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Risk assessment of transmission line structures under severe thunderstorms

C.Q. Li†

Department of Civil Engineering, Monash University, Victoria, 3145, Australia

Abstract. To assess the collapse risk of transmission line structures subject to natural hazards, it is important to identify what hazard may cause the structural collapse. In Australia and many other countries, a large proportion of failures of transmission line structures are caused by severe thunderstorms. Because the wind loads generated by thunderstorms are not only random but time-variant as well, a time-dependent structural reliability approach for the risk assessment of transmission line structures is essential. However, a lack of appropriate stochastic models for thunderstorm winds usually makes this kind of anaysis impossible. The intention of the paper is to propose a stochastic model that could realistically and accurately simulate wind loading due to severe thunderstorms. With the proposed thunderstorm model, the collapse risk of transmission line structures under severe thunderstorms is assessed numerically based on the computed failure probability of the structure.

Key words: risk; failure probability; transmission line; thunderstorms; wind loads; stochastic model; poisson process; upcrossing rate.

1. Introduction

To assess the risk of structural collapse of transmission lines subject to natural hazards, it is necessary to identify what hazard may cause the structural failure. A recent survey of failures of transmission line structures in Australia (Hawes and Dempsey 1993) indicates that a large proportion of failures (more than 90%) are due to severe thunderstorms, such as tornadoes and downbursts. It is evident that wind loads that are generated by severe thunderstorms are poorly defined, despite the fact that quite extensive research on wind loads has been carried out in Australia over the last 30 years. This is particularly so for the design of transmission line structures. In fact, severe thunderstorms have not been taken into account in current Australian design standards for wind loads because of lack of statistical data and a lack of knowledge as well. It is therefore desirable to develop a stochastic model of wind loads that could include the features of severe thunderstorms for the design of transmission line structures.

The survey also shows that more than 76% of failures of transmission line structures under thunderstorms are structurally initiated. It is obvious that the risk assessment of transmission line structures is crucial in the process of structural design. Actually, risk analysis of transmission line structures has been accorded considerable attention in, for example, the

† BE., ME., Ph.D., MIEAust., CP Eng.

United States and South Africa. Since wind loadings are not only uncertain but also time-variant, it is well justified that the risk analysis of transmission line structures under thunderstorm wind loads should be in the framework of time-dependent reliability theory. Time-dependent structural reliability problems are those in which either applied loads or structural resistance, or both, are modelled as stochastic processes. To some extent, the theory of time-dependent reliability has been well developed, and it is the time to apply this advanced approach to practical engineering strutures.

The present paper is concerned with the risk assessment of transmission line structures subject to severe thunderstorms. First, a stochastic model is proposed which may realistically and accurately simulate wind loadings generated by severe thunderstorms. With the proposed thunderstorm model, the risk of transmission line structures due to severe thunderstorms is assessed numerically according to the computed failure probability of the structure. The failure probability of the structure is based on the failure probability of its structural components that form a failure mechanism. The major advantage of the proposed thunderstorm model is that the size effect of thunderstorms on wind load intensity has been taken into account. Statistical data that are required to support the parameters of the model may be available from meteorological stations.

2. Modelling thunderstorms

2.1. Severe thunderstorms

Thunderstorms have their genesis in the initial uplift of warm, moisture-laden air (Simiu and Scanlan 1978). There are several different types of thunderstorms, depending on the origin and the associated meteorological activities. All types of thunderstorms can occasionally become severe. Acording to Australian climatology, a thunderstorm is considered severe if it produces winds in excess of 28.3 m/s (55 knots) (Li and Holmes 1994). In the United States, it is set at 25.9 m/s (Golden and Snow 1991). The most severe thunderstorm is a tornado, which is not the major cause of transmission line failures in Australia and therefore will not be discussed in the paper. Another type of severe thunderstorm is the so-called downburst. A downburst is an intensive downdraft and gust front system (in some literature, especially meteorological literature, gust front is separated from downburst, but herein they are considered to be one system). Downbursts can induce an outburst of damaging winds near the ground, with near surface speeds in excess of 50 m/s. The strong wind tends to flow outward radially from where the descending current strikes the earth. The typical physical size of damaging storms is 6 to 8 km across. At a point beneath the thunderstorm strong winds may sustain for up to 30 minutes.

