Deterioration of Bridge Deck Element Based on Neutral Axis Analysis

LEONARDO ZUNINO, MAURIZIO MORGESE,
GIUSEPPE DESIDERIO, ALI MAHER, VALENTINA VILLA
and MARCO DOMANESCHI

ABSTRACT

This study investigates the use of the neutral axis as a damage-sensitive feature for structural health monitoring in composite bridge sections. A methodology was developed to calculate the position of the neutral axis and evaluate its changes over time, involving strain measurements from sensors installed along the cross-section of a bridge specimen tested at The BEAST® (Bridge Evaluation and Accelerated Structural Testing lab) at Rutgers, The State University of New Jersey. The BEAST® laboratory is the first full-scale facility designed for accelerated bridge testing under controlled conditions. It applies repeated vehicle loading and environmental cycles, such as freeze-thaw and de-icing, to simulate decades of deterioration in just a few months. This unique setup provides continuous monitoring data to support the evaluation of structural performance over time. The results reported herein demonstrate that increasing neutral axis-centroid deviations correlate with bridge deck degradation. The findings validate the feasibility of neutral axis-based damage detection, highlighting its applicability in structural health monitoring applications.

INTRODUCTION

The integrity of aging infrastructures is a global concern, as many bridges and decks are subjected to increasing loads, harsh environmental conditions, and extended service lives. Structural Health Monitoring (SHM) systems, which continuously or periodically track structural responses, provide timely information that can guide maintenance and rehabilitation, thus reducing the risk of failures [1, 2].

While many SHM approaches focus on global vibration characteristics or localized crack detection [3, 4], methods that leverage strain-based metrics provide a direct link to internal force redistribution and material degradation [5, 6]. These approaches offer enhanced sensitivity to stiffness changes and progressive damage that may not be immediately visible through displacement or frequency-based indicators. Among strain-based techniques, tracking the position of the neutral axis has shown particular promise as a reliable and interpretable indicator of structural health.

Maurizio Morgese, Ph.D., Email: maurizio.morgese@rutgers.edu. Center for Advanced Infrastructure and Transportation (CAIT), Rutgers, The State University of New Jersey, NJ, USA

Previous work by Sigurdardottir and Glisic [7,8] demonstrated that tracking the Neutral Axis in beam-like structures can be an effective way to detect damage, specifically stiffness reductions or cracking. In their approach, shifts in the neutral axis location are treated as a direct consequence of changes in stiffness distribution. However, factors such as axial loads, temperature changes, and environmental effects can mask real damage signatures. Consequently, careful data cleaning and the inclusion of thermal strain corrections are necessary for an accurate neutral axis evaluation. In particular, Wu et al. (2023) [9] and Wu et al. (2024) [10] showed that temperature gradients—both linear and nonlinear—can significantly shift the NA, highlighting the need for advanced thermal-varying models to ensure that measured neutral axis variations truly reflect structural conditions rather than environmental fluctuations.

The analysis presented herein focused on a composite steel-concrete section tested at “The BEAST®” laboratory, managed by the Center for Advanced Infrastructure and Transportation (CAIT) at Rutgers, The State University of New Jersey. This large-scale experiment setup aims to replicate years of traffic loading, freeze-thaw cycles, and saline exposure in a compressed timeframe. The approach proposed herein involves the collection of strain data from sensors, followed by correction for thermal effects, subsequent application of statistical filtering to clean the data, and identification of the neutral axis position over time. This process demonstrates that large deviations in the neutral axis location are indicative of progressive structural deterioration.

EXPERIMENTAL SETUP

Rutgers University’s CAIT facility, known as “The BEAST®” (Bridge Evaluation and Accelerated Structural Testing lab), applies accelerated life-cycle loading to full-scale bridge deck specimens (shown in Figure 1). The facility replicates decades of service life within a compressed timeframe by combining mechanical loading with aggressive environmental conditioning. Load lanes are configured so that simulated heavy trucks, with prescribed wheel paths, repeatedly pass over different girders at frequencies representative of highway traffic. Throughout each test cycle, the structure is exposed to controlled freeze–thaw events and periodic brine deployment to induce chloride penetration and corrosion.

The full-scale specimen consists of a composite deck measuring 50 ft by 25 ft, supported by four longitudinal steel girders spaced at 7.5 ft intervals. The concrete deck was cast using high-performance concrete (HPC), e hile the steel girders were fabricated from ASTM A709 Grade 50 structural steel.

