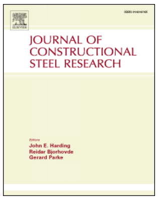
Journal of Constructional Steel Research 138 (2017) 298–307

Contents lists available at ScienceDirect

Journal of Constructional Steel Research



Damage avoidance solution to mitigate wind-induced fatigue in steel traffic support structures

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ARTICLE INFO

Article history:
Received 28 September 2016
Received in revised form 24 June 2017
Accepted 28 June 2017
Available online xxxx

Keywords:
Wind-induced fatigue mitigation
Load-balancing
Traffic signal structure
Quantitative risk assessment
Natural wind hazard
Full-scale structural monitoring

ABSTRACT

Non-redundant, cantilevered traffic signal support structures undergo frequent wind-induced excitation; the subsequent vibrations result in stress reversals that lead to fatigue, and possibly fracture, particularly at the welded connections. To accommodate more lanes and reduce roadside hazards, spans continue to increase—as do the number of connection failures. Presented herein is a low-cost damage avoidance approach to mitigate wind-induced fatigue effects for cantilevered traffic support structures. Load-balancing is provided to relieve the dead load tensile stresses in the tube-to-transverse plate connections, thereby increasing fatigue capacity. The proposed damage avoidance system adds a beneficial fail-safe, load-balancing redundancy for cantilevered traffic signal structures. The benefit of the proposed system is quantified using a probabilistic fatigue assessment framework. Full-scale prototype testing is conducted in an ambient wind environment to serve as input and statistically describe response. Fatigue performance is modeled as mean stress dependent from which a dependable service life is derived. The efficacy of the proposed damage avoidance technique is assessed for a variety of wind environments where it is shown the dependable service life increases by an order of magnitude.

1. Introduction

Steel structures that consist of a horizontal, cantilevered steel arm attached to a vertical tubular pole are commonly used to support traffic signal clusters above roadways. Non-redundant traffic signal support structures consistently undergo wind-induced excitation, and the subsequent vibrations result in stress reversals can lead to fatigue and fracture, particularly in the welded connections. As spans progressively increase to accommodate more lanes or to reduce the potential roadway hazard pose by near-set poles, a similar trend has been observed related to the number of connection failures. Within the United States, some 60% of states surveyed in the early 2000s reported excessive traffic signal vibrations or fatigue cracking in overhead traffic supporting structures [1].

Two approaches may be taken to enhance or extend the fatigue life: (1) demand reduction by decreasing response such as increasing damping; or (2) via fatigue capacity improvement. Mast arm or attachment aerodynamics have been modified to reduce excitation [2–4]; however the effectiveness has been limited due to inconsistent installations or targeting a mechanism with limited influence [5]. Viscous [6,7], impact [8], and signal-integrated tuned-mass dampers [9,10] have been shown to increase system damping, and thus reduce vibrations. Alternatively, fatigue capacity improvement has been accomplished by investigating weld treatment techniques or studying the effect of detail geometry [11–13]. However, detail optimization is most effective only if past cases of overstressing and poor weld quality [14] have been eradicated. In practice, designers have countered by using larger sections and heavily stiffened connections to eliminate vibrations and increase connection fatigue capacity—at the expense of increased material, production, and installation costs.

Safety concerns remain despite previous research. Non-redundant, cantilevered sign structures justifiably remain in favor over portal-type structures due to the reduced cost and roadside collision risk. Structural redundancy in cantilevered structures is typically of little concern because common practice considers the fatigue life of weldments to be independent of mean stress [15]. Contrary to this common practice, AASHTO [16] fatigue classifications for tube-to-transverse base place connections have been assigned based on test results obtained from testing that has applied cyclic loads about an elevated mean to simulate the tensile mean stress to replicate realistic, dead loading conditions [11–13,17]. When these results have been compared to those subjected to fully reversed loading conditions (zero mean stress) [18,19] researchers have acknowledged one clear and potentially contentious trend. That is, the determined fatigue resistance of tube-to-base plate connections is overstated when not accounting for the effects of dead load [11,12]. More discussion on these test results will follow.

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http://dx.doi.org/10.1016/j.jcsr.2017.06.037
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Mander and Cheng [20] combined aspects of rocking, structural flexibility, and prestressing when introducing their damage avoidance design (DAD) methodology. Several DAD post-tensioned (PT) solutions have been developed for wall-to-foundation connections [21], and beam-column connections in concrete moment-resisting frames [22, 23]. In parallel, researchers have developed ways to mitigate the weld fracture potential in steel moment-resisting frame structures during seismic events [24–33]. Practically all the above referenced works that used PT achieved response reduction and increased capacity. Dampers have also been used with PT components to simultaneously increase capacity and further reduce response [22–24,28,30–33]. While not appreciably increasing stiffness, DAD PT solutions have the potential to not only reduce response, but also increase fatigue capacity via mean stress manipulation in lightweight, cantilevered steel structures. As such, there lies a potential for a beneficial transfer of concept from seismic- to wind-related disciplines.

This paper proposes a low-cost supplemental system aimed to increase the fatigue resistance by introducing a load-balancing redundancy not only to cantilevered traffic signal structures, but also a variety of lightweight, tubular structures that use welded or bolted connections found across several engineering fields. The system incorporates concepts of PT and load-balancing—with favorable applications implemented in structural concrete [21–24] and steel [24–33]. To increase structural safety by adding redundancy while increasing fatigue capacity, the PT system [34] presented herein is an excitation-independent solution to connection fatigue for the retrofit of in-service and integration into current and future structures.

