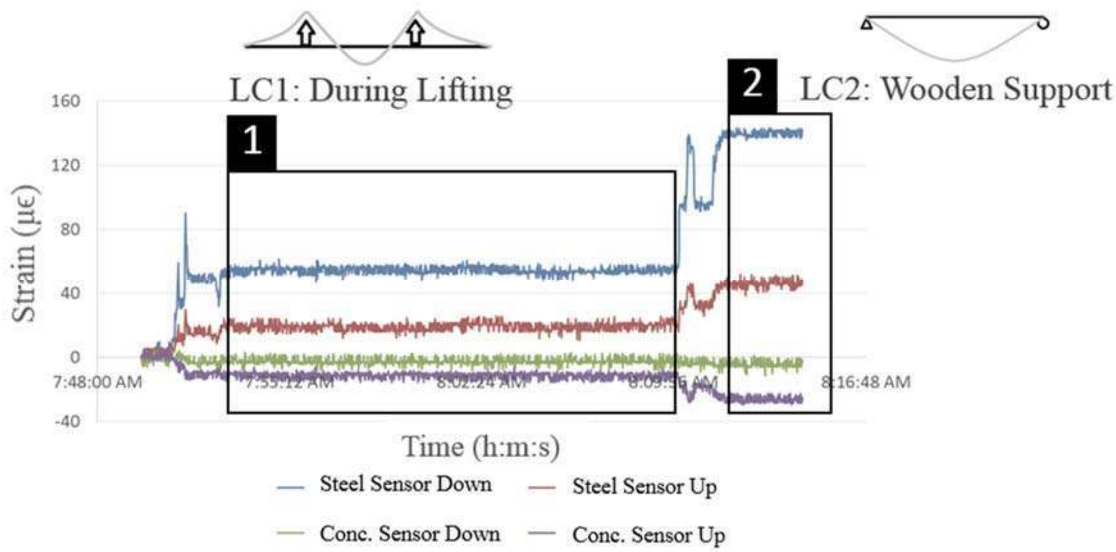

Figure 2: Elastic strain over time – Girder A

The strain values at each sensor location are expected to resemble a linear strain profile across the depth of the cross-section. Therefore, simple linear regression was used to calculate the position of the neutral axis [5]. The mean and standard deviation of sensor measured neutral axis position at each girder location are as listed in Table 1. The neutral axis position for each load case appears to be relatively stable. However, the location of the neutral axis varies depending on the sensor set used in the calculation (sensor on steel, sensors in concrete, or all sensors in a cross-section).

		Load Case 1			**Load Case 2**		
		Steel	Concrete	All	Steel	Concrete	All
Girder A	μ	558	512	500	541	520	517
	σ	18	13	7	7	5	3
Girder F	μ	498	498	497	500	500	502
	σ	17	13	10	5	4	3
Girder K	μ	533	498	497	511	490	488
	σ	19	6	7	10	3	3

Table 1: Neutral axis position for Load Cases 1 and 2 (mm).

3 FINITE ELEMENT MODEL OF THE TEST STRUCTURE

A 3D finite element model of the test structure was constructed using Abaqus CAE [6-8]. The main components of the structure were made with 8-noded solid elements. Steel reinforcement was modelled with wire elements and constrained as embedded region. The long-gauge fiber optic strain sensors were modelled using truss elements, and embedded in the concrete deck or tied to girder flanges through aluminum L brackets. Figure 3 is an image of the finite element model of the test structure placed under self-weight.

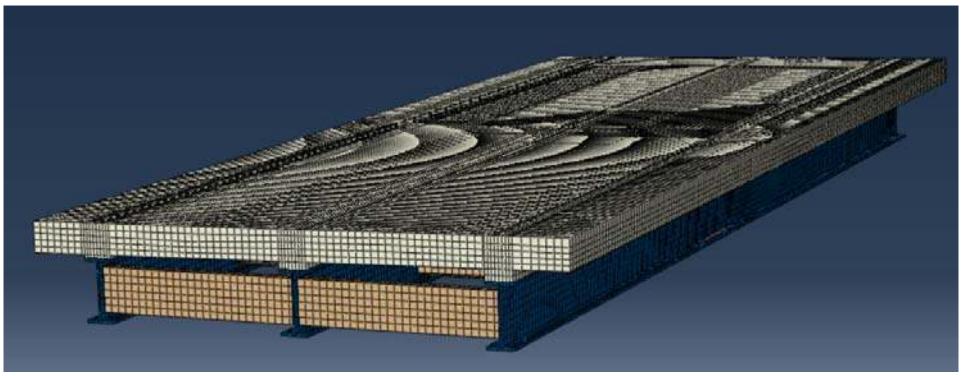

Figure 3: Finite element model of test structure. [7]

The material strength of the concrete at seven days was determined using results from compressive cylinder strength tests performed during the curing the concrete slab. Table 2 summarizes the material information used for constructing the finite element model.

