Engineering Structures 123 (2016) 482–489

Contents lists available at ScienceDirect

Engineering Structures

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

Base geometry influence on impact load failure of a traffic signal pole

Min Ook Kim, Amanda C. Bordelon *, Uma Ramasamy, Chris P. Pantelides

Civil and Environmental Engineering, University of Utah, 110 Central Campus Drive, Salt Lake City, UT 84112, USA

A R T I C L E I N F O

Article history:
Received 11 April 2015
Revised 12 May 2016
Accepted 24 May 2016
Available online 14 June 2016

Keywords:
Traffic signal pole
Impact loading
Finite element method
Simulation

A B S T R A C T

A galvanized tapered steel traffic signal pole impacted by a flat-front school bus was found not to break away at the base anchors bolts, but instead fail within the pole tube at a unique height associated with an inner back-up ring component. This failure was simulated with a 3D finite element model. The model was also used to investigate deformation and failure for various front bus shapes, pole thicknesses, and inner back-up ring heights. A higher back-up ring was found to delay failure at the point of impact, but in every case, the traffic signal pole always failed from the bus impact and associated impact load.

Published by Elsevier Ltd.

1. Introduction

In the United States, traffic signal poles are designed based on three available criteria and standards: (i) AASHTO standard specification for structural supports for highway signs, luminaires, and traffic signals (LTS) [1], (ii) state specific DOT specification, and (iii) commercial production criteria. The expected failure mode for such pole structures is based on wind fatigue loading [2–6]. AASHTO LTS indicates minimum wind load requirements for a given application. AASHTO LTS also addresses impact loads; upon impact, the structure should break-away from the underground base support system. The point of having break-away supports is to save the vehicle. As such, the structures should not be perfectively rigid; in the case of the traffic signal pole, it should not slice through the vehicle, or have the vehicle wrap around it. AASHTO LTS leaves it to the owner's decision to require testing of the pole to behave a certain way under an impact event.

Impact loading has been investigated by some researchers [7–12]. The key parameters found to influence the magnitude of deformation of the tube structure are the velocity of the impact load [7], the type of tube material [9,11], break-away support of the pole base [9–11], and magnitude of axial compressive loading [8,12]. Several numerical studies [13–15] were carried out to investigate vehicle collisions with a traffic signal pole. However, previous studies focused more on the dynamic vehicle response rather than deformation characteristics or failure behavior of pole structures. As mentioned previously, the pole structure should not be perfectively rigid and/or unyielding to minimize fatal injuries after a vehicle crashes into it. In this regard, understanding the effect of the vehicle front shape, pole thickness, and height of back-up ring on the deformation and failure behavior of a pole are important to develop new design criteria for traffic signal poles.

A specific incident involving a Utah Department of Transportation (UDOT) owned traffic signal pole has initiated the research presented in this paper. This incident involved a school bus which crashed into a pole and resulted in a unique and potentially hazardous buckling, shear brittle failure and collapse of the traffic signal pole with the mast and luminaire arms. The failure mode of the real structure was investigated based on the photo documentation from the actual event and measurements of the failed structure. The primary purpose of this paper is to investigate design characteristics that could significantly influence the failure mechanism of traffic signal poles subjected to an impact load by a bus. This research uses 3D numerical analysis to determine the stress values in the pole components under a simulated impact load on the entire structure.

2. Research significance

A significant cause of injury or fatality of drivers could arise from a vehicle collision with an existing rigid infrastructure, such as a traffic signal structure. In this regard, it is important to understand the deformation characteristics of the traffic signal pole itself subjected to impact loading. A review of the literature shows that very few research studies have investigated the welded base-pole connection design; in addition, there is little research available

* Corresponding author.
E-mail addresses: tominookkim@gmail.com (M.O. Kim), bordelon@civil.utah.edu (A.C. Bordelon), uma4ramiah@gmail.com (U. Ramasamy), c.pantelides@utah.edu (C.P. Pantelides).

http://dx.doi.org/10.1016/j.engstruct.2016.05.041
0141-0296/Published by Elsevier Ltd.

simulating heavy vehicle impact loading. This study investigates the failure of an actual pole, along with the performance of simulated alternative designs of poles with different thicknesses or geometry of the back-up ring at the base. The present study also provides the details of using finite element analysis to predict the stress and deformation characteristics and failure behavior of a traffic signal pole structure subjected to impact loading.

