Engineering Structures 164 (2018) 305–315

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Fatigue analysis of sign-support structures during transportation under road-induced excitations

Saeed Arabi[a], Behrouz Shafei[a,*], Brent M. Phares[b]

[a] Department of Civil, Construction, and Environmental Engineering, Iowa State University, Ames, IA 50011, United States
[b] Bridge Engineering Center, Institute for Transportation (InTrans), Iowa State University, Ames, IA 50011, United States

ARTICLE INFO

Keywords:
Sign-support structures
Transportation
Fatigue
Finite-element analysis
Road profile
Suspension system
Stress concentration factor

ABSTRACT

Dynamic Message Signs (DMSs) are increasingly used in highways as an effective means to communicate time-sensitive information with motorists. To ensure the long-term performance of DMSs, it is critical to ensure that the truss structures that hold them can resist not only extreme loading events, but also fatigue induced by service loads. The existing studies, however, are primarily focused on the loads that DMS-support structures experience during their service life and neglect the potential contribution of stresses induced during the transportation of them from the fabrication site to the location of installation. As a result, the potential damage that this important category of structures may sustain during transportation had remained largely unknown. To investigate this aspect, a comprehensive field test and numerical study were conducted. For field investigation, one span of a four-chord, overhead sign-support structure was instrumented to perform a short-term structural health monitoring. In addition, detailed finite element simulations were conducted to obtain an in-depth understanding of the potential modes of damage under the excitations induced by the road profile. The outcome of this study is expected to contribute to evaluating the extent of fatigue and structural vulnerability of DMS-support structures during transportation.

1. Introduction

Overhead highway signs, luminary poles, and traffic signals are critical transportation infrastructure components, which play an important role in guiding the traffic and ensuring the public safety. Among them, the use of Dynamic Message Sign (DMS) has been rapidly increased, primarily because of advancements in the DMS technology and its unique capability to provide the motorists with live traffic information. DMSs are mounted on either a cantilever or bridge type truss structure, which is normally prefabricated elsewhere and shipped to the site. Considering that the truss structures offer an economic and dependable means of holding the DMS cabinet, their structural performance has become a subject of interest for those working on the design and maintenance of transportation infrastructures. Since hollow pipes and angle sections are commonly used in such structures, the DMS-support structures have a relatively small mass, high flexibility, and low damping ratio (in the range of 1%). The listed properties make this category of traffic structures particularly vulnerable to high-cycle, low-amplitude excitations [1]. Failure of DMS-support structures has been reported in several locations in the United States. The most common cause of failure is believed to be metal fatigue. Mast arm to column connection, column to base plate connection, and anchor bolts are among the critical parts of the support structures susceptible to failure [2–4]. In addition, joints and weldments are often the areas of concern, as they experience fatigue-induced damage. Cracks have been observed, especially in the joints within the toe and leg of fillet welds propagating into the main chords in some cases [5].

Among the relevant studies in the literature, Barle et al. [6] investigated the truss joints of sign structures by modeling the stress fields under static and dynamic loads. This study estimated the fatigue life and made suggestions for design improvements. Roy et al. [7] examined the weld geometry at the joints and evaluated crack modes through experimental fatigue tests. In a study not limited to the joints, Rice et al. [8] combined numerical simulations with field measurements to better understand the fatigue characteristics of sign structures. Sanz-Andrés et al. [9] provided a qualitative explanation of the main characteristics that capture the effect of vehicle force causing fatigue damage. Huckelbridge and Metzger [10] conducted a fatigue analysis of a sign structure under the vibration of truck passage. Different types of overhead truss structures were studied by Fouad et al. [11] to understand the influence of natural wind gusts. In a separate effort, Kacin et al. [12] conducted a fatigue life analysis for an overhead sign-support

---

* Corresponding author.
E-mail address: shafei@iastate.edu (B. Shafei).

https://doi.org/10.1016/j.engstruct.2018.02.031
Received 20 June 2017; Received in revised form 3 February 2018; Accepted 6 February 2018

structure. For this purpose, the ANSYS package was utilized to model the structure and identify the critical members in both pristine and damaged conditions. Wind-induced fatigue analysis of high-mast light poles was conducted by Chang et al. using long-term field monitoring data [13,14]. In a later study, Chang et al. investigated the effects of thermal loads on the aluminum DMS-support structures [15].

Despite the contribution of the former studies, they are found to be primarily focused on the loads that the structure experiences during the service life, disregarding the potential contribution of stresses induced during transportation from the fabrication site to the location of installation. As a result, the potential damage that this important category of structures may sustain during transportation is largely unknown. To investigate this aspect, a comprehensive field test and numerical study is conducted in the current study. For this purpose, one span of a four-chord, overhead sign-support structure is instrumented with strain gauges. The main objective of this short-term monitoring is to capture the strains induced in the truss members because of the excitations caused by the road profile.

