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Research Article

# Sustainability evaluation of highway sign support by field testing and finite element analysis

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## ABSTRACT

The primary objective of this study is to evaluate the sustainability of highway sign supports through field testing and finite element analysis. The study aims to develop a predictive maintenance model to evaluate the service life of these structures. Sign support systems are important structures in the Connecticut Department of Transportation (CTDOT) bridge management system. Periodic sustainability inspections and maintenance activities are needed as a long-term, cost-effective maintenance strategy. The research involved non-destructive field testing of a cantilever-type highway sign support, followed by finite element modeling using Highway Sign Structures Engineering (HSE) by SAFI software. Data from accelerometers, strain gauges, and anemometers were collected and analyzed to validate the model. The experimental setup was done in collaboration with CTDOT. The data was collected and analyzed, and it was used to verify the three-dimensional finite element (FE) model developed, which was used to test the structure's design capacity. The study found that the sign support structure experienced significant wind loading on a few occasions, with stress levels reaching about 20% of its elastic limit. The finite element model accurately predicted structural behavior under design load conditions, demonstrating its potential for predictive maintenance applications.

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## 1. INTRODUCTION

This research performed a non-destructive field test of a highway sign support to develop a finite element model simulating the structure for behavior analysis due to limited state loads. The advancements in sensor technology and data analysis have provided new opportunities for real-time monitoring and predictive maintenance of these structures. The experimental setup was in collaboration with the Connecticut Department of Transportation (CTDOT), where the project focused on field instrumentation and testing of a highway sign support that was a cantilever-type structure. The data was collected and analyzed, and it was used to verify the three-dimensional finite element (FE) model developed, which was used to test the structure's design capacity. The research shows the potential to increase the service life of sign support structures, which is currently set at 34 years.

An event occurred on I-190 SB in Worcester, Massachusetts, that underscores the importance of this project. On August 9$^{th}$, 2022, a cantilevered sign support collapsed on the roadway, obstructing the low-speed and middle lanes (Fig. 1). Thankfully, no motorists were injured, and the Massachusetts Department of Transportation (MassDOT) had the road cleared the following day [1]. Still, such an incident illustrates the potential risk associated with these structures and what can happen if they are not regularly maintained.

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**Figure 1**. Collapsed sign support.

This and other similar instances highlight the need for improved maintenance and monitoring of highway sign supports. A Federal Highway Administration (FHWA) study reported that poorly maintained sign supports can become hazardous, especially when vehicles strike [2]. The study underscores the importance of regular inspections and preventive maintenance to ensure the structural integrity of these supports. The study published guidelines emphasizing the critical role of maintenance in preventing accidents caused by damaged or missing signs. These guidelines recommend regular cleaning, vegetation control, and timely repairs to maintain the effectiveness and safety of highway sign supports [2].

Recent studies have shown that regular maintenance and inspection can significantly extend the service life of highway sign supports. For instance, a survey by Tuhin highlighted the importance of structural integrity and regular inspections to prevent failures [3]. Another study by Patel (2024) discussed the design improvements and maintenance strategies for highway sign supports to enhance their durability [4].

The American Association of State Highway and Transportation Officials (AASHTO) has also updated its guidelines for the structural supports of highway signs, luminaires, and traffic signals, emphasizing regular maintenance and advanced materials [5]. These updates reflect the latest research and technological advancements in the field, providing a more robust framework for maintaining highway sign support.

A survey focusing on asset management, design process, inspection frequency, material usage, and failure types was drafted and circulated to all the Departments of Transportation (DOTs) to investigate sign support structures effectively. Data from each response was recorded, organized, and interpreted to assess the common issues affecting sign support structures and the effective management practices of these structures. The first step in the development process of the survey was to assemble and review current practice, technical literature, research findings of recently completed and ongoing projects, and procedures and codes addressing highway sign support on deterioration models, asset management, evaluation, and testing. The review focused on recent sign support risk assessment and field-testing developments.

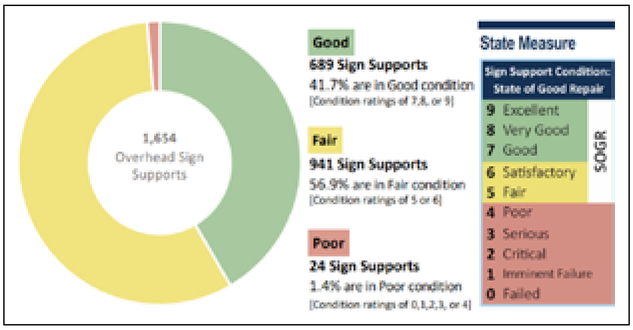


**Figure 2**. CTDOT Sign support inventory with performance scale.

Documents published by state DOTs standardizing elements of their sign support assets are evidence of sound asset management. Several DOTs have published Transportation Asset Management Plans (TAMPs) to secure federal funds and comply with federal legislation, specifically the Moving Ahead for Progress in the 21$^{st}$ Century (MAP-21) Act and the Fixing America's Surface Transportation (FAST) Act [6]. Responsible for approximately 1,654 sign supports, CTDOT has established performance measures (Fig. 2) and maintenance programs to manage sign support assets better. Supports with a score of 0 have failed; a score of 9 indicates that the support is in excellent condition. Assets receiving scores between 5 and 9 are said to be in a State of Good Repair (SOGR).