Material	Concrete	Steel	Aluminum
Density (kg/m^3)	2,400	7,800	2,799
Young's Modulus (MPa)	34,000	203,000	69,000
Poisson's Ratio	0.2	0.3	0.33
Material Strength (MPa)	46.8	400	200

Table 2: Finite element model material properties [7].

4 ANALYSIS OF NEUTRAL AXIS POSITION

Using finite element simulations, the locations of zero strain in the model of the undamaged structure under self-weight was extracted as the predicted location of the healthy neutral axis. The predicted neutral axis position was then compared with the sensor measured neutral axis at each location of interest, as shown below in Figure 4.

Based on the comparison, the predicted neutral axis position agrees very well with sensor measurements at Girder F. This result validates the finite element neutral axis prediction, because Girder F is far away from locations of minute damage, and is considered as a healthy baseline location. In addition, the damage was successfully detected by change in position of the neutral axis, or by dispersion of results obtained by different sets of sensors, or both. However, at Girder A and Girder K, where damage in the concrete slab affects the neutral axis position, unexpected upward movement of the neutral axis is observed. This result confirms a similar trend observed from previous research [1]. Two potential causes for this unusual behavior were identified, change in resultant axial forces in girders with damage, and variability in support positions. The former is further examined in this paper, while the latter will be studied in the future work.

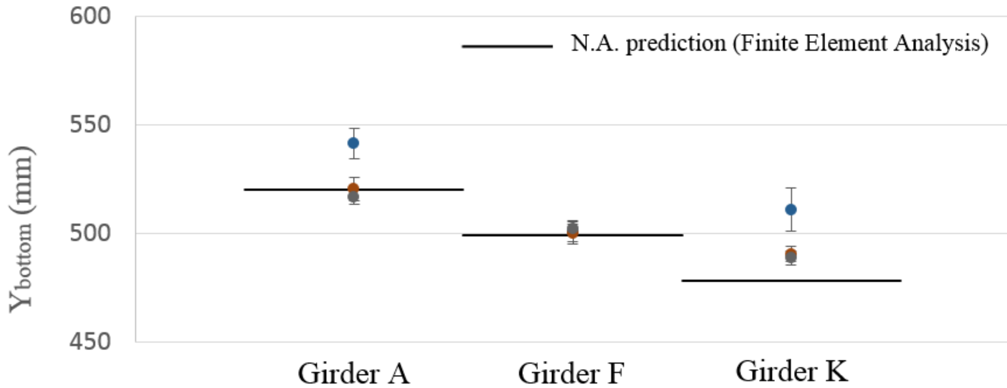

Figure 4: Sensor measured neutral axis position vs. prediction of healthy location.

5 ANALYSIS OF STRAIN PROFILES AT SENSOR LOCATIONS

Load Cases 1 and 2 were simulated using the finite element model as static loading events. The simulated sensor strains were extracted and compared to actual sensor measurements, as illustrated in Figure 5. The strain profiles from actual sensor measurements and finite element simulations correspond to linear behavior, which confirms the assumption of linear theory. It was shown that the magnitude of strain change from Load Case 1 and Load Case 2 was consistent between the simulated strains and the actual sensor strains, which further validates the stiffness definition of the materials in the finite element model. However, the finite element simulated strains are shown to have lower magnitudes for both load cases, which suggests a constant shift of strain that was not considered in the analysis. The strain profile comparisons for Girders A and K display very similar results.