Downbursts include microbursts and macrobursts (Fujita 1985). Microbursts are smaller and more concentrated downbursts, the physical size of which is about 4 km or less in horizontal extent. The record observed wind speed in a microburst is 67 m/s. A macroburst is a large downburst. The physical size of thunderstorm activities in Australia is shown in Table 1 (Holmes 1993).

Downbursts are identified in this paper directly from their signatures on anemometer charts of severe storms which produce high speed winds with a relatively short duration. This is different from those that were identified by thunderdays (Gomes and Vickery 1976). The

Table 1 Types of thunderstorm winds in Australia (from Holmes 1993)

Type	Horizontal scale	Duration
Microburst	1-4 kilometers	2-4 minutes
Macroburst	4-10 kilometers	4-30 minutes
Ourflows (gust fronts, squall lines)	10-100 kilometers	1-10 hours

records of meteorological stations indicate that downbursts may not necessarily associate with thunders. On the other hand, thunderstorms with thunderdays do not always produce downbursts with high wind speeds.

2.2. Stochastic model

The difficulty of stochastically modelling thunderstorm wind loads for transmission line structures lies in the fact that when thunderstorms occur, they do not necessarily strike a transmission line and hence the supporting structures, because the scale of thunderstorms is usually small and localised. This is quite different from large scale storms to which the whole reference area is subject to storm winds. This is why stochastic models for severe thunderstorms are rarely available for transmission line designs.

In the modelling of wind loads due to severe thunderstorms, the following stochastic features of the storm need to be recognised: 1) thunderstorms change from time to time during the whole life time of transmission line structures; 2) at a given time, it is not definite whether thunderstorms occur or not, i.e., the occurrence time of thunderstorms (i.e., wind loads) is a random variable; 3) when thunderstorms do occur, the intensity of the storm, i.e., the magnitude of the wind load is uncertain. This means that the wind load due to thunderstorms is a time-variant random variable; and 4) when a thunderstorm occurs, it is not certain how long it will last, i.e., the duration of the wind load is a random variable too. Based on these characteristics of thunderstorms, it is appropriate to assume that the wind loading due to thunderstorms be modelled as a Poisson renewal process. A Poisson renewal loading process is a pulse process $Q(t)$ (see Fig. 1), in which the occurrence time of the

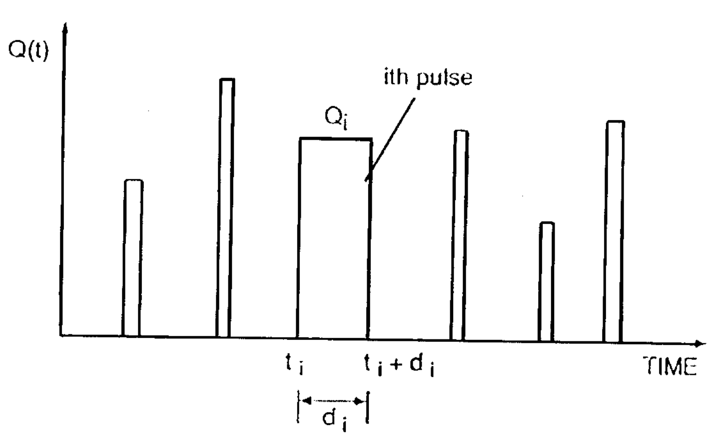

Fig. 1 Poisson loading process

loading pulse, its duration and intensity are all treated as random variables (see, e.g., Melchers 1987). Generally, independence is assumed between the load intensities and the duration in each occurrence of loading pulses as well as there being independence from one occurrence to another. A pulse process is described by a mean occurrence rate λ, a random variable duration d (with mean μ_d) and an intensity random variable Q (magnitude of the load) with probability distribution function $F_Q(q)$. The product $\lambda \cdot \mu_d$ represents the proportion of time that the load pulse is acting. In practice, transient loads have $\lambda \cdot \mu_d$ values much less than 1. When $\lambda \cdot \mu_d \gg 0$, the pulses are likely to overlap, leading to a so-called 'compound Poisson process'. A detailed application of the Poisson loading model is available in Li and Melchers (1992).