The NCHRP Report, 494 Structural Supports for Highway Signs, Luminaries, and Traffic Signals, includes a section discussing inspection, retrofit, repair, and rehabilitation of fatigue-damaged support structures. The Federal Highway Association (FHWA) assesses support as reasonable and fair but is a poor system. Recent data suggests that 41.7% are in good condition, 56.9% are in fair condition, and 1.4% are in poor condition [7]. CTDOT's TAMP combines each rating system so that sign supports in good condition correspond to scores 9-7, sign supports in fair condition correspond to scores 6 and 5, and sign supports in poor condition correspond to scores 4-0 [6].

The sign supports maintained by CTDOT are categorized by type, where 643 are cantilevered, 617 are entire spans, and 394 are bridge-mounted [6]. A fourth type is the butterfly support. The kind of support determines the inspection interval, where full-span supports are inspected every 6 years, and the cantilever and the bridge-mounted supports are inspected every 4 years. If a support is fabricated out of aluminum, it shall be inspected every two years, no matter the type of support [8].

A clearly defined maintenance schedule and an organized method for logging inspection data are crucial to asset management. Other DOTs have implemented standardized documents, defining installation and inspection methods, signing support selection criteria, and repairing manuals [9]. The Wisconsin Department of Transportation (WisDOT) has published a table of available sign support types and selection criteria for each support [9]. WisDOT also has a chapter in its Facilities Development Manual dedicated to standardized sign support structure designs and selection processes [10]. These standardized designs help contractors fabricate a reliable sign support structure without redesigning the whole structure every time a job comes out to bid. Also included on WisDOT's website is a list of Load and Resistance Factor Design (LRFD) Standardized Overhead Sign Structure Plans [11]. Nebraska Department of Roads (NDOR) published a complete inspection and installation manual for sign supports and high mast lighting [12]. NDOR's manual includes pictures of best practices concerning torquing, anchor bolt plumpness, plate connection tolerances, corrosion prevention, and other necessary installation and inspection considerations. Michigan Department of Transportation is the only state DOT that has published a repair manual for sign support structures, indicating that most DOTs would replace the whole structure entirely rather than make repairs [12]. A supplemental literature review was also conducted on fatigue stresses, as these forces are attributed to most sign support structure failures [13].

Life cycle planning is driven by one underlying principle: timely investments in an asset result in improved condition over a more extended period and lower long-term cost. CTDOT uses age-based deterioration curves based on a 34-year service life to execute life cycle planning. The condition-based models need more development to be successfully implemented, so the age-based approach is strictly adhered to. Once a sign support has reached the end of its 34-year service life, they are replaced. If an age-based modeling approach is being used, it is essential to have a database documenting how old the assets are. According to the Minnesota Department of Transportation data, 73% of its overhead sign support structures are between 0 and 40 years old [14], which backs up CTDOT's 34-year service life expectancy claim.

Setting long-term performance goals and proper life cycle planning assists in scheduling sign support replacement and repair. CTDOT's TAMP outlines some performance targets for sign support management. In 2019, it was projected that 96.6% of sign supports would be in an SOGR by the end of 2020, and 95.2% of sign supports would be in a SOGR by the end of 2022. A 10-year goal was also established by CTDOT's TAMP, which set out to achieve a SOGR for 90% of sign supports. The decrease in the percentage of sign supports in an SOGR around 2026 is due to a large number of supports reaching their life expectancy simultaneously (Fig. 3). CTDOT's TAMP maintains that funding for sign supports will be approximately $4 million per year, with the replacement of 40% of sign supports in poor condition funded by other projects. It is noteworthy that 100% of the funds in the sign support budget go towards replacement. Perhaps allocating some of those funds towards repair could be more economical.

CTDOT estimates that it costs $140,000 to replace a cantilever support, $250,000 to replace a full-span support, and $50,000 to replace a bridge-mounted support

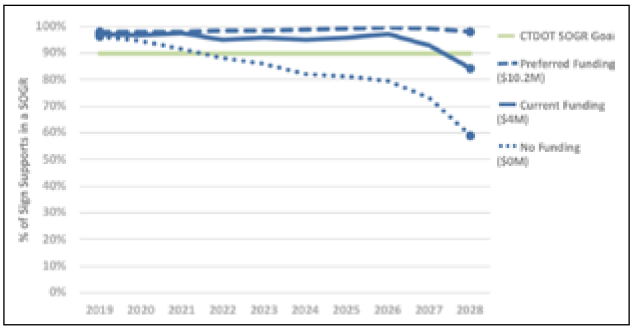


**Figure 3**. CTDOT Sign support performance projections.

[2]. Since these assets are not cheap, selecting those that need replacement the most is crucial. While common sense would say those supports scoring lowest on the SOGR scale will be replaced first, replacement criteria are not entirely condition-based. Sign supports are often replaced because the sign panel size increases due to changes in FHWA's Manual on Uniform Traffic Control Devices (MUTCD) for Streets and Highways requirements. A bigger sign panel requires support stronger than the existing support. Sometimes, projects that alter the roadway can lead to the replacement of excellent support. Other times, sign support projects are issued by location, so every sign support along the designated corridor will be replaced regardless of its condition. These non-condition-based replacements create the potential for waste and excess cost, resulting in economic loss.