Prior to the start of the first monitoring session, the structure was placed on level ground with no external loading, and the strain sensors were expected to measure zero initial strain values. However, due to fabrication defects or early-age behavior of the composite slab, non-zero initial strains could have developed in the structure and caused a constant shift in measured strain values. The magnitude of the initial strains could be calculated based on the relationship shown in Equation 1, where $\varepsilon_{\text{sensor measurement}}$ represent known values from strain sensor measurements, $\varepsilon_{\text{due to loading}}$ are simulated sensor strains from the finite element analysis, and $\varepsilon_{\text{initial condition}}$ are values of initial strain at each sensor location, which were previously assumed to be zero.

$$\varepsilon_{sensor\ measurement} = \varepsilon_{due\ to\ loading} - \varepsilon_{initial\ condition} \tag{1}$$

Using this relationship, the value of the non-zero strain condition at each sensor location can be estimated, as shown in Figure 6. The strain profile at all girder locations are approximately linear, with a magnitude of approximately 30 με of compressive strain at the bottom of the structure, and

0 to 10 με of tensile strain near the top of the concrete deck. During the first few days of curing, the test structure was placed in a fairly controlled environment, and strains due to thermal effects are not expected. Therefore, current research suggest early-age shrinkage of the concrete slab as a source of the non-zero initial condition.

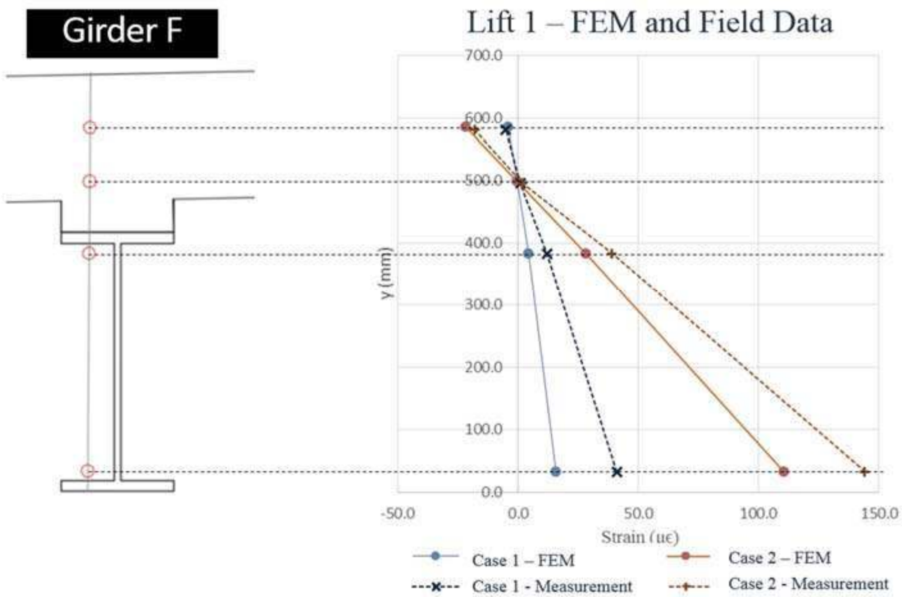

Figure 5: FEM simulated sensor strains vs. monitoring data [7].

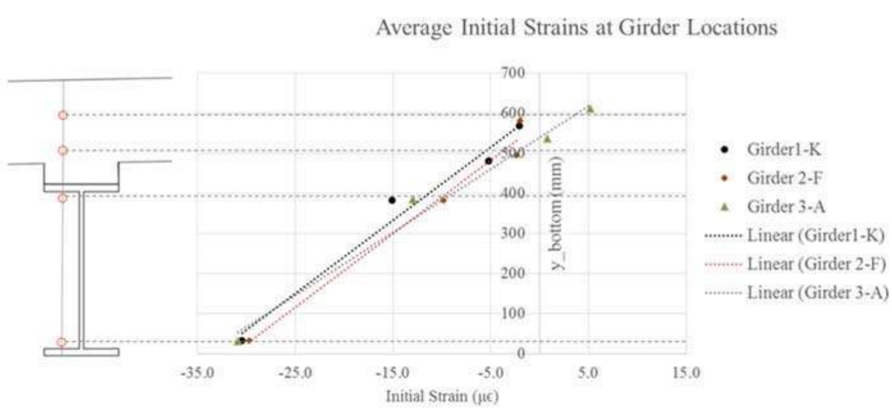

Figure 6: Non-zero initial strain profile at sensor locations [7].

