DOI: 10.3217/978-3-99161-057-1-119

Understanding the Dynamic Behavior of Large Sign Structures Under Wind Loading

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ABSTRACT: Dynamic Messaging Signs (DMS) are much larger and heavier roadside signs than typically placed on their respective support systems. The excess weight and size of these signs, in conjunction with their breakaway support systems, introduces wind-induced vibration problems not seen in the past. The AASHTO LRFD Specification for Structural Supports for Highway Signs, Luminaires, and Traffic Signals (SLTS), including interim revisions through 2022, does not yet address vibration design for these nontraditional roadside signs. The DMS support system, specifically the friction fuse connection, is susceptible to the formation of stress concentrations and potential fatigue issues. A DMS was instrumented with strain gages, accelerometers, anemometers, and temperature sensors to characterize both the wind loading and response of the structure. A dynamic numerical model was validated with experimental field data and used to evaluate the fatigue life of the DMS instrumented in the field. The results of the dynamic analysis performed with the validated FEM model differed significantly from the analysis with the equivalent static pressure equation for natural wind gusts prescribed in the AASHTO Specification, which highlights the importance of considering the dynamic behavior of these heavier sign panels. Extension of the dynamic method to models of other large DMS in service showed a greater fatigue stress and corresponding shorter estimate of the fatigue life.

KEY WORDS: Field Monitoring; Wind Loading; Sign Structures.

1 INTRODUCTION

Wind-induced vibrations are often a key consideration for the design of the structural supports of signs and signals. These vibrations introduce oscillations that can lead to fatigue concerns and potentially premature failure of the structure. The current AASHTO LRFD Specification for Structural Supports of Highway Signs, Luminaires, and Traffic Signals (SLTS) addresses fatigue design for overhead sign and signal structures and high mast light towers [1]. Fatigue design for roadside signs is not addressed because these are traditionally smaller and have not observed fatigue problems in the past. However, as roadside signs get heavier and larger, there is concern that these structures may be susceptible to fatigue under wind loading.

Dynamic messaging signs (DMS) include luminous elements that display words, numbers, or symbols to communicate real-time roadway and traffic information to drivers [2]. The roadside versions are often located in the clear zone alongside the roadway and as a result, must feature breakaway or yielding supports to limit injury to drivers and damage to vehicles that may swerve off the roadway [1], [3]. The DMS are much larger and heavier than signs typically placed on breakaway posts. The signs range from 1.8m x 4.3 m to 2.4m x 5.5m, weigh over 680 kg, and have post heights that range from 4.7m to 6.7m [4].

The 2025 interim revision of the AASHTO 2013 (ASD) Specification for SLTS acknowledges the potential impact of the mass of dynamic messaging signs and requires their cantilevered support structures to be designed for fatigue [5]. However, the revision states that design of these structures will require considerations beyond the specification. This ambiguity leaves the designer to determine if equivalent static analysis or dynamic analysis is more appropriate to evaluate the fatigue life of the support structure.

In this work, the behavior of roadside dynamic messaging signs under wind loading was investigated to determine which analysis method should be considered in design. A DMS was instrumented in the field and the experimental field data were used to characterize the wind loading and response of the structure. The field data was further used to update a dynamic numerical model for comparison with an equivalent static pressure analysis. Ultimately these were used to evaluate the fatigue life of these DMS support structures.

2 DMS FIELD MONITORING

A post-mounted DMS (DMS 169-142.45NB) located in Brooklyn Park, MN with a Type A support detail was instrumented in the field to investigate its structural performance under wind loading. The Type A support featured a slip base and a friction fuse connection just below the sign panel (Figure 1). The friction fuse consisted of two plates used to splice two lengths of the support post: (1) a fuse plate with a weakened portion designed to fracture under impact, and (2) a hinge plate designed to yield.

The instrumentation consisted of two accelerometers, two cup and vane anemometers, one temperature probe, and 76 strain gages. Figure 2 provides an overview of the instrumentation. The single-axis accelerometers were used to identify the natural frequencies of the structure. The cup and vane anemometers measured the mean wind speed and direction. The strain gages were used to measure the dynamic response of the support and friction fuse connection under wind loading. The supports were expected to undergo strong-axis bending, weak-axis bending, and potentially torsion. The post

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strain gages included two strain rosettes on each face of the web as well as strain gages at the tip of the flanges. These strain gage sets were located at four different locations along the two support posts. The field data was collected over five months from August 2017 through January 2018.