To combat the adverse effects of non-condition-based replacements, CTDOT's TAMP outlines five investment strategies: (1) Program sign support projects based on poor conditions, (2) Reduce the number of sign supports by putting signs next to the road whenever possible, (3) Increase efforts to maintain the sign panel size by decrease the sign legend spacing, (4) Overdesign sign supports with an augmented factor of safety so they can support next-generation sign panels, and (5) Reduce the number of bridge mounted sign supports to decrease dead load supported by the bridge and lower inspection costs.

Failure rates of sign support systems are scarce. Each study for the project showed that significant structure collapse occurs infrequently and can be avoided with preventative analysis and a predictive failure model. Sign support asset management is a topic that has not been extensively studied [15]. However, developing predictive deterioration models for sign support systems is feasible by identifying key factors such as materials, age, location, and wind loading. As cars and trucks pass under signs, the wind gradually wears off them on the sign supports.

Specifically, the supports' welded joints are the primary degradation point. Failure analysis of the highway sign structure and design improvement showed that hairline fractures occur due to wind loads. Kipp et al. [16] also revealed that analyzing the structures under various wind loads is more practical than a pure static load, as varying wind speeds can cause more damage to structures over time. The study attempted to model

Overhead Highway Sign Support Survey

1) Approximately how many highway sign supports are currently in your state?
   a. Less than 500
   b. 500 - 1000
   c. 1000 - 1500
   d. 1500 - 2000
   e. More than 2000, approximately: __________
2) What is the approximate inspection frequency of highway sign supports, in years?
   a. 5
   b. 10
   c. 15
   d. 20
   e. Other: _________
3) What is the best estimate, in years, for the replacement of a highway sign support?
   a. 10-19
   b. 20-29
   c. 30-39
   d. 40-49
   e. 50+
4) What are the approximate percentages of highway sign supports with the following designs?
   a. Full-span ____ %
   b. Cantilever ____ %
   c. Bridge-mounted ____ %
   d. Other:__________________________
5) What are the approximate percentages of material types used to construct sign supports?
   a. Steel: ______ %
   b. Aluminum: ______ %
   c. Concrete: ______ %
   d. Other:___________________________
6) Which type of highway sign support requires the most maintenance?
   a. Full-span
   b. Cantilever
   c. Bridge-mounted
   d. Other:___________________________________
7) What is the most common reason for replacing a highway sign support structure?
   a. The structure has reached the end of its useful life
   b. The structure needs to be updated according to new or existing specifications
   c. Modifications to the roadway cause the structure to be relocated
   d. Other:___________________________________
8) What is the most typical failure of highway sign support structures?
   a. Crumbling or cracked foundations
   b. Loose nuts or bolts
   c. Broken welds
   d. Tilting or leaning
   e. Other:_____________________________________
9) Are the current designs for highway sign support structures standardized?
   a. Yes
   b. No
10) Are damping or energy absorbing devices being used in current sign support designs?
   a. Yes
   b. No

**Figure 4**. Overhead highway sign support survey sent to the nation DOTs.

wind effects on different sign support systems and identify their weak points for future repair schedules. It was concluded that the two critical points in the structure were the midpoint of the span and the base of the columns. The probability of failure and reliability of the curves should depend on the lanes and the average daily traffic under each structure. This study also validated using predictive computer modeling for measuring sign support wind degradation.

Looking more at the types of sign supports specifically, field testing and analysis of aluminum highway sign trusses looked at how existing designs can be modeled to increase their wind load capacity. The study by Barle et al. [17] showed this to be the case by examining cantilever-type and Type-III overhead sign supports. The conclusion was that increasing the drag coefficient on these structures could reduce the wind load. By analyzing these, we can see that minor modifications to sign supports have a significant impact.

Different types of sign supports have varying tolerances for wind capacity and respond differently to stresses. Two studies support this conclusion: by Yang et al. [18] and by Ehsani et al. [19]. These two papers conclude that monotubes rely on stiffness for reliability rather than strength criteria, while the opposite is true for box truss structures. Therefore, the type of sign support affects reliability if all other factors are equal.

The idea of conducting regular inspections of aging models can identify problems before they occur. Al Shboul et al. [20] analyzed predictive failure models and showed that simulating wind speeds can comprehensively approach predictive failure. This work supports the findings of Barle et al. [17], who concluded that variable wind speeds cause more wear and tear than static wind speeds. The conclusions drawn by Al Shboul et al. [20] were used to detect two severe fractures in signs that would have otherwise gone unnoticed. This discovery was due to new inspection practices [21]. While the study is more technical, the hypothesis suggests that wind is among the highest risk factors for sign support degradation, primarily caused by passing traffic underneath.