The composite specimen is equipped with an extensive network of vibrating-wire and strain gauges, displacement transducers, and environmental sensors that continuously track mechanical and climatic actions. Among these, two interior steel girders of the composite specimen are instrumented, at midspan, with a “vertical quartet” of four strain gauges—two embedded at different depths in the concrete slab, one bonded to the steel web, and one on the bottom flange—enabling reconstruction of the strain gradient through the section height. Strains were sampled at 20 Hz and averaged over consecutive three-minute intervals, forming the time series used for neutral-axis tracking and structural health assessment.

Figure 1. The BEAST Lab overview.

METHODOLOGY

In this section, the methodology adopted to assess the structural performance of the composite section of a bridge is presented, from data acquisition to the derivation of the deterioration index.

Data Collection and Preprocessing

Strain data were collected from four strain gauges positioned on the same vertical along the composite section at midspan, in regions assumed to represent the maximum deterioration of the structure. Specifically, two gauges were welded directly onto the steel web, and two were embedded in the concrete slab above.

Outliers were identified as values deviating significantly from the local trend, using a threshold based on scaled median absolute deviation over a moving window of approximately 50 samples. These points were replaced with `NaN` and linearly interpolated to preserve continuity in the time series.

Effective Strains

After outlier removal and the cleaning process, thermal effects were corrected using temperature measurements from thermocouples associated with each strain gauge, converting temperatures from Fahrenheit to Celsius and computing thermal strains using a combined coefficient of thermal expansion $\alpha = 2.2 \times 10^{-6},^{\circ}\mathrm{C}^{-1}$ for reinforced concrete. For strain gauges welded directly onto steel members, no thermal correction was applied, following manufacturer recommendations.

$$\varepsilon_{\text{eff,concrete}} = \varepsilon_{\text{cleaned}} - \varepsilon_{\text{thermal}}, \tag{1}$$

$$\varepsilon_{\text{eff,steel}} = \varepsilon_{\text{cleaned}} \,. \tag{2}$$

where the thermal strain $\varepsilon_{\text{thermal}}(t)$ accounts for the temperature shift from the start of each test. The resulting data better isolates mechanical load-induced strains.

Neutral Axis Calculation

At each time step, the effective strain values measured by the four sensors—positioned at known vertical coordinates along the section—are used to fit a linear strain profile as a function of height:

$$\varepsilon(y) \approx m\,y + c, \tag{3}$$

where y is the known vertical coordinate of each sensor, and $\varepsilon(y)$ is the corresponding effective strain. The neutral axis location y_{NA} is the height at which $\varepsilon(y_{NA}) = 0$, i.e.,

$$y_{NA} = -\frac{c}{m}. \tag{4}$$

Theoretical Centroid Calculation

The theoretical centroid y_C of the composite section is computed by classical mechanics of materials, accounting for effective slab width, steel beam dimensions, and a modular ratio $n = E_s/E_c$. The centroid is calculated using the following formula:

$$y_C = \frac{nA_s y_s + A_{c1} y_{c1} + A_{c2} y_{c2}}{nA_s + A_{c1} + A_{c2}}, \tag{5}$$

where A_s is the area of the steel beam, located at a centroidal height y_s; A_{c1} is the area of the effective concrete slab with its centroid at height y_{c1}; and A_{c2} is the area of the web portion of the concrete, with centroid at y_{c2}. The modular ratio $n = E_s/E_c$ accounts for the stiffness difference between steel and concrete.

NA-C Difference

The time history of $y_{NA}(t)$ is then compared to the theoretical centroid y_C. The resulting difference

$$\Delta(t) = y_{NA}(t) - y_C \tag{6}$$

is treated as an indicator of the overall structural condition of the composite section, reflecting potential changes in stiffness, progressive deterioration of the concrete slab, loss of composite action between steel and concrete, or the onset of localized damage phenomena. To mitigate the influence of non-stationary effects—typically present at the start or end of each load test—a portion of the initial and final data is discarded.