In addition to the investigation of data collected from instrumentation, detailed finite-element (FE) simulations are conducted to obtain an in-depth understanding of the extent and potential modes of damage. The stresses that the truss structure experience during transportation directly depend on vibrational excitations, which requires an integrated model for simulating the road profile and the suspension system of the truck used to transport the prefabricated structure. To achieve this goal, a set of road profiles are generated based on ISO Specifications [16]. This covers a range of road surface conditions from good to poor. In the next step, a passive suspension system is modeled. This model transfers the excitations induced by the road roughness to the structure considering the mass, stiffness, and damping parameters. The Simulink package is used for solving the differential equations associated with the suspension system. Using the developed Simulink model, the suspension-induced movements, which excite the truss structure at its supports, are calculated during transportation.

The excitation time-history of the supports is employed as an input to the detailed FE model of the truss structure. This model, which has been developed using the ABAQUS package, is utilized to obtain the time-history of strains and stresses at various structural members and their joints. The FE model is validated first with the field data collected from the strain gauges during transportation. Stress time histories of the most critical members of the truss are then extracted from the FE model. Using the rainflow cycle counting method [17], the stress ranges and their corresponding cycles are derived for fatigue analysis. Based on the Miner's linear fatigue damage accumulation rule, the fatigue-induced damage is calculated using both experimental data and numerical simulation results. The outcome of this study contributes to evaluating the extent of damage that this category of structures may experience during transportation and if it has a critical effect on the expected service life.

2. Field study

To evaluate the effects of road-induced excitations on DMS-support truss structures during transportation, a field study has been conducted on one of the three blocks of a truss structure, which was shipped from the State of Kansas to Iowa for installation. The truss under consideration was transported for a distance of approximately 110 miles (1 mile = 1.609 km). The average speed of truck was in the range of 40–50 miles per hour. During monitoring, twelve one-axial strain gauges were mounted on the truss and the strain data were recorded in 33 data sets for a period of three hours with the frequency of 100 Hz [18]. Fig. 1 shows the transported truss and the position of some of the mounted strain gauges. Fig. 2 provides the identification number of all the strain gauges used for instrumentation and Fig. 3 illustrates the strain time histories recorded by the Sensors S1 and S12 over 120 s for the 3rd and the 30th data sets as two examples. A review of the data collected from all the 12 strain gauges indicates that the strain time histories follow a similar pattern overall and there is no abnormal strain in the recorded time histories. Fig. 3(a) clearly shows that there are peaks in the strain time histories, which occur at the same time in all the data sets (see for example the strain at the 10th and 115th second). This trend can be related to the road profile. The similarity observed in the time histories, as well as the absence of any major outliers, highlights that the collected data have an acceptable quality. To obtain a more in-depth understanding of the range of strains, the collected data have been processed and the maximum and minimum strain values for each sensor in each of the 33 recorded data sets are summarized in Fig. 4. As it can be seen in this figure, the strains are mostly in the range of -20 to $+20$ micro-strain, although there are some data points which exceed this range. Table 1 summarizes the maximum and minimum strain values for each sensor. Since the data have been recorded in separate time intervals during transportation, the average of maximum and minimum values obtained for each time interval has also been included in Table 1. This table provides an envelope with a peak and average value for each sensor, which reflect the range of strains that each truss member may experience. This range is also used to evaluate the accuracy of predictions obtained from the FE model generated for this study.

As failure due to fatigue is the most critical mode of failure in sign-support structures, a detailed fatigue analysis is conducted using the data collected from the field. The goal of this analysis is to evaluate the potential contribution of road-induced excitations to the fatigue-induced damage. For this purpose, the rainflow cycle counting method is utilized to count the number of cycles for various stress ranges that the structure has experienced during transportation. The Miner's rule is used in the current study to determine if any fatigue-induced damage occurs during transportation [19]. To conduct the fatigue analysis, the strain time histories are first converted to the stress time histories using the well-known Hook's Law. Although this direct conversion may involve some approximation (due to shear and/or bending moment), the percentage of error is deemed negligible because the truss consists of long and hollow members, mainly under a uniaxial loading condition.

Based on the stress time-histories obtained along the length of truss members, the stress time histories at the joints can be predicted. Despite the similarities between the patterns of stress time histories at the middle and end of a truss member, it is known that the stresses are magnified at the joints due to strain concentration effects. The strain concentration factor (SCF) is reported in the AASHTO Standard Specifications for Structural Supports for Highway Signs, Luminaires, and Traffic Signals (hereafter referred to as AASHTO Specifications) based on the type of connection [20]. Using the magnified stress time histories, the number of cycles for various stress ranges are obtained for the fatigue analysis. Fig. 5 presents the histograms of stress ranges and their respective number of cycles for 6 sensor/joint locations. The histograms are plotted in a logarithmic scale to depict the number of cycles clearly. A review of the developed histograms shows that all of the cycles are below the constant amplitude fatigue threshold (CAFT), which is 4500 psi (1 psi = 6895 Pa) for the slotted tube to gusset plate connections [20]. This eliminates the concern about experiencing a high level of fatigue-induced damage during transportation.

3. Numerical study

In addition to the field investigation, a detailed FE model of the instrumented truss structure has been generated in the ABAQUS package to obtain a comprehensive assessment of the structural response of individual truss members further to their potential modes of damage and failure. To model the joints with necessary details, shell elements are used for the truss members and connecting gusset plates. This approach allows for the determination of stress distribution within the thickness of each truss member. Fig. 6 shows an overview of the FE