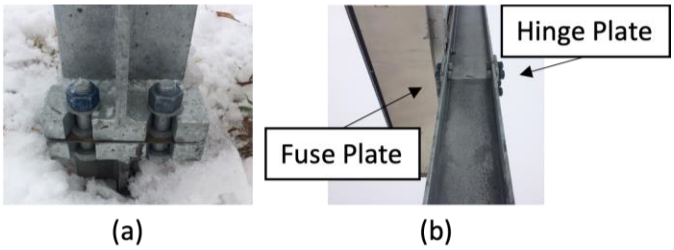

Figure 1. Type A breakaway connection: (a) slip base, (b) friction fuse.

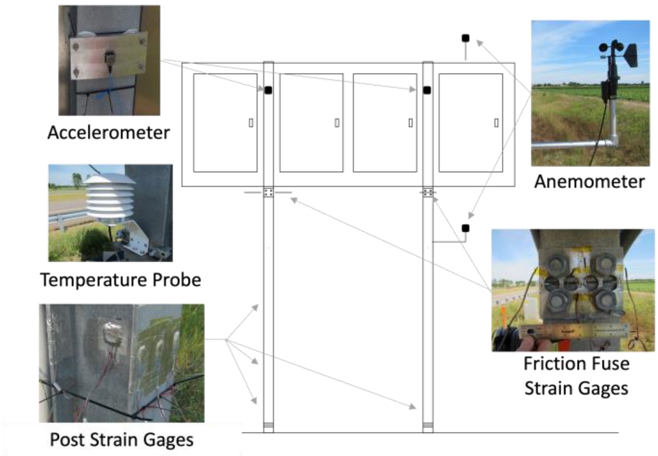

Figure 2. Overview of DMS field instrumentation.

3 ANALYTICAL MODELS

Three different models were used for analysis of the DMS structure: two simplified models and one finite element model. The simplified models consisted of a static beam model and a dynamic beam model. In the static beam model, the wind pressure applied to the sign was assumed to distribute evenly to the four panel support points. The resulting point loads on the cantilever posts were used to determine the stresses and the corresponding strains along the height. In the dynamic beam model, the inertial effects of the sign mass were considered by applying the mass of the sign to a rectangular prism that was supported by a cantilever beam with stiffness equivalent to the two columns. A single-mode dynamic model was used to capture the behavior of this system subjected to a dynamic drag forcing function due to the wind pressure on the sign face.

The third model featured a linear elastic finite element (FE) model created to evaluate the fatigue stresses generated in the friction fuse connection during wind loading. The friction fuse connection was modeled as a separate detailed three-dimensional component to capture stress concentrations, particularly in the fuse plate. The support posts were modeled with standard beam elements and the panel was modeled using standard four-node shell elements. The FE model was validated with the field data assuming the structure would have similar natural frequencies to those measured in the field.

All three analytical models assumed ASTM A36 steel with an elastic modulus of 200 GPa and yield strength of 248.2 MPa. The posts were W8x24 cross-sections with a moment of inertia of 3442.3 cm^4. Additionally, the dynamic models assumed a damping ratio of 0.02.

4 RESULTS

The two simplified models were compared using the measured wind demand and corresponding strain response. A change in the measured wind speed normal to the sign face corresponded to a change in pressure that was applied as a drag force to the sign supports. For the simplified static model, the expected change in strain at the base of the post was determined and compared with the measured change in strain in the cross section. For the dynamic model, a transient drag force due to the measured wind speeds and corresponding pressure was applied to the single degree-of-freedom system. The change in strain at the base of the post between two times of interest was determined from the transient response for comparison. The strain distributions predicted by the dynamic response aligned better with the measured strains than those strains predicted by the static model (Figure 3). The comparison of the two simplified models demonstrated that considering the effects of the inertia of the sign panel is important to capture the behavior.

