Reliability Engineering and System Safety 132 (2014) 261–273

Contents lists available at ScienceDirect

Reliability Engineering and System Safety

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

Reliability assessment of power pole infrastructure incorporating deterioration and network maintenance

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ARTICLE INFO

Article history:
Received 3 March 2014
Received in revised form
18 July 2014
Accepted 26 July 2014
Available online 7 August 2014

Keywords:
Time-dependent structural reliability
Power distribution
Timber utility poles
Wind vulnerability
Wood degradation
Uncertainty

ABSTRACT

There is considerable investment in timber utility poles worldwide, and there is a need to examine the structural reliability and probability based management optimisation of these power distribution infrastructure elements. The work presented in this paper builds on the existing studies in this area through assessment of both treated and untreated timber power poles, with the effects of deterioration and network maintenance incorporated in the analysis. This more realistic assessment approach, with deterioration and maintenance considered, was achieved using event-based Monte Carlo simulation. The output from the probabilistic model is used to illustrate the importance of considering network maintenance in the time-dependent structural reliability assessment of timber power poles. Under wind load, treated and untreated poles designed and maintained in accordance with existing Australian standards were found to have similar failure rates. However, untreated pole networks required approximately twice as many maintenance based pole replacements to sustain the same level of reliability. The effect of four different network maintenance strategies on infrastructure performance was also investigated herein. This assessment highlighted the fact that slight alterations to network maintenance practices can lead to significant changes in performance of timber power pole networks.

1. Introduction

It is estimated that there are over 5 million timber power poles in Australia, with a net worth of over $10 billion [1]. The network maintenance cost for this considerable asset is substantial, with the annual maintenance budget estimated to be $26 million in 1999 for the three eastern states of Australia alone [2]. The level of investment in timber power poles in other countries is even greater than in Australia. For example, there are between 120 million and 200 million treated timber poles in service in the United States (U.S.) [3]. Given the scale of these infrastructure networks it is reasonable to assume that even a small improvement in design and network maintenance strategies would lead to considerable cost savings. The need for optimisation of power pole network management in an Australian context is heightened by the fact that projected pole replacement requirements may lead to critical timber pole supply shortages in the near future [4].

Another important consideration is the consequence of power pole failures, which are primarily caused by wind loading of deteriorated poles [5]. These consequences range from loss of power to business and homes, to catastrophic bushfire (wildfire) events with significant loss of life and infrastructure. Ignition of bushfires by power lines is a somewhat rare event which has devastating consequences. For instance only 1% of fires in Southern California in the U.S. are caused by power line fires, however this 1% occurrence rate was responsible for 10% of the total fire damage in the region from 1960 to 2009 [6]. These electrical fires were caused by a range of wind related power line component failures including conductor clashing, trees falling on lines, pole failures and conductor failures. Catastrophic fires specific to power pole wind failures in recent history include the Malibu bushfire in 2007, which burned 1552 ha of land and destroyed 14 structures, and the Parkerville bushfire in Western Australia in January 2014, which destroyed 55 homes, cost in excess of $20 million and resulted in the loss of one life. These events highlighted the importance of ensuring the structural reliability of power poles is kept at an acceptable level across the vast power networks.

The most appropriate approach for improving component failure rates and maintenance strategies for a network with high variability among infrastructure elements is probabilistic assessment. Probability based methods provide essential asset management tools in other areas of civil engineering, such as bridge management, due to the ability to incorporate and quantify uncertainty and variability

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http://dx.doi.org/10.1016/j.ress.2014.07.019
0951-8320/

across an infrastructure network [7–10]. Surprisingly, however, there is little research utilising probabilistic methods to examine the structural reliability of power distribution poles, and to investigate the effectiveness of different asset management strategies. This represents an important gap in the existing literature as probabilistic analysis is highly appropriate to the management of timber power pole networks, which exhibit high elemental variation within networks due to differences in; (a) strength characteristics, (b) durability characteristics, (c) the loading and deterioration conditions poles are subjected to. The work presented in this paper seeks to address this gap in the literature by examining the vulnerability of timber power distribution poles subject to extreme wind events and timber decay, and investigating the effect of various design and network maintenance strategies on infrastructure performance.