Reviewing related peer literature and their methods reinforces the study's validity. Two key research publications on the topic are "Road Asset Management Systems" by Miller et al. [22] and "Analysis of Traffic Sign Asset Management Scenarios" by Harris et al. [23]. These two publications provided the basis for the approach to asset management and categorization. Kruse et al. [24] demonstrated how asset management using technology such as GIS information can be effective. Their study supports the subsequent research, highlighting the advantages of using advanced software to monitor assets. Combined with a predictive failure model, this can result in a more efficient maintenance plan.

## 2. METHODOLOGY

### 2.1. Survey

Studying the existing literature on sign support management and structural analysis facilitated sound project design. A survey focusing on asset management, design process, inspection frequency, material usage, and failure types was drafted and circulated to all DOTs to investigate sign support structures effectively. Each step, from writing the survey to sensor installation and data treatment, required us to draw upon knowledge from articles discussing fatigue stress, reports covering inspection procedures, and drawings standardizing sign support design. After sufficient literature review, the survey was drafted (Fig. 4) and distributed to all the United States Departments of Transportation. Data from each response was recorded, organized, and interpreted to assess the common issues affecting sign support structures and the effective management practices of these structures.

Survey circulation was conducted by contacting three to five individuals from each State DOT affiliated with a traffic engineering division, a structures division, or a maintenance division. Because sign supports are often considered an ancillary asset, they usually fall under the jurisdiction of the previously mentioned divisions. Any trends relating to material usage, inspection techniques, design considerations, and failure modes were identified.

The response rate was 46%, and graphical representations were constructed to show specific trends in the data. The scatterplot (Fig. 5) plots inspection frequency against the number of sign support structures. Each data point on the scatterplot represents a DOT who participated in the survey. The y-axis represents the years passed between inspections, and the x-axis represents the number of sign support structures a given DOT maintains. A linear regression was used to graph a line that best fit the recorded data. Although the linear regression produces a relatively low $R^2$ value, it's important to note that a DOT with as many as 34 times the sign support structures performs inspections at a similar frequency.

The pie chart (Fig. 6) shows DOT estimates for sign support life expectancy. Each section of the pie chart constitutes a percentage of DOT response and corresponds to an approximate life expectancy. 72% of DOTs claim sign support structures can remain in service after 40 years, potentially underestimating the service life estimated in CTDOT's TAMP. Those DOTs reporting an estimated sign support service life expectancy greater than 50 years also commented on its response that repeated maintenance would be performed on the structures before programming a replacement. Other DOTs, however, reported that structures would be replaced before significant maintenance was required. Other notable findings reported in survey responses include: (1) 29% of DOTs reported that 25% to 48% of their sign supports were constructed of aluminum, while the other 71% reported over 93% of sign supports were constructed of steel, (2) a revision to an anchor bolt tightening procedure has reduced hardware section loss due to corrosion, (3) Inspections are being prioritized based on asset condition and location. Those structures in a worse condition which require more maintenance and structures located in areas exposed to adverse external factors (i.e., flood plains, snow belts) are being inspected at a higher frequency, and (4) Other DOTs report annual inspection of bridge-mounted sign supports indicating that these particular assets are high maintenance.

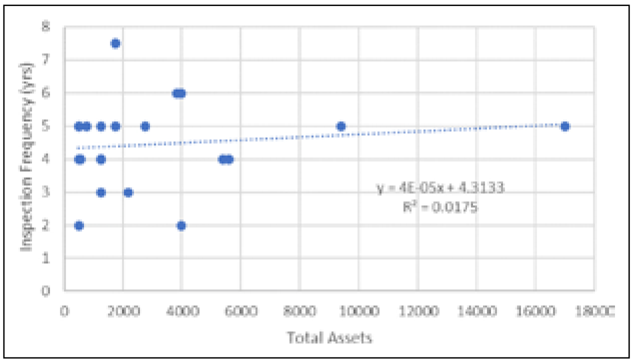


**Figure 5**. DOT Inspection frequency scatterplot.

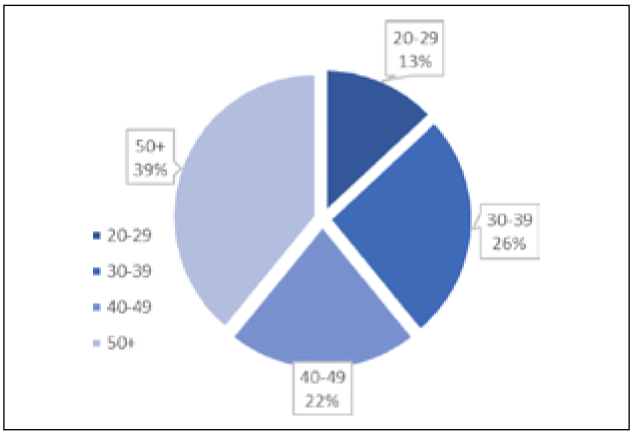


**Figure 6**. Sign support life expectancy pie chart.

After polling the United States DOTs, it is apparent that some DOTs are more diligent in managing assets beyond pavements and bridges, like sign supports, than others [9]. Reading through various Transportation Asset Management Plans published by different DOTs and analyzing survey responses has brought the most effective management strategies to the surface.