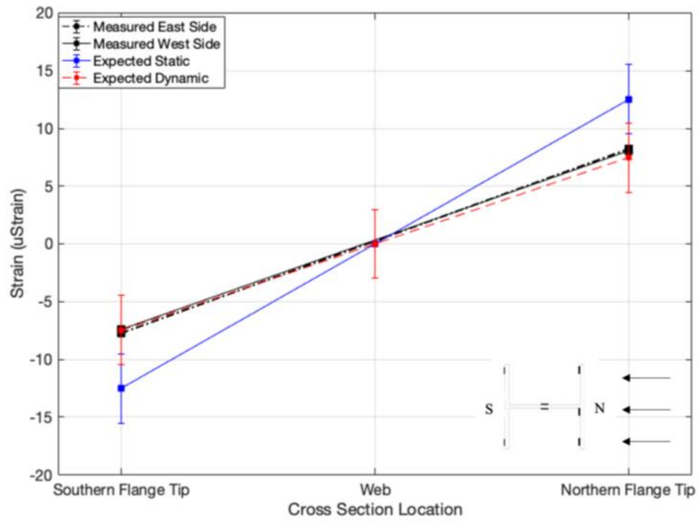

Figure 3. Comparison of the strains predicted by the simplified models and measured strains in the east post for a specific wind event. Error bars on predicted strains reflect the noise on the measured strains.

Based on the comparison, a dynamic FEM was used and required dynamic wind loading functions as inputs to the model for fatigue analysis. To generate the limit-state wind loading, a representative wind spectrum was used to generate zero-mean wind speed time histories. A Davenport spectrum with a terrain coefficient of 0.005 for open, unobstructed terrain best characterized the power spectrum of the measured wind data during the deployment [6]. The spectrum was scaled to the mean hourly wind speed of the region and a corresponding filter was applied to white noise inputs with unit covariance to generate wind speed time histories [7]. The pressure loading functions were generated from these simulated wind speed histories using a variation of the method presented in reference

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[8]. Typically, the stress range only due to the fluctuating wind load would be considered in the fatigue analysis. However, because the gravity load of the sign was thought to play an important role in the resulting stresses within the connection, the wind pressure function included both the mean and fluctuating pressure. The combined mean and fluctuating pressure were thought to provide a more realistic representation of the magnitude of the fluctuating tension stresses and whether these would overcome the compressive stresses due to gravity. Five independent pressure functions were applied to the dynamic FEM to determine an average wind-induced stress range. The fatigue limit-state stress range was taken as the resulting amplitude of the tension stress within the friction fuse connection.

The fatigue demand in the connection was computed using two methods: (1) using the equivalent static pressure equations outlined in Article 11.7 of the AASHTO 2015 LRFD Specification for SLTS [1], (2) the dynamic FEM model with wind loading functions mentioned above. When using the equivalent static approach, the peak fatigue stress range was 49.6 MPa. The dynamic FEM model resulted in a peak fatigue stress range of 63.9 MPa. Both results exceed the constant amplitude fatigue threshold (CAFT) of 48.3 MPa for an infinite fatigue life. Further, the equivalent static approach underestimates the stress range predicted by the dynamic model.

5 CONCLUSION

The additional weight of dynamic messaging sign (DMS) panels requires fatigue under wind loading to be considered in design. However, the AASHTO 2015 LRFD specification does not address fatigue design for these nontraditional roadside sign structures. Field monitoring of a DMS structure was used to validate simplified and detailed numerical models and determine the fatigue life of the instrumented DMS structure. Additionally, the effectiveness of the different modeling approaches to capture the behavior of the sign structure to wind loading was evaluated.

A comparison of the modeling approaches to the field data highlighted the importance of considering the inertial effects of the sign panel mass on the response of the structure. Limit state pressure loading functions were generated as inputs to the validated dynamic FE model. The resulting fatigue stress demand in the breakaway connection was compared with the traditional equivalent static pressure analysis method. The peak stress demand from the dynamic FE model was 28% larger than the static approach further emphasizing the importance of using a dynamic model when evaluating these structures.

The resulting stress demands were used to calculate the fatigue life of the instrumented DMS. The dynamic modeling technique can be extended to other in-service DMS support structures to estimate their fatigue life.

ACKNOWLEDGMENTS

Funding support was provided by the Minnesota Department of Transportation (MnDOT). Numerical computations were performed using resources provided by the University of Minnesota Supercomputing Institute (MSI). The work does not necessarily represent the views or policies of MnDOT or MSI.

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