Journal of Constructional Steel Research 138 (2017) 463–472

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

High-cycle fatigue performance of high-mast illumination pole bases with pre-existing cracks

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ARTICLE INFO

Article history:
Received 12 April 2017
Received in revised form 13 July 2017
Accepted 26 July 2017
Available online xxxx

Keywords:
High-cycle fatigue testing
High-mast illumination poles
Pre-existing cracks

ABSTRACT

This paper presents the results of high-cycle fatigue testing of high-mast illumination poles (HMIPs) with pre-existing cracks at the pole-to-base plate connection detail. Resonant bending fatigue tests were conducted on five pairs of HMIP base specimens at nominal stress ranges of 41.4 MPa (±20.7 MPa), 27.6 MPa (±13.8 MPa), 20.7 MPa (±10.3 MPa) and 6.9 MPa (±3.4 MPa). The length and depth of pre-existing cracks was measured and the propagation of the individual crack was monitored throughout the testing using an ultrasonic inspection technique. The experimental results suggested that the fatigue lives of the tested specimens can exceed the predicted life for AASHTO fatigue category E details and approach category D details even in the presence of pre-existing cracks. The results provide insight into the fatigue response of HMIP with pre-existing cracks at the base connections at very low stress ranges and high cycle counts. The findings suggest that the pre-defined constant amplitude fatigue limits for AASHTO details may not strictly apply to HMIP details with pre-existing cracks.

1. Introduction

High mast illumination poles (HMIPs) are important structures in the national traffic system. In the last two decades, HMIP failures have been reported by the state departments of transportation (DOTs) across the United States in New Jersey, Iowa, Florida, Wisconsin, California, Massachusetts and Wyoming [1]. These failures were largely attributed to fatigue cracks and/or wind induced loads at critical and/or stress sensitive regions of HMIPs. The National Cooperative Highway Research Program (NCHRP) has sponsored a number of research projects related to HMIPs [2–4], however, HMIPs in the inventory of the Texas Department of Transportation (TxDOT) have different details compared to previously studied HMIPs in NCHRP sponsored projects. The long term serviceability and structural reliability of HMIPs with pre-existing cracks are still not fully understood. Available data shows that there are currently 2908 poles in service in the State of Texas (Timothy Bradberry, personal communication, October 28, 2014). The poles in TxDOT's inventory are comprised of either 8-sided or 12-sided cross-sections with heights ranging from 30.5 m (100 ft) to 53.3 m (175 ft). All the poles in TxDOT inventory are galvanized. The complex interaction between cold working, welding, and galvanizing during fabrication may induce cracking at the pole-to-base connection detail during fabrication [5]. Research conducted by the European Commission on the failure mechanism of welded joints during galvanizing [6] concluded that the potential for liquid metal assisted cracking (LMAC) is influenced by the stiffness of the joint, presence of residual stresses, zinc bath composition, and dipping speed. Cracks have been identified in many 12-sided galvanized poles although there have not been any reported failures of TxDOT poles. However, as mentioned above, HMIP failures have been observed in other states and reported to be attributed fully or in part to the presence of these cracks [1]. Fig. 1 below shows the typical HMIPs and their base connection details in the state of Texas.

The current TxDOT HMIP standard designs were adopted in Texas in the early 1980s. At the time, the fatigue life of the poles was not explicitly incorporated as a design consideration. However, there was an awareness that the pole shaft-to-base plate welded connection was susceptible to fatigue. As such, best-practice of the time was adopted in the detailing of the connections. This included using a 76 mm (3 in.) thick base plate, complete joint penetration (CJP) welds, and an external collar, which effectively doubles the thickness of the shaft at the base of the pole (also called a ground sleeve), to improve the fatigue resistance of the joint. Previous research has demonstrated that the TxDOT HMIP details generally exhibit superior fatigue performance to other types of details used in the USA [5,7–15]. The presence of cracks that form during fabrication can undermine the integrity of these details but these fabrication flaws could not be reliably detected using available inspection technologies of the time. By the early 1990s, TxDOT permitted the use of an alternate detail in which the external collar was removed to facilitate fabrication. This alternate was approved on a case-by-case basis after completion of static tests by the fabricators to

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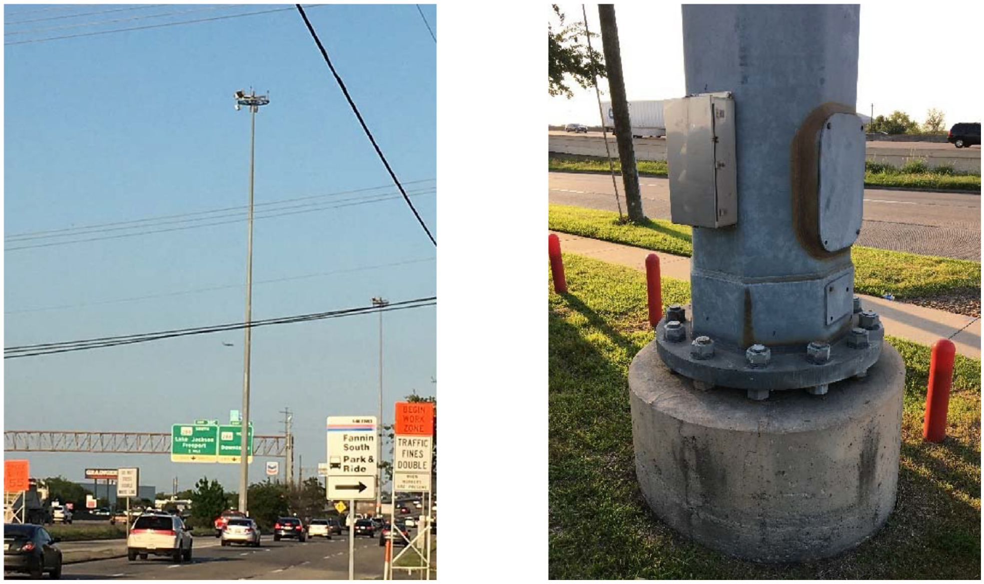
http://dx.doi.org/10.1016/j.jcsr.2017.07.020