The current modeling approach utilized by CTDOT is an age-based approach rooted in the service life of the actual sign panel—not the sign support. After 17 years, the sign panel is due for a replacement. Once the sign panel is replaced twice, CTDOT determines that the sign support structure should also be replaced, resulting in a 34-year service life. The current age-based modeling approach may shorten the service life of sign support structures. The project's primary objective is to develop and verify condition-based models better. The condition-based models need more development to be successfully implemented, so the age-based approach is currently the only option. Once a sign support has reached the end of its 34-year service life, they are replaced. The experimental effort of this project is meant to provide the CTDOT with a condition-based model to consider adopting.


**Figure 7**. CTDOT Asset no. 21740.

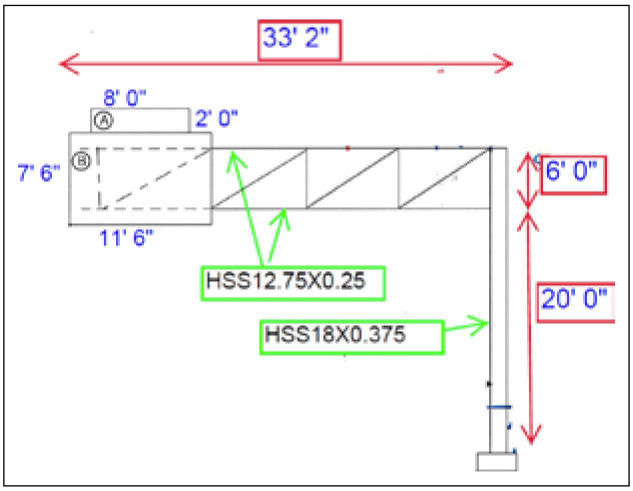


**Figure 8**. Dimensions schematic of sign support 21740.

### 2.2. Instrumentation and Field Test

The CTDOT bridge management and maintenance team coordinated the non-destructive condition assessment field test. This task evaluated the compiled database of sign supports in Connecticut and sorted the inventory to identify suitable candidates for equipment installation. The efforts were closely coordinated with CTDOT representatives, key stakeholders such as transportation enforcement and maintenance, and planning authorities.

In 2022, CTDOT sign support asset 21740, located over I-384 in Manchester, Connecticut, was chosen for the field test portion of the project (Fig. 7). The sign support type is a Truss Arm Cantilever made of steel. This task involved the use of a data acquisition system and instrumentation that included (1) Anemometers to obtain wind velocity and direction, (2) Accelerometers to obtain the acceleration response of the structure, and (3) Strain Gauges to measure the strain response of the structure. The accelerometer type has a 5g sensitivity option for dynamic structural testing in tough field conditions. Four strain gauges were installed at the base of the pole of the overhead sign support structure, four strain gauges at the top arm of the lattice structure holding the arm, and one accelerometer and one anemometer at the top arm. Figure 8 shows the dimensions schematic of the sign support. The equipment supplier field staff required one bucket truck provided by CTDOT for use during the installation day. The instruments remained connected to the structure for six months to collect data continuously.

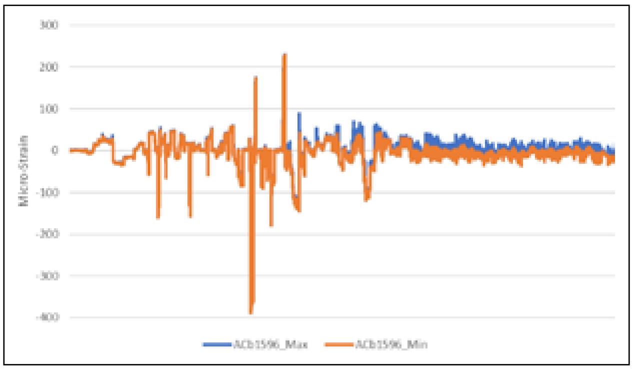


**Figure 9**. Graph of the top strain gauges data for channel 1 - Up and down positions.

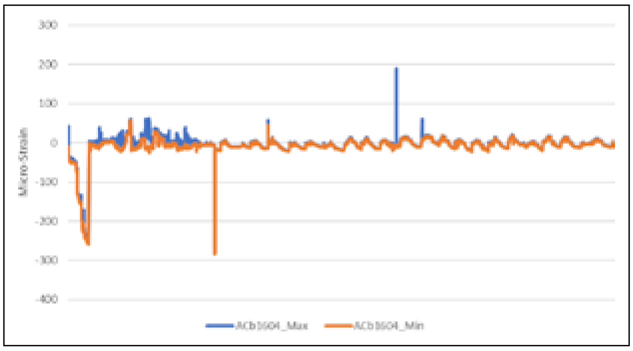


**Figure 10**. Graph of the top strain gauges data for channel 2 – East and west positions.

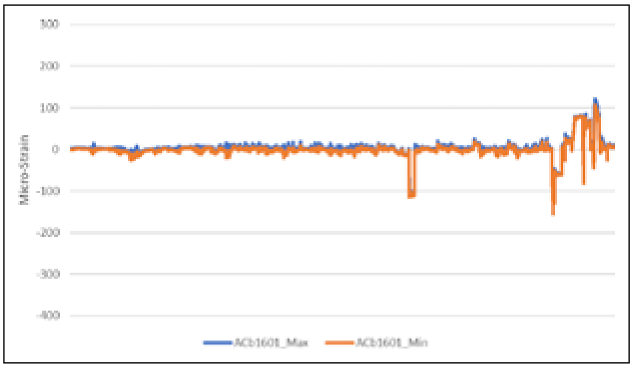


**Figure 11**. Graph of the bottom strain gauges data for channel 3 – North and south positions.

## 3. RESULTS AND DISCUSSION

### 3.1. Field Test Results

The instrumentation system was installed and active for six months, starting in November 2022. The data acquisition system (DAS) collected the data from the various sensors and saved it onto the system's hard drive. The drive was accessible remotely through a modem that transmitted the data online and made it available through a software application.