3. Actual event investigation

Fig. 1 shows the condition of the traffic signal pole and bus after the incident. The pole was located on a curbed median at the intersection of a major arterial highway and a secondary highway. The pole has been constructed recently so operational life and fatigue damage were not an issue. This incident occurred on a cold day with an air temperature of −9.4 °C and possible patches of ice on the road surface. The region was below freezing temperatures for over 24 h. The mass of the bus was 12,917 kg, which is significantly larger than standard impact crash vehicles used to test existing break-away structures [16,17]. The posted speed limit at this location is 89 km/h. The bus driver stated that he initially was going to make a right turn, but changed his mind, lost control and then slid into the concrete curb and hit the pole. As shown in Fig. 1, it was expected that the impact first occurred on the right passenger-side and the front of the bus.

3.1. Failure mode

Additional visual observations were made of the failed traffic signal pole components to identify or verify surface markings, deformation locations, and dimensions. These were also compared to the original design drawings and to a new traffic signal pole installed at the same location to determine orientation and height of impact relative to the roadway. Fig. 2(a) and (b) show the buckling of the pole and the remaining fractured base section of the pole. The pole surface showed two distinct markings indicating locations of impact. These markings have black and yellow paint streaks or even small pieces of a rubber-type material attached. It was estimated that the pole itself buckled from the impact load, but then failed in shear 50 mm from the top of the base. Fig. 3 shows the schematic representation of the deformed shape of a pole subjected to impact by a bus. The dimensions of the bus relative to the pole structure can be seen in Fig. 4.

Elmarakbi et al. [9] reported that a relatively high speed of 64 km/h from the impacting passenger vehicle can cause shear failure of the bolts in the base plate. In the present actual scenario, the vehicle was a flat-facing school bus of much greater mass than a sedan vehicle; even at a slow speed, enough energy could be generated to cause failure of the pole. In addition, the sharp change in thickness near the base, due to the inner welded back-up ring, likely caused a stress concentration and led to the specific shear failure location 50 mm from the bottom. The back-up ring and the pole geometry are investigated in the finite element model in order to understand their influence on the failure location and deformation expected in a similar impact load scenario.

Fig. 1. Photo taken after incident showing the condition of the traffic signal pole and bus.

3.2. Pole support and material

Fig. 5 shows photos and design drawings for the back-up ring, base plate, base weld, and tube pole – base plate connection. The inner-back-up steel ring is used to provide material for deeper penetration and improved bond of the base weld beyond the pole thickness. Since failure occurred in the pole wall rather than breaking away at the bolts, as seen in Figs. 2(b) and 5, the effect of anchor bolts on the failure of the pole was not investigated in this study.

The material of the pole was a low-carbon galvanized steel. The design yield strength was 405 MPa and ultimate strength was 473 MPa. These properties were verified to be 13% and 5% lower than the specification, respectively, based on a small sample set of ASTM E8 tested dogbone specimens cut from the actual pole. A longitudinal friction stir-weld was used to close the tube. The longitudinal weld was found to only have a 52% partial penetration depth into the pole thickness at the height of the bus impact; this is compared to a 69% average penetration depth near the base of the pole. Although this reduced penetration depth may have influenced failure of the pole, for simplification of the simulation model, no longitudinal welds were added to the model.

4. Finite element modeling

A 3D finite element model, using finite element software [18], was developed to verify the stresses and deformations expected from the bus impact load on the pole. The model was also used to verify the predicted sequence of failure of the actual pole structure. The geometry of the pole model was taken from the manufacturer drawings. This geometry was first created in a 3D computer-aided design drawing, and then uploaded into the finite element program. The simple layout and dimensions of the bus and the pole structure along with loading conditions is summarized in Fig. 4.

4.1. Assumptions for modeling

Several assumptions were made to simplify the finite element model. First, the impact load on the pole was applied as a rigid body force. The bus was assumed to be a rigid body with no rotation such that it would not deform, rebound after impact, or lift-off from the ground. These assumptions provide a worst-case loading scenario of the bus impacting the pole. The entire model was fixed at the bottom of the base without considering the effect of the anchor bolt configuration on the stress distribution or deformation of the pole. It was assumed that the entire pole would fail for a bus moving at a velocity of 48 km/h. The time to failure was considered as the time to reach the ultimate strength of the pole material.

4.2. Traffic signal pole

As shown in Fig. 6, the model of the traffic signal pole structure was divided into seven parts: luminaire arm, mast arm, pole, back-up ring, base plate, inner and outer base welds. Fig. 6 also shows the actual in-place traffic signal pole for comparison. The two arms and the pole parts were modeled using shell elements (S4R), while the ring, base plate, and two base welds were modeled using three-dimensional eight-node brick elements (C3D8R). The differences in