(a) HMIPs in Houston, TX (b) HMIP base connection details

Fig. 1. Typical HMIPs in Texas.

demonstrate that their alternate details could achieve the full plastic moment capacity of the section at the pole base (Timothy Bradberry and Jim Yang, personal communication, November 11, 2014).

Since the approval of this alternate detail, research has suggested that removing the collar makes the pole details more susceptible to the formation of pre-existing cracks during fabrication and that the cracks in these poles propagate more rapidly [16]. In the early 2000s, TxDOT adopted new ultrasonic inspection techniques which can more reliably detect the presence of cracks after galvanizing the poles. Cracks detected using these enhanced techniques, and the surrounding galvanizing, must be repaired prior to erection. In the TxDOT inventory, there are a total of 258 poles that have been inspected in service for presence of cracks at the pole shaft-to-base plate connections. Among the 258 investigated poles, 60 of them were found to be cracked. Repair of the cracked poles is underway based on the inspection results. The existing inventory of poles includes 973 poles without ground sleeves and which may have pre-existing cracks (mostly fabricated during the 1990s and early 2000s, before the adoption of enhanced ultrasonic inspection techniques).

Other state DOTs have reported similar challenges with HMIP base connection details [1–4]. Field monitoring of luminaires on the Burlington cable-stayed bridge in Iowa confirmed that it was wind-induced excitation rather than traffic-induced vibration that had a significant impact on the light system failure [17]. Research activities on HMIPs and related traffic light and signal facilities have been conducted at several universities and research institutes with major support from state DOTs and NCHRP [2–4]. AASHTO *Standard Specifications for Structural Supports for Highway Signs, Luminaires and Traffic Signals* [18] have been revised in its entirety through a major research project sponsored by the National Cooperative Highway Research Program (NCHRP Project 17–10) [19]. The new document was approved in 1999 by all state Departments of Transportations for adoption by AASHTO and was published in 2001. Lehigh University's Center for Advanced Technology for Large Structural Systems (ATLSS) conducted field instrumentation and testing of high-mast lighting poles [20]. It was found that vortex shedding response predicted using AASHTO provisions may be unconservative. They further indicated that loose anchor nuts had a significant effect on the measured stresses in the tube wall of the pole adjacent to the base plate welds. Additionally, a minimum base plate thickness of 76 mm (3 in.) was recommended to improve fatigue resistance for tall high-mast poles which were >42.7 m (140 ft) high. Previous research by the Midwest Transportation Consortium (MTC) [21] stated that the highest stress ranges at a HMIP base were caused by buffeting at wind speeds above 32 kph (20 mph). Contrary to the AASHTO design specifications, vortex shedding excitation was observed primarily in the second mode of vibration of the HMIP. In the final report for NCHRP project 10–70, Roy et al. [4] reported that tube-to-transverse plate connections are the most critical fatigue details. The stress concentration increases with fewer sides and sharper bend corners, and this would reduce the constant amplitude fatigue limit (CAFL) of connections in multi-sided sections. In NCHRP project 10-74, Connor et al. [2] concluded that mitigation of vortex-induced vibration mainly affected the accumulation of load cycles and infinite life design was appropriate for HMIPs. The researchers also developed and recommended static pressure-range values for fatigue design of HMIPs and to account for both geographic variation in yearly mean wind velocity and variation in experimental data.

High cycle fatigue tests on other types of structural details have been performed, but information on the 12-sided TxDOT HMIP details without ground sleeve was limited. In conventional fatigue experimental programs on HMIP base specimens, testing stress ranges and time frames are often limited by the servo-hydraulic actuator test setups. Therefore, fatigue tests on HMIP have focused on nominal stress ranges from 41.4 MPa (6 ksi) to 137.9 MPa (20 ksi) [11], and consequently lower number of cycles. However, for lower stress ranges [20,22] (<41.4 MPa) and at higher cycles (50–100 million), relatively little is known about the crack propagation and fatigue life of HMIP base connections with pre-existing cracks. The predominant loads that HMIP experience during their service lives is wind induced loading. The degradation of the poles is primarily attributable to vortex shedding induced vibrations in the second and third vibration modes [8]. Previous research supported by TxDOT reported that the maximum nominal stress range at the pole connection caused by vortex shedding is <6.9 MPa (1 ksi) [11]. Previous research also indicate that the nominal stress range at the pole base connection is approximately 6.9 MPa (1 ksi) [5,8]. Thus, this research focuses on filling this knowledge gap (lower stress ranges and higher cycles) by using the resonant bending testing approach to reach high cycle counts in a short duration. The overarching objective of this research is to establish a comprehensive understanding of the fatigue resistance and reliability of HMIPs with pre-existing galvanization induced cracks at the pole-to-base plate detail that are subjected to wind induced vibrations. Resonant bending