A Poisson loading process can be expressed as

$$Q(\lambda, d, q_i, t, t_i) = \begin{cases} Q_i & \text{when it occurs} \\ 0 & \text{otherwise} \end{cases} \tag{1}$$

where i refers to ith loading pulse and t denotes time (usually year). One more feature associated with transmission lines is that when the thunderstorm occurs (represented by each pulse in the process), it does not necessarily strike the transmission line structures, which means that there is no wind loading. Therefore each loading pulse in the process should be allowed for by the probability that each occurrence of thunderstorms has struck the transmission line and hence the structures.

The probability that a thunderstorm strikes a transmission line structure may be determined by employing geometrical probability, and by introducing a reference area. The reference area may be defined in such a way that both thunderstorm activities and transmission line damage can be taken into account. One way may be to define an area in which the thunder is audible. Now assume that such a reference area has been given. The geometrical feature of transmission lines, in the reference area, is that only one dimension, i.e., the length of the transmission line is of significance. Accordingly, the geometrical size of a thunderstorm is measured by a path length. The path length, denoted by b, of a thunderstorm is defined as the reference distance that the thunderstorm passes with a certain speed. It is the trace of the storm not the physical size of the storm (in meteorological terms, it is known as 'run of wind'). Some data required to estimate the path length may be available from, for example, anemometer charts of meteorological stations. Assume that the ith thunderstorm occurs with a path length b_i. According to the principles of geometrical probability, the probability of any point of the transmission line being hit, denoted by H, is

$$H(b_i) = \begin{cases} b_i/L & \text{if } b_i < L \\ 1 & \text{if } b_i \geq L \end{cases} \tag{2}$$

where L is the significant design length of the transmission line in the reference area, along which the damage is most likely to occur. Eq. (2) is similar to that derived by Milford and Goliger (1995) for tornado risk in South Africa when their reference area is represented by $L \times L$.

Since b_i is a random variable, the probability of a strike at a point along the transmission line by the ith thunderstorm in Eq. (2) is (Li and Holmes 1994):

$$p_{is} = \int_0^\infty H(b)\cdot f(b)\,db \tag{3}$$

where $f(b)$ is the probability density function of path length b. Thus the probability distribution function governing each loading pulse should be modified as

$$F_Q'(q) = F_Q(q)\cdot p_{is} \tag{4}$$

3. Verification of the model

The feature of the proposed wind load model, which is distinguished from other models for large scale winds, is that the probability of a thunderstorm strike on transmission line structures (i.e., Eq. (3)) is used to allow for the fact that when a thunderstorm occurs it does not necessarily strike the transmission line. Eq. (3) can be further expressed, by substituting Eq. (2) and ignoring the almost impossible case of $b_i > L$, as

$$p_{is} = \int_0^\infty \frac{b}{L}\cdot f(b)\,db = \frac{\mu_b}{L} \approx \frac{1}{L}\cdot\frac{1}{k}\sum_{i=1}^{k} b_i \tag{5}$$

where the path length b may be obtained from anemometer charts of meteorological stations, as schematically shown in Fig. 2. In Eq. (5), k is the number of thunderstorms that were recorded in the reference area. It can be seen that only the mean of path length, μ_b, is of significance.

To calibrate the thunderstorm model, in particular, Eq. (3), the results of a study on severe wind in New South Wales, Australia, which was carried out by Australian Bureau of Meteorology (ABM, 1992) may be used. The results are expressed in terms of return period, R, versus extreme wind speed, i.e.,