Deterioration Index

To quantify the structural evolution of the section, a preliminary deterioration index is defined based on the statistical analysis of $\Delta(t)$. Specifically, the mean and standard deviation of the filtered NA–centroid difference are computed. A sustained increase in the mean value over time can be interpreted as a shift of the neutral axis toward the compression zone, potentially indicating a reduction in effective stiffness—particularly in the concrete slab or its composite interaction with the steel girder. This behavior may arise from loss of effective slab area, degradation of concrete properties, or diminished bond and interaction between steel and concrete.

Rather than representing a discrete damage state, this index reflects a continuous degradation process in the mechanical performance of the section. It can thus serve as a useful indicator of progressive structural deterioration, especially when considered in relation to environmental exposure (e.g., freeze-thaw cycles) and load history.

RESULTS

Strain Data Processing

Figure 2 shows the evolution of strain signals from the four sensors located along the depth of the section for a representative test (Test 4). The top row illustrates the cleaned raw strain data, obtained after spike removal and smoothing. The bottom row displays

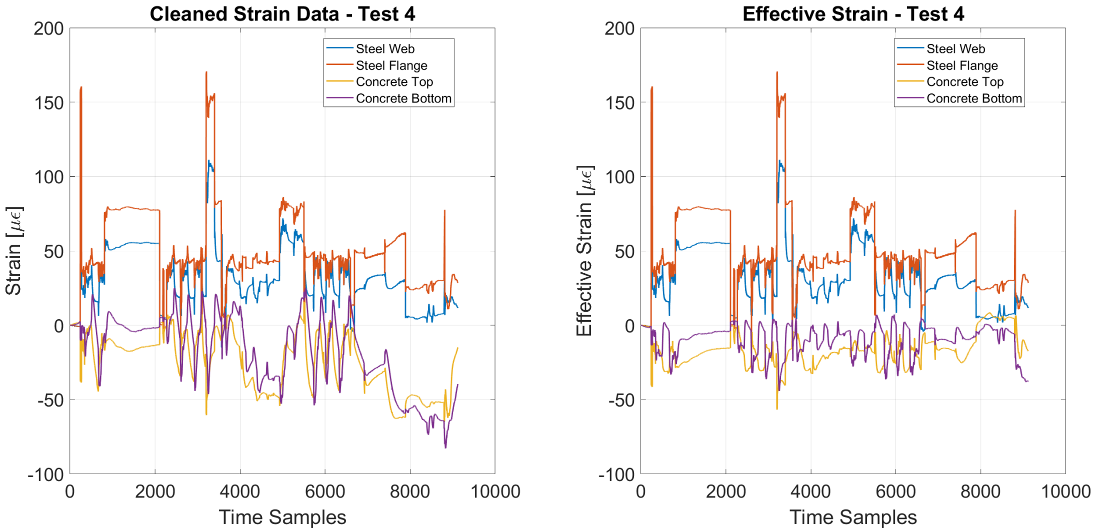

Figure 2. Strain signals for Test 4 (left) and effective strain after thermal correction (right).

the corresponding effective strains after thermal compensation, clearly highlighting the bending profile induced by external loads.

Neutral Axis Evolution

From the effective strain profiles, the neutral axis position was computed at each time step using a linear regression approach. Figure 3 displays the time history of the neutral axis position for two representative tests, alongside the theoretical centroid of the composite section. In Test 4 the neutral axis remained relatively stable and close to the centroid, whereas in Test 15 a noticeable downward shift was observed during the central portion of the test, suggesting a transient loss of stiffness in the upper concrete region and/or a reduction of the effective slab area.

Deterioration Index

To synthesize the structural evolution over time, a deterioration index was computed for each test based on the mean of the neutral axis–centroid difference $\Delta(t)$. Figure 4 summarizes this index for all available test cases, allowing a direct comparison between different phases of the experimental campaign. A progressive increase in the mean neutral axis shift was observed in later tests, supporting the hypothesis of cumulative stiffness loss in the concrete slab or at the steel-concrete interface.

CONCLUDING REMARKS

Neutral-axis tracking, supported by automated data cleaning and thermal correction, proved effective for gauging the health of The BEAST® composite girder. For each test, the NA–centroid offset $\Delta(t)$ reacted to changes in concrete slab, while its mean value—a simple deterioration index—showed an upward trend over successive loading and brine/freeze-thaw cycles.