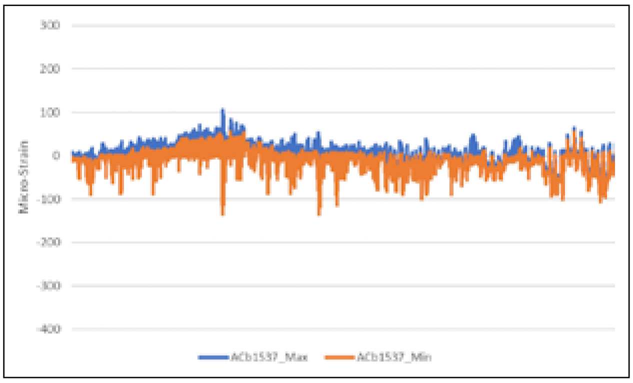


**Figure 12**. Graph of the bottom strain gauges data for channel 4 – East and west positions.

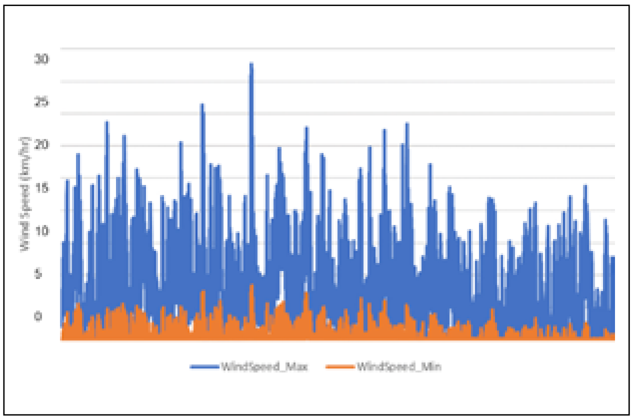


**Figure 13**. Graph of wind speed sensor.

**Table 1.** Experimental absolute maximum strain and stress values compared to yield limit

| | | Micro-strain | Ratio | Percentage | Stress MPa (ksi) |
|---|---|---|---|---|---|
| Strain limit | | 1,724 | | | 345 (50.0) |
| Top strain | Up-Down | 386 | 0.224 | 22.4% | 77 (11.2) |
| Top strain | East-West | 281 | 0.163 | 16.3% | 56 (8.2) |
| Bottom strain | North-South | 155 | 0.090 | 9.0% | 31 (4.5) |
| Bottom strain | East-West | 133 | 0.077 | 7.7% | 27 (3.9) |

The following graphs, Figure 9, Figure 10, Figure 11, and Figure 12, provide the strain gauge data over time. Figure 13 presents the wind speed data over the same time frame.

The experimental results show that the top horizontal arm experienced higher strains than the bottom of the vertical pole. Further, the maximum strain was experienced only once and reached a value of 380 micro-strain. Otherwise, the strain range was between 50 micro-strain and 130 micro-strain.

Table 1 compares the experimental data and the yield limit, showing that the maximum strain reached after months of testing and exposure to wind load was only 22.4% of the elastic yield capacity of the structure. This indicates the strength and resilience of this sign support structure and that significant potential strength remains in the structure.

### 3.2. Finite Element Modeling and Verification

A finite element model (FEM) was developed to analyze the sign support that was field tested under various design loads as specified by the American Association of State Highway and Transportation Officials (AASHTO) – LRFD, titled 'Structural Supports for Highway Signs, Luminaires, and Traffic Signals (LTS),' [5]. This task focused on improving the reliability of methods for determining traffic loading on sign supports. The field data collected was utilized to build the FEM three-dimensional sign support structure using the software Highway Sign Structural Engineering (HSE), created by the Structural Engineering Software company SAFI.

Verifying the FE model with the experimental data provided the opportunity to understand better the behavior of the sign support and the loading influence. The model was developed, and the wind load applied was the average value of 28 km/hr (45 mph) obtained from the wind speed data. The limit state values (Fig. 14) show that the vertical pole has a value of 0.18 (18%) of the actual pole capacity, within a 10% difference compared to the experimental data. Similarly, the top horizontal cantilever arm has a limit state value of 0.10 (10%) of the capacity, which is, on average, about 8% less than the experimental data.

These results show that the model is accurate and can be used to predict the behavior of the sign support at complete design load capacity. The second model was then developed with the whole design load applied by the AASHTO LRFD-LTS code, which accounts for the wind load at the region where the sign support is, namely Hartford, Connecticut. The analysis results depend on including or excluding fatigue stress in the limit state load combinations. Fatigue has a significant impact on the results, as seen in Figure 15 and Figure 16. Fatigue stress is so substantial that some sections exceed their limit state.