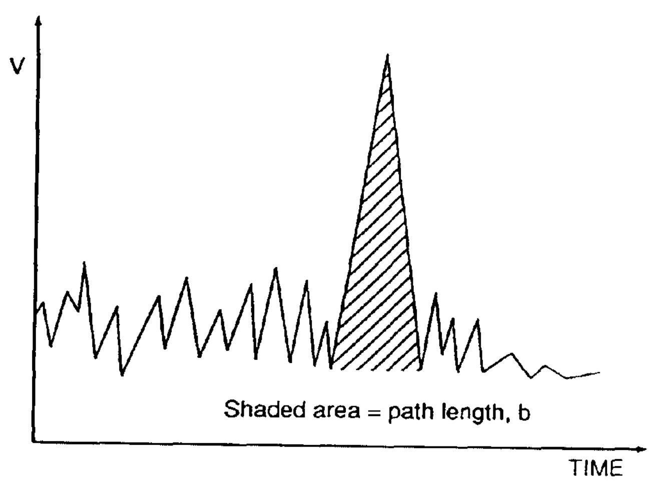

Fig. 2 Path length of a thunderstorm

$$R = \frac{1}{1 - F_V(v)} \tag{6}$$

where V is the annual maximum wind speed and $F_V(v)$ is the probability distribution function of V. In the case of thunderstorm winds Eq. (6) needs to be modified for two reasons: (1) the extreme wind speed is with respect to per thunderstorm rather than per year, i.e., it is not annual maximum wind speed. Therefore a mean occurrence rate of thunderstorms, λ, should be applied; (2) the probability distribution function of wind speed should be weighted by the probability of a strike. Thus Eq. (6) becomes

$$R = \frac{1}{\lambda[1 - F_V(v)]p_{is}} = \frac{L}{\lambda[1 - F_V(v)]\mu_b} \tag{7}$$

Data required in Eq. (7) are available from meteorological station and herein a typical station at Moree in New South Wales, Australia is selected, which are shown in Table 2. As can be seen, 19 storms were identified as severe thunderstorms in 27 years' records, with a mean occurrence rate of λ=0.7. From the wind speed data of Table 2, an extreme value anaysis is straightforward, which shows that wind speeds generated by thunderstorms in Moree area are of Gumbel distribution with $1/\alpha$=3.199 and u=27.596 (m/s). Also it may be noted that in Table 2, more than one storm were recognised as severe thunderstorms in one year, for example, in 1965, 1972, etc., which again illustrates that the extreme value of wind speed is not annual maximum but is associated with thunderstorms only.

The mean path length is obtaind from anemometer charts which μ_b=54.06 km. Using L=100 km, a return period vs wind speed can be plotted and compared with the results from the Bureau (ABM 1992), which is shown in Fig. 3. It can be seen that the results from both the

Table 2 Moree thunderstorm winds 1965-1991

Date	Gust (knots)	Gust (m/s)	Direction
10/1/65	50	25.7	225
30/9/65	50	25.7	270
28/10/67	50	25.7	292.5
22/1/71	58	29.8	157.5
24/10/72	71	36.5	225
12/11/72	70	36.0	225
9/1/73	56	28.8	202.5
1/11/76	60	30.9	202.5
26/3/77	59	30.3	315
24/2/80	51	26.2	247.5
4/12/80	58	29.8	247.5
14/12/80	50	25.7	202.5
29/12/82	68	35.0	157.5
31/12/82	63	32.4	202.5
9/12/83	51	26.2	202.5
11/11/84	51	26.2	320
21/1/88	57	29.3	210
7/2/90	53	27.3	40
29/11/91	55	28.3	240

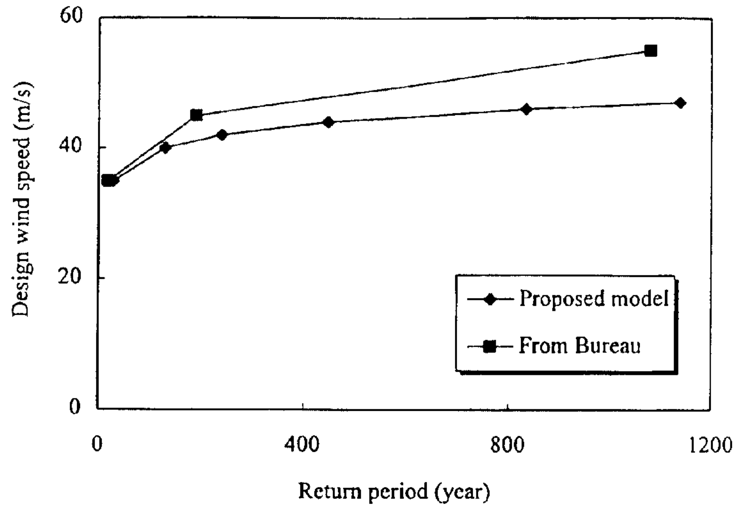

Fig. 3 Comparison of wind speeds

proposed model and the Bureau's study are consistent.