6 SIMULATION OF THE EARLY-AGE SHRINKAGE BEHAVIOR OF CONCRETE

Finite element analysis was used to simulate the test structure under the effect of early-age shrinkage of the concrete slab. A non-linear contact problem was set-up between the model of the test structure and the ground surface, which was represented by an analytical rigid plane. As the early-age shrinkage effect of the concrete slab is analogous to thermal shrinkage due to temperature change, concrete shrinkage was modelled with isolated thermal contraction in the concrete slab. The thermal expansion coefficient of the concrete was defined to be 10 με/°C.

The purpose of this simulation was to identify the magnitude of the imposed strain that corresponds to the initial strain profile discovered from the analysis of sensor data in the previous section. Five values of imposed strain were simulated, and the resulting average strains induced at the top and bottom of the cross-section of the test structure are shown in Figure 7. Based on this plot, an imposed shrinkage strain of 30 με can cause initial strains in the test structure that best resembles the observed strain profiles. This value is reasonable for normal-weight concrete after seven days of casting [9]. Therefore, the upward movement of the neutral axis observed at locations of damage could be in part induced by non-zero initial conditions caused by early-age shrinkage of the concrete slab.

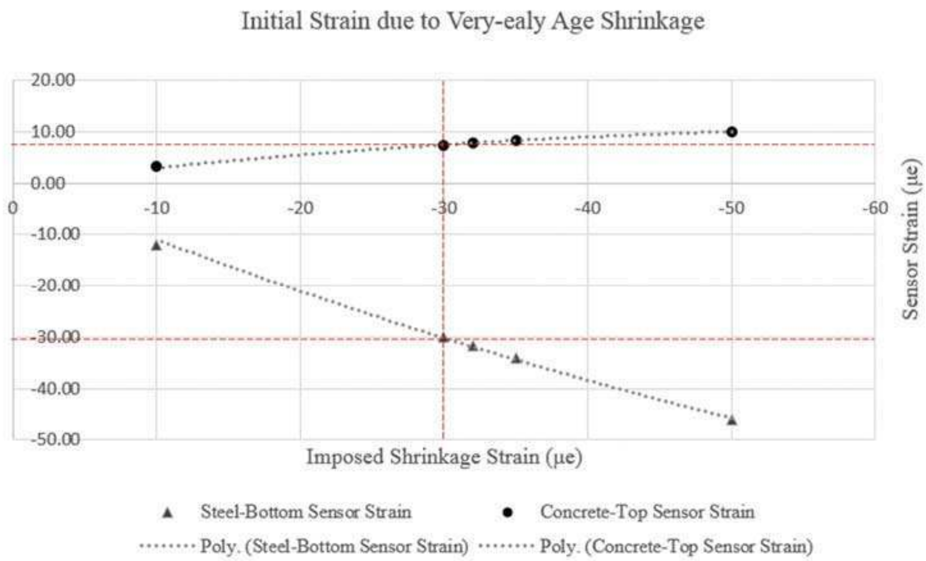

Figure 7: Initial strains from finite element simulation.

7 CONCLUSION AND FUTURE WORK

The method of neutral axis for damage detection in composite beam structures was applied to a test model structure with artificial minute damage, which was monitored by long-gauge fiber optic strain and temperature sensors through a series of loading events. The method was efficient in detecting the minute damage either through the change of the location of the neutral axis, or through dispersion of results obtained by different sets of sensors, or through both approaches.

Using an integrated analysis that combines sensor measurements with finite element simulations, results confirmed an unexpected upward of the neutral axis at locations of minute damage. Finite element analyses indicate non-zero initial conditions caused by early-age shrinkage of the concrete slab as one of probable causes of the observed upward movement of neutral axis. Further analysis is needed to understand the upward movement of the neutral axis in composite beam structures under various damage conditions. In particular, the support conditions will be studied as the next step in the research.

ACKNOWLEDGEMENT

The material presented in this paper is supported by the USDOT UTC Program Grant No. DTRT12-G-UTC16 and the National Science Foundation Grant No. CMMI-1362723. The views, findings, recommendations, and conclusions stated or implied in this paper are solely the opinions of the authors. They are not intended to represent the opinions of the funding agencies. The authors would like to acknowledge Dorotea Sigurdardottir, former graduate student in the Department of Civil and Environmental Engineering at Princeton University, for her precious help in initiating the current research. The authors would also like to thank Professor Gucunski's research group at Rutgers University for their collaboration on the testing of the ANDERS slab. Special thanks to Hiba Abdel-Jaber, Kaitlyn Kliewer, and Jack Reilly.

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