The method requires only four strain gauges and lightweight computations, making it suitable for real-time SHM deployments. Future work will set alert thresholds and

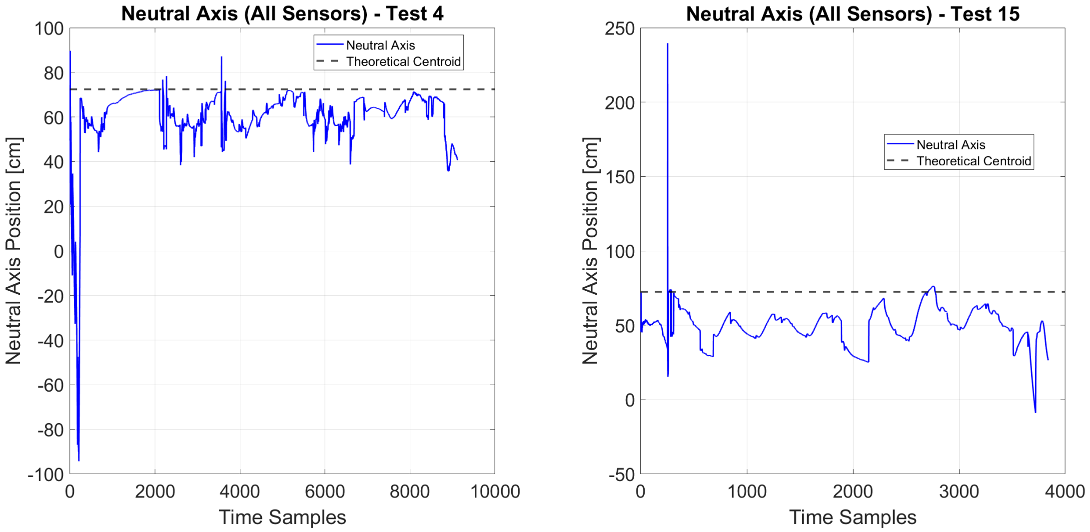

Figure 3. Neutral axis evolution during Test 4 (left) and Test 15 (right), compared to the theoretical centroid.

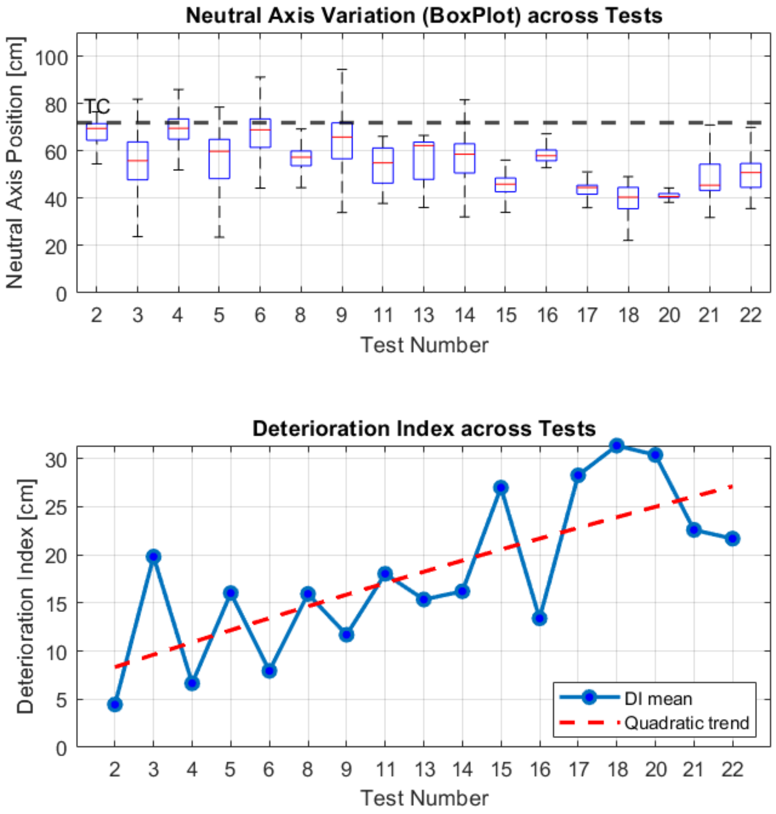

Figure 4. Top: Neutral axis position distribution across different tests, compared to the theoretical centroid (TC). Bottom: Evolution of the deterioration index (mean NA–centroid deviation) across tests with quadratic trend.

validate the index on in-service bridges, but the present results already confirm neutral axis monitoring as a fast, low-cost indicator of progressive deck deterioration.

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