4. Probability of structural failure

Since wind loads generated by severe thunderstorms are the dominant time-variant loading on the transmission line structures, it is the only load that is considered in the risk analysis of transmission line structures in this paper. The risk assessment is based on the probability of structural failure. Consider first the failure probability of structural components of a transmission line structure. The design criterion, known as limit state, for the structural components to be safe can be expressed as

$$S_j(t) \leq R_j(t), \quad j=1, 2, ..., m \tag{8}$$

where $S_j(t)=S_j[Q(t)]$ is the so-called 'load effect function' for each structural component, $Q(t)$ is the thunderstorm wind loading which is modelled as a stochastic process, and R_j is the resistance of the jth structural component. In Eq. (8) m is the number of components, the failure of which will lead to a failure mechanism, such as the collapse of the structure as a whole. When the structural analysis is linear, the load effect function can be expressed as

$$S_j(t)=c_j Q(t), \quad j=1, 2, ...m \tag{9}$$

where c_j is a coefficient from structural analysis. So that the statistics of the load effect process $S(t)$ may be readily calculated using stochastic process theory. When the structural analysis is nonlinear, obtaining the statistics of load effect process $S(t)$ is more computationally involved. Fortunately, in practice, structural analysis for transmission line structures is usually linear.

For reliability problems involving stochastic processes, the structural failure depends on the time that is expected to elapse before the first occurrence of the stochastic process upcrossing a threshold (barrier level), determined by limit state functions, sometime during the lifetime $[0, t_L]$ of the structure. Equivalently, the probability of the first occurrence of such an excursion is the probability of structural failure $p_f(t)$ during that time period. Under some assumptions (Melchers 1987), the so-called 'first passage probability' can be evaluated by

$$p_f(t) = p_f(0) + \int_0^{\infty} \nu(\tau)\, d\tau \tag{10}$$

where $p_f(0)$ is the probability that the structure fails on first loading, i.e., at time $t=0$. Evidently $p_f(0)$ is time-independent and can be calculated using, e.g., First Order Second Moment (FOSM) method (which will not be described herein). The main difficulty in application of Eq. (10) to realistic engineering problems is the determination of the upcrossing rate $\nu(t)$.

When the load effect S_j is a scalar Poisson renewal process (such as the wind load herein), the upcrossing rate $\nu(t)$ in Eq. (10) can be obtained, for a given $R_j=r_j$ and using the limit state function in Eq. (8), as follows (see Melchers 1987 for details)

$$\begin{aligned} \nu_{cj}(t) &= \lim_{\Delta t \to 0} \{\frac{1}{\Delta t}\, [P(\text{upcrossing in } \Delta t]\} \\ &= \lim_{\Delta t \to 0} [\frac{1}{\Delta t} \cdot P\{[S_j(t) \le r_j(t)] \cap [S_j(t+\Delta t) > r_j(t)]\} \cdot \lambda] \\ &= F_{S_j}[r_j(t)] \cdot \{1 - F_{S_j}[r_j(t)]\} \cdot \lambda \end{aligned} \tag{11}$$

where ν_{cj} is the upcrossing rate of load effect S_j in the jth structural component relative to R_j, the structural resistance (threshold) to be upcrossed, $F_{S_j}(s_j)$ is the probability distribution function of the load effect S_j, and λ is the occurrence rate of the load process. Taking into account the 'strike' effect (i.e., Eq. (4)), and for high reliability structures, Eq. (11) becomes

$$\nu_{cj} = G_{S_j}(r_j) \cdot p_{is} \cdot \lambda \tag{12}$$

where $G_{S_j}(r_j)=[1-F_{S_j}(r_j)]$. The solution is the same as that in Li and Holmes (1994), derived in a different way. Substituting Eq. (5) into (12), the time-variant failure probability for each structural component can be computed using Eq. (10).