In the following, a DAD system is proposed to mitigate wind-induced fatigue in steel traffic support structures. Then, its advantages are discussed and quantified using a probabilistic framework. Via PT, the detrimental dead load tensile stresses found in tube-to-transverse end plate connections are relieved by introducing an alternative load path to balance the moments arising from the significant dead load associated with the cantilevered arm spanning several traffic lanes. Prototypes of the fail-safe system are installed to a full-scale traffic signal structure and field testing/monitoring is conducted to study the wind-induced behavior of the structure in a natural wind environment. Using fatigue performance modeled as a function of mean stress, dependable service lives are determined for a typical traffic signal structure without and with application of the proposed technique for several distinct wind environments, taking into account both: (1) the modeled change in fatigue resistance; and (2) any observed changes in natural wind response. The evaluated fatigue performance of the modified structure demonstrates the efficacy of the proposed DAD technique.

2. Damage avoidance fatigue mitigation strategy

Tensile mean stress due to dead loads adversely affects the fatigue life of tube-to-transverse plate connections [11,12]. As such, fatigue proneness may be markedly reduced upon design mean stress manipulation. PT stress may be applied at the connection to superimpose a compressive state of stress to reduce the detrimental tensile mean stress. Although the structural response may not be reduced, the applied compression action will improve the fatigue resistance of the tube-to-transverse plate connection, thus the fatigue life will increase.

Fig. 1 demonstrates how the described concept may be applied to a traffic signal structure to improve the fatigue life of tube-to-transverse plate connections. As shown in Fig. 1(a), a PT tendon may be installed to run the length of the mast arm, being anchored at each end to installed bearing plates. Fig. 1(b) better depicts the end detailing by showing the bracket on the back side of the arm-pole connection, curved to evenly distribute the PT force over the backside of the pole section back into the arm-pole connection. Fig. 1(c) also shows a sample application for protecting the vertical pole from fatigue damage. Despite the applied location, the anchorage at the connections should be to balance [24] the self-weight of the structure and attached signal clusters, as depicted in Fig. 1(d). Analogous to a gravity loaded prestressed concrete beam, optimal tendon eccentricity for the mast arm would generally conform to the shape of the dead load moment, increasing toward the mast arm-pole connection. Tendon eccentricity is shown in the superposition of stresses shown in Fig. 1(d); however it may not be a requirement to fully remove the detrimental tensile mean stress present in the arm-pole connection to markedly increase the fatigue life.

It should be noted that even if the region around the arm-to-end plate weld were to fail through fatigue and/or fracture during an extreme event or other overloading scenario, the arm would remain suspended, being held in position by the internal tendon under a high PT stress. As a result, the proposed system provides a fail-safe performance strategy, thereby preventing collapse of the mast arm when an unstable fatigue crack develops. Notwithstanding the fail-safe nature of the PT design modifications, the compressive stress on the critical location of the weld also has a beneficial effect by improving the fatigue life of the connection. This is discussed in the following section.

2.1. The influence of mean stress on fatigue resistance

Tube-to-transverse base plate specimens typical of traffic signal structures fatigue tested under zero (or low) mean stress levels have resulted in longer fatigue lives when compared to companion specimens tested under higher mean stress conditions that were evidently intended to mimic dead load stresses [11,12]. This trend is evident via comparison of past fatigue test results given in Fig. 2.

The results presented in Fig. 2(a) [11,13] stem from fatigue tests conducted on specimens (common to the prototype structure selected later herein) under superimposed loads that led to a typical mean tensile stress of approximately 145 MPa. This stress corresponds to the expected dead load stress at the arm-to-transverse plate connection for a typical structure with a fully equipped (loaded), 13.4 m mast arm [11]. Thus, this value is adopted herein because the mean stress in the arm-pole connection of the later selected prototype structure is slightly lesser due to the lack of wiring, etc., related to a fully-functional structure. Because multiple fatigue studies were considered, the calibrated model is inclusive of a variety of representative materials and common arm-pole connection details used in the field. The superimposed relationships depict the median fit and uncertainty related to the fatigue resistance (and hence damage model) for several details related to tube-to-transverse base plate connections common to traffic signal structures. Fig. 2(a) depicts that when a customary slope of $c = -3$ is used to describe fatigue resistance with an elevated mean stress, variability in fatigue life may be adequately modeled using the well-known, two-parameter lognormal distribution with a one-million cycle median stress of $S_{r,m} = -57$ MPa and a lognormal standard deviation of $\beta_{D|Sr} = 0.55$.

To develop a relationship describing the mean stress dependence of this connection class, the efficacy of the Walker [35] mean stress correction model was investigated. The Walker correction is a generalized form of the well-known Smith, Watson, and Topper (SWT) [36] correction for mean stress effects. The Walker correction takes the form

$$\sigma_{ar} = \sigma_{max}^{1-\gamma_w}\sigma_a^{\gamma_w} = (\sigma_a + \sigma_m)^{1-\gamma_w}\sigma_a^{\gamma_w} \tag{1}$$

in which σ_{ar} = the equivalent completely reversed stress amplitude (zero mean stress); σ_{max} = the maximum stress; σ_a = the stress amplitude such that $\sigma_a = S_r/2$ (where S_r = the cyclic stress range); σ_m = mean stress; and γ_w = the Walker parameter, given by $\gamma_w = 0.8818 - 0.0002\sigma_u$, where σ_u = the ultimate tensile strength in MPa [37]. The Walker model reduces to the SWT correction when $\gamma_w = 0.50$. For a typical mast arm steel, the Walker parameter $\gamma_w \approx 0.80$.

Fig. 2(b) depicts transformation of the previously fit relationship using Eq. (1), converting the nominal stress range (at an elevated mean stress of 145 MPa) to a fatigue damage-equivalent stress range ($2\sigma_{ar}$) under fully reversed conditions. This result is shown alongside