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Fatigue analysis of overhead sign support structures

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ABSTRACT

Sign structures stand along highways and roadways to guide motorists to their destination. Such structures are repeatedly subjected to natural wind load and gusts from vehicles passing underneath. Over time, the members within the structure may begin to succumb to fatigue due to cyclical loading. In this paper an algorithm to determine the fatigue life of an overhead four-chord truss sign structure is presented. The algorithm includes a time varying natural wind loading and a finite element model. The stress history of selected critical elements is extracted from the model's solution. Complete stress ranges are counted and a linear damage accumulation method is used to find the fatigue life of some critical members. The fatigue life analysis is carried out by simulating pristine condition and three different damage scenarios.

1. Introduction

Sign support structures including cantilever, butterfly, and bridge supports (also known as overhead or span type supports) can be found along any major highway. These structures mount signage that helps commuters navigate their way. Similarly, variable message signs (VMSs) are used to control, inform, and warn the commuters through the display of a number of messages that may be changed or switched on or off as required. Owing to their functionality, highway sign support structures must span great distances to provide drivers with needed information without introducing the danger associated with the occurrence of intermediate supports on medians or other locations adjacent to the roadway [1]. Because of their long span length and relatively small cross-sectional area and mass, these sign structures are flexible. This flexibility gives sign structures low natural frequencies. The damping is also low, typically around 1% of critical damping. These properties make these structures susceptible to large-amplitude vibration and fatigue cracking under wind loading [2].

In general, highway sign supports withstand in-service dynamic loads caused by wind loading, and for those structures mounted on bridges, bridge vibrations induced by passing vehicles [3]. Defective welds, aging material, and harsh environmental conditions combined with the structural properties of sign supports make them more prone to damage. Cracks are found propagating within the leg of a fillet weld or at the toe. Depending upon the amount of time the crack has to grow, these cracks can propagate into the main supporting member [4]. While identifying cracks in sign structures is the first step in addressing the problem, determining the residual lifetime allows for the most cost-effective solution among repair, retrofit, or replacement.

The AASHTO 2001 specifications [5] divide wind loadings into: galloping, vortex shedding, natural wind gusts, and truck induced gusts. Galloping is an aeroelastic phenomenon that occurs when the across-wind oscillations of a structure create variations in the angle of attack of the wind flow. Galloping does not occur on cylindrical elements alone; it is caused by wind loading acting on the attachments. Vortex shedding is caused by the shedding of tiny whirlpools of air created as the structure disrupts the natural air flow. Wind gust loading is the result of varying gust patterns. Wind flow velocity components can fluctuate over a broad range of frequencies, causing strong fluctuating pressures that can induce vibration.

Truck induced gusts occur as the result of the passage of large trucks underneath the sign structure. Higher speeds cause a significant disturbance in airflow, causing gust loading on both the frontal area of the structure and the underside of the members, creating torsional and bending moments in the connections [6]. The horizontal gust created by a truck is much smaller than that created by natural wind. The magnitude of the vertical pressure is directly proportional to the speed of the truck. Also, the higher the sign is above the roadway, the lower the magnitude of the gust [7]. The magnitude, direction, and frequency of pressure distributions on VMS caused by trucks passing underneath were determined by Cook et al. [8]. It was found that the truck induced gusts caused both negative and positive pressure as they passed and that the maximum positive pressure occurred at an angle of 75° to the front

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of the sign while the maximum negative pressure occurred normal to the sign face. By studying the effect of height on pressure, a 10% reduction in pressure for each foot of sign elevation increase was observed. Kaczinski et al. [9] characterized the susceptibility of cantilevered structures to excessive displacement or fatigue damage. An equivalent static load range was developed for the four common wind related causes of fatigue to identify the fatigue sensitive connection details in a sign structure and to determine the fatigue strength of anchor bolts. Fouad et al. [10] and Fouad and Calvert [11] studied fatigue and vibration in overhead structures to determine the impact of the extreme wind load and fatigue provisions on the design of cantilevered overhead sign support structures.

Natural wind on sign structures is usually characterized by a fluctuating wind force [4,9,12,13]. A wind force spectrum can be obtained by using either the Davenport wind velocity spectrum [14] or the Kaimal wind spectrum [15]. Dexter and Ricker [12] applied a randomly occurring wind load with base wind speeds ranging from 0 to 26.8 m/s (0 to 60 mph). Extreme speeds with a mean occurrence of greater than 1 year were considered not relevant for the fatigue analysis. Ginal [4] studied three overhead sign structures by considering a 2.24–22.4 m/s (5–50) mph wind speed range and the Kaimal spectrum. Finally, Li [13] developed a wind load time history to be used in a finite element analysis of several sign support structures types. The range of wind speeds used in the analysis varied from 0–13.4 m/s (0–30 mph) and the Kaimal spectrum was used.