5. The risk of structural collapse

When the failure probability of structural components is known, the risk of structural collapse under severe thunderstorms depends on the mechanism of the collapse. For some structures the failure of one structural component results in the structural collapse, e.g., statically determinate structures; while for other structures, the failure of one or two structural components does not constitutes a structural collapse, e.g., redundant structures. In structural reliability analysis, the former is modelled as a series system and the latter a parallel system. The failure probability of a series system is

$$p_f = \bigcup_{j=1}^{n} p_{fj} \tag{13}$$

and the failure probability of a parallel system is

$$p_f = \bigcap_{j=1}^{m} p_{fj} \tag{14}$$

where p_{fj} is the failure probability of the jth component in the structure, $\cup$ and $\cap$ denote the union and intersection of events, n is the number of structural components of a series structures and m is the number of structural components that are required to form a mechanism. Within the FOSM theory, both the series system and the parallel system structures are tractable. Generally, the series system can be dealt with more easily in conjunction with bounding techniques, whereas the parallel system poses some difficulties in reliability analysis. For this reason, even for redundant structures, it is usual to attempt to convert a parallel system to a series one. This is possible, for example, if the progressive collapse modes of the redundant structure can be identified. In this case, each mode of structural collapse can be represented by a limit state function. The attainment of any one of the various limit state functions is equivalent to failure of the structure.

Transmission line structures are typical complex structures with a large number of structural components and high degrees of redundancy. It is obvious that the generation of limit state functions for this kind of structures is extremely difficult and it might be understandable that accurate computation of the failure probability of this type of structures is an illusive task. In this paper, two criteria are used to define the failure of the structure. One is for critical components, such as leg members, in which the failure of any leg member is equivalent to the failure of the structure, i.e., it is modeled as a series sytem. The other is for non-critical components, such as bracing members, in which only a certain number of members fail can the structure fail, i.e., it is modelled as a parallel system. The failure of a parallel system may be identified by losing stability of the structure or part of the structure.

For a series system, the computation of the failure probability is relatively easier, using bounding techniques, such as Cornell's upper and lower bounds (Cornell 1969)

$$\max_{j=1}^{n} (p_{fj}) \le Pf \le 1 - \prod_{j=1}^{n} (1 - p_{fj}) \tag{15}$$

For parallel system, the failure sequence method (Li and Melchers 1994) may be employed. The basic idea of the method is to identify the failure sequence of structural components, and instead of generating limit state functions, the following formula is used for the evaluation of failure probability of the structure

$$p_f = P\left(\bigcap_{j=1}^{m} F_j\right) = P(F_1) \cdot P(F_2 | F_1) \cdots P(F_m | F_1 \cdots F_{m-1}) \tag{16}$$

where $P(F_j)$ is the failure probability of jth structural component and is computed using Eqs. (10) and (12) of the previous Section.

6. Application example

For the risk analysis of transmission line structures, using the stochastic model of thunderstorm winds, the following parameters need to be determined from thunderstorm records of the meteorological station in a given reference area: 1) the mean occurrence rate λ. Occurrence rates vary from areas to areas. But for a given area a constant λ may be assumed;

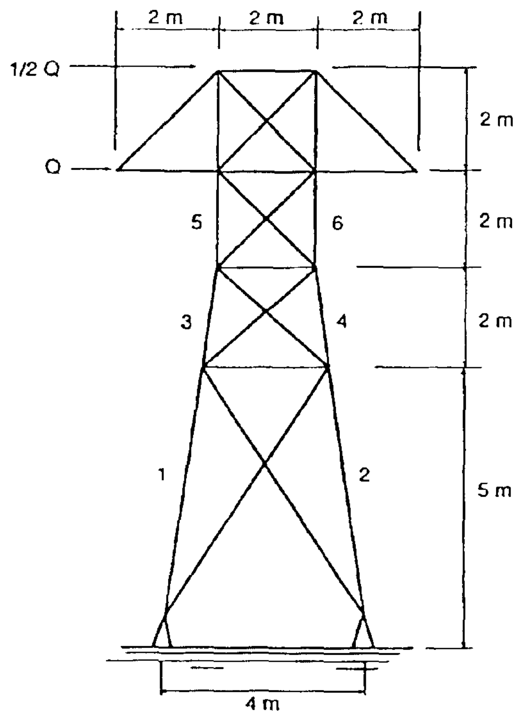