The study's findings are based on a specific type of highway sign support structure (cantilever-type) and may not directly apply to other sign supports. The results may vary for different designs, materials, and environmental conditions. The finite element analysis model relies on certain simplified assumptions to make the problem workable. These assumptions include idealized material properties, boundary conditions, and load applications, which may not fully capture the complexities of real-world scenarios. The FEA model was validated using data from a single field test. While the model agreed well with the test data, further validation with additional field tests on different structures would strengthen the confidence in the model's predictions. Addressing these limitations in subsequent studies

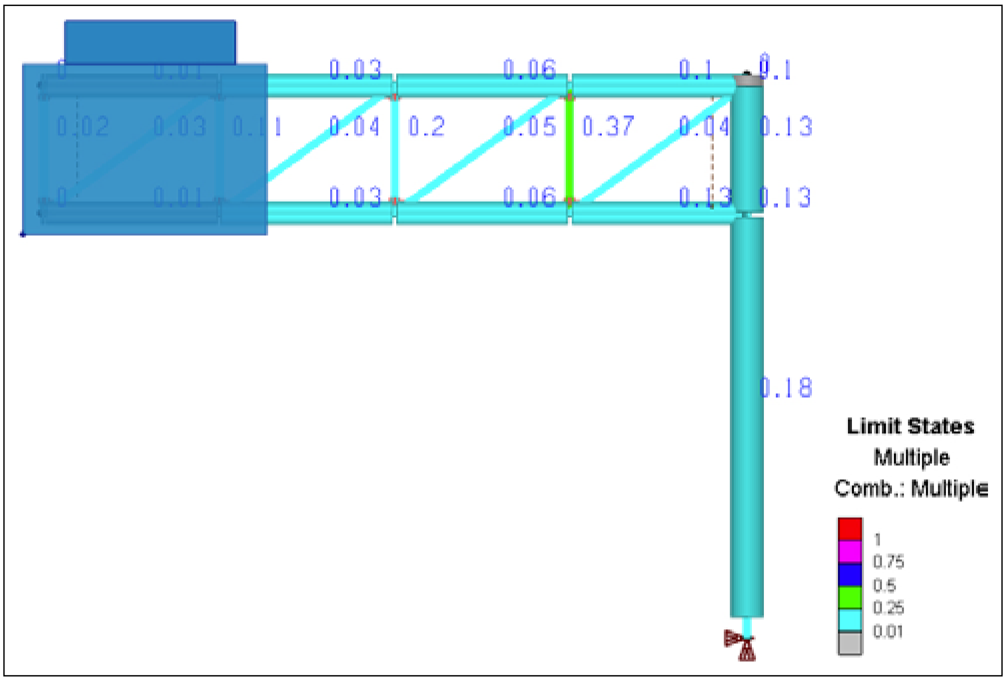


**Figure 14**. FE Model analysis due to wind load of 28 km/hr (45 mph) to simulate experimental data.

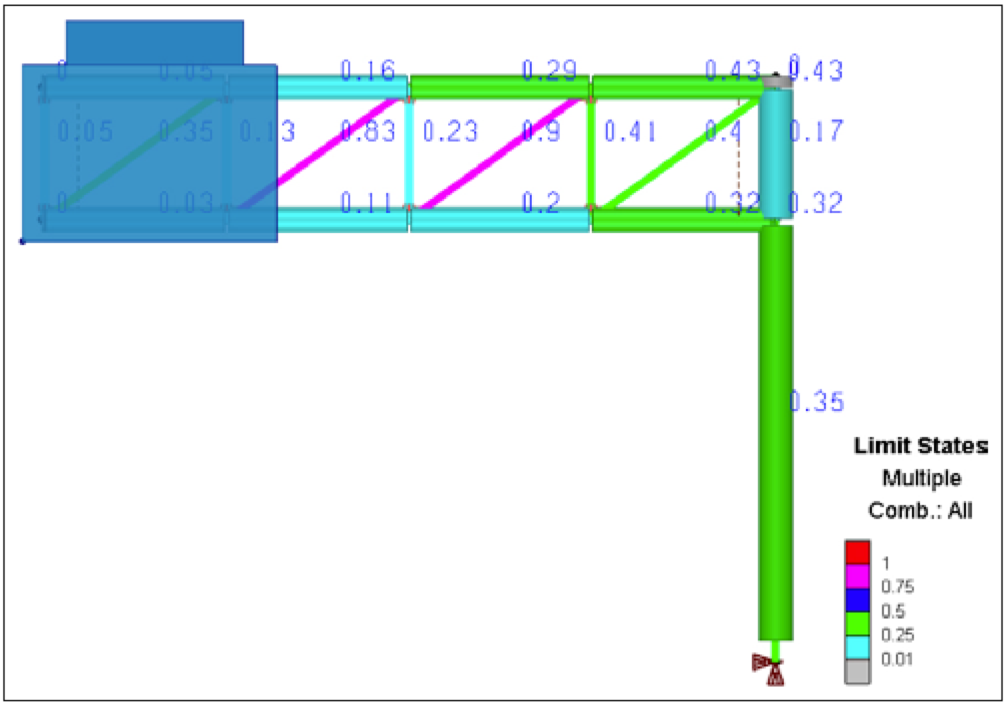


**Figure 15**. Limit states for all load combinations where results exclude fatigue.

will help to refine the models and improve the reliability of the findings, ultimately contributing to the development of more robust and sustainable highway sign support systems.