Fatigue modeling of highway sign structures was carried out by several researchers [3–5,10,12,13,16,17]. Such studies varied by the type of wind loading included, the type of structure analyzed, the wind spectrum considered, and the method to carry out the transient analysis. Desantis and Haig [18] analyzed the fatigue failure of a cantilever sign structure using the commercial finite element analysis program ANSYS. Two tapered poles formed the chords of the cantilevered truss and a VMS was attached at the end. Dexter and Ricker [12] performed a finite element fatigue analysis of a cantilevered two-chord truss and a cantilevered four-chord box truss, both of which support VMSs and experienced excessive vibration in the field. The structures were modeled using ABAQUS. Natural wind gusts were applied to the entire exposed area of the sign and structure. The horizontal component of truck induced gusts was neglected because it was considered small when compared to the magnitude of natural gusts, while the vertical component was applied to the bottom of the VMS. Ginal [4] evaluated the fatigue performance of three full span overhead sign support structures using ANSYS. The effect of fatigue life due to both truck induced pulses and natural wind were determined separately. Wind data were collected in terms of speed and direction from the National Climatic Data Center (NCDC) (http://cdo.ncdc.noaa.gov). A rainflow counting algorithm to transform stress histories into stress ranges was used and the Palmgren–Miner rule to assess yearly fatigue damage was employed. The fatigue life predicted for the critical members in the three structures under investigation ranged between four years and 27 years. Finally, Li [13] utilized ANSYS to model a cantilevered double mast arm, a cantilevered single mast arm, a box truss, a monotube, and a tri-chord sign structure, focusing on the modeling of critical connections in these structures. Only natural wind was considered. As such, all loads other than natural wind were ignored, for galloping has rarely been observed in the field except for single mast arms, only structures with large dimensions are subjected to vortex shedding, and truck induced gusts are more critical in structures with large areas parallel to the ground. Similarly to Ginal's work, the fatigue analytical method included the use of SN curves, Miner's rule, rainflow counting, and fatigue limits. Transient analyses were performed on the finite element models to obtain stress-time histories at critical details. Li found that practically all connections in the box truss, cantilevered monotube, and tri-chord truss have an infinite lifetime. Park and Stallings [17] performed a fatigue evaluation of two overhead box trusses to investigate the applicability of the AASHTO 2001 sign support specifications to non-cantilevered structures. Field monitoring tests were performed using strain gages and a wind anemometer. The response associated with both natural and truck induced gusts was measured, and it was found that natural wind caused most of the significant cycles. Only very few members were found to have finite fatigue life.

In this paper the finite element software ANSYS was used to create the model of an overhead sign structure to: (a) determine the effect of wind loads on the fatigue life performance, (b) identify the elements of the structure prone to fatigue cracking, and (c) establish a relationship between damage severity and reduction of the fatigue lifetime. One of the main novelties of the work consists on the quantification of the effects of existing damage on the reduction of the life span of the structure. In addition the fatigue life of the structure supporting four and five signs was calculated. Natural wind load was considered and the Kaimal wind spectrum was used. Wind data relative to the Pittsburgh International Airport were considered. Three welded diagonal members were specifically analyzed being among the most critical. The stress history of such elements was found and coupled to a rainflow counting algorithm in order to calculate the complete stress cycles within the time history. The AASHTO stress-life curves were adopted to estimate the damage associated with a particular stress cycle. Finally, the Palmgren Miner rule of linear damage accumulation was used to find the fatigue life each critical member.

The method was employed to analyze the structure in pristine condition and with simulated damaged elements. The reduction of the fatigue life when damage is present was quantified.

2. Sign structure and finite element model

2.1. The structure

The overhead four-chord box truss shown in Fig. 1 was studied. The structure, built in 1988, spans 59.1 m (194 ft) over nine lanes of traffic. The structure is made of steel members, while the signs are flat aluminum panels. Both the box truss and the upright webs are constructed with angles, while the uprights posts are made of wide flanges. Design plan and drawings of the structure are in [19,20].

The structure mounts five signs of varying shapes and sizes, though the original plans for the structure showed four signs. Since erection, another sign has been added. A catwalk spans over the northbound lanes. Both welded and bolted connections are present. The chords are continuous members that are spliced in four locations. On the top and bottom truss sections a plate is welded to the chord and the diagonals are connected to this plate via high strength bolts. The cross bracing is connected with bolts to a separate plate that is welded to the chord. On the front and back truss the diagonals and the vertical members are fillet welded to the chord. The signs on the structure are attached to the truss through vertical W sections.

2.2. The finite element method

In this study ANSYS version 11.0 software was chosen to model the structure and to run a transient analysis with a wind load applied as a traction force. The model was linear elastic and the small deformations caused by the wind loading were assumed to cause an elastic response. As the gravity is not a time-variant variable, its effect was not included in the analysis.