A number of researchers have published studies examining structural reliability and wind vulnerability of timber distribution poles in an Australian context [11,12], with more recent studies being carried out in a U.S. and European contexts [13–16]. Although these studies represent valuable contributions to the existing sparse literature in this area, continued improvements are necessary in order to realistically represent power distribution networks in service. The first way in which this is achieved in this paper is through the incorporation and examination of the effect of network maintenance strategies on structural reliability of a pole in a power distribution network. This network maintenance, (not to be confused with individual pole maintenance actions such as pole reinforcement or in-situ timber treatment), typically involves pole inspection at 3 to 6 year intervals to ascertain remaining load carrying capacity, and pole replacement when capacity is found to be inadequate. Only a handful of studies in the existing literature consider the effect of network maintenance actions on the structural reliability of pole networks [13,14]. But, given that power pole networks throughout the world, are inspected and replaced in order to reduce annual wind failure rates, a realistic assessment of the structural reliability of a distribution pole in a working network must incorporate the effect of these inspections and subsequent maintenance replacements.

Of the probabilistic studies considering maintenance, Gustavsen and Rolfseng [13] examined the effect of; (a) no network maintenance, and (b) replace poles once they deteriorate to 90% of original capacity. This 90% capacity replacement criteria seems somewhat stringent when it is considered that the corresponding figures for the United States and Australia are 66% and 50%, respectively [17,18]. Bjarnadottir et al. [15] examined a number of hurricane risk mitigation strategies for U.S. timber power poles. However, this investigation was carried out in the context of a cost benefit analysis. Consequently, presentation of the structural reliability of poles in an inspected and maintained power distribution network was outside the scope of their study.

A time-dependent event-based probabilistic methodology is presented in this paper which facilitates assessment of structural reliability of infrastructure elements that experience deterioration and maintenance over their service life. A case study is then presented which utilises the event-based probabilistic model to obtain the wind vulnerability and structural reliability of timber power poles designed to existing standards [19], in a network maintained in accordance with existing standards. It is shown in the paper that the utilisation of this more realistic modelling approach has a significant bearing on the power pole wind vulnerability results, when compared to an approach without network maintenance incorporated. The time-dependent event-based probabilistic model is also used to assess the effectiveness of a number of different network maintenance strategies. This is a starting point for the probability based optimisation of timber utility pole network maintenance strategies.

The second way in which the work presented herein builds on the existing literature is through the examination of both treated and untreated poles in the case study. Of the recent studies which consider structural reliability of timber poles, Keshavarzian and Priebe [16] did not consider deterioration, the deterioration model utilised by Gustavsen and Rolfseng [13] did not facilitate the detailed examination of treated and untreated timber poles. The Bjarnadottir et al. studies [14,15] did consider deterioration, but focused solely on untreated poles. While a portion of electrical distribution networks are made up of older untreated poles, the vast majority of newly installed poles are treated poles [20]. Consequently, there is a clear need to examine the structural reliability performance and maintenance implications of both treated poles and untreated poles. This paper addresses this need by examining treated and untreated timber poles designed to Australian Standards, with deterioration represented by a sophisticated multi-layer timber decay model developed by Wang et al. [21,22] based on using 35 years of decay field data.

The following section of this paper presents the development of the probabilistic model. The general methodology of the time-dependent event-based model is first explained before a more detailed and specific discussion is presented on the different aspects of the model. Section 3 of the paper presents details of the illustrative case study which explores the vulnerability and reliability for treated and untreated poles in maintained networks. The results of the illustrative example are presented in Section 4. Section 5 examines the effects of changes to existing network maintenance strategies on network performance. The final section presents the results of a sensitivity study which investigates the relative influence of individual parameter variation on the overall model output.

2. Probabilistic methodology

The objective of reliability analysis is to evaluate the probability of occurrence of a specified scenario [23]. For a given failure mode the associated failure probability (P_f) is;

$$P_f = P[G(x_i) \le 0] \tag{1}$$

where $G(x_i)$ is the limit state function and x_i are the random variable realisations [24,25]. In a structural reliability context the limit state function, G, in its most basic form is;

$$P_f = P[R - S \le 0] \tag{2}$$

where R represents resistance of the element considered and S represents load applied [26]. As pointed out by Barone and Frangopol [27], however, resistance and indeed load, are often time-dependent variables with resistance generally deteriorating over time for engineering systems. Thus, Eq. (2) becomes;

$$G(t) = R(t) - S(t) \tag{3}$$

where $R(t)$ and $S(t)$ are instantaneous resistance and load effects at time t, respectively [27,28]. In the context of examination of a network of structural systems such as power pole networks, bridge networks, road networks etc. network maintenance must also be considered. This network maintenance plays an important role in reducing the effect of deterioration on the probability of failure of elements in the network at a given time, t. Consequently, in order to realistically represent the performance of an infrastructure network over time a probabilistic model must incorporate;

- Resistance
- Applied load
- Deterioration of infrastructure elements over time
- Effects of network maintenance