## 4. CONCLUSIONS

The research evaluated sign support management strategies, including repair manuals, Transportation Asset Management Plans, standardized drawings, and structure selection criteria. The researchers gathered and analyzed survey feedback from DOTs throughout the US. This effort initiated the second phase of the research work that involved the instrumentation and testing of a highway sign support structure.

The sustainability evaluation of highway sign support systems through field testing and finite element analysis has provided valuable insights into these critical infrastructure components' structural integrity and longevity. The study's findings underscore the importance of regular maintenance and inspection to ensure the safety and durability of high-

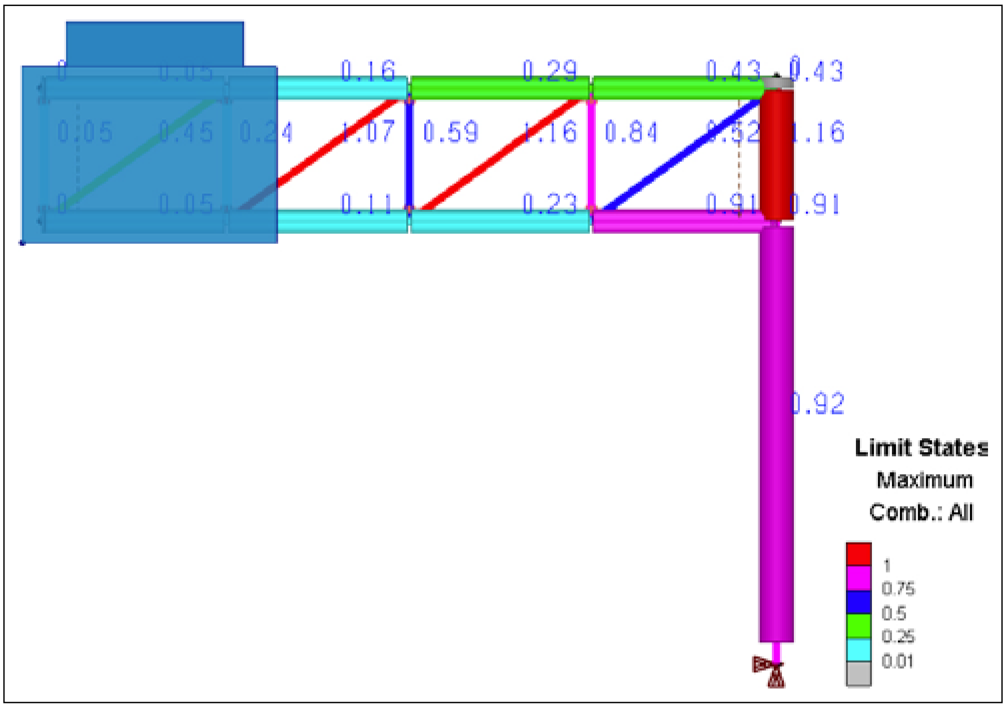


**Figure 16**. Limit states for all load combinations where results include fatigue.

way sign supports. The field testing in collaboration with the Connecticut Department of Transportation (CTDOT) revealed that the sign support's top horizontal arm experienced higher strains than the bottom of the vertical pole. The maximum strain recorded was 380 micro-strain, which is 22.4% of the elastic yield capacity of the structure. This data highlights the areas of the structure most susceptible to stress and potential failure, providing a basis for targeted maintenance efforts.

The finite element model was developed and verified using the field test data, which accurately predicted the behavior of the sign support under various loading conditions. The model demonstrated that the structure could reach its design capacity, mainly when considering fatigue loading. This finding suggests that the current design standards are adequate but could benefit from enhancements to address long-term fatigue stresses. The research emphasizes the need for a comprehensive asset management approach that includes regular inspections, timely maintenance, and advanced modeling techniques to predict and mitigate potential failures. By adopting these practices, transportation agencies can enhance the safety and reliability of highway sign supports, ultimately contributing to a more sustainable and resilient transportation infrastructure.

The study's recommendations for prioritizing repairs based on the condition and age of the sign support, designing structures to resist long-term fatigue stresses, and conducting further research on different types of sign supports are crucial for extending the service life of these structures. In conclusion, the study provides a robust framework for evaluating the sustainability of highway sign support systems. The combination of field testing and finite element analysis offers a powerful tool for understanding the behavior of these structures under various conditions and making informed decisions about their maintenance and design. Future research should continue to explore the application of these methods to other types of sign supports and to develop more refined models that can further enhance the safety and longevity of highway infrastructure.

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## ETHICS

There are no ethical issues with the publication of this manuscript.

## DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

## CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

## USE OF AI FOR WRITING ASSISTANCE

Not declared.

## PEER-REVIEW

Externally peer-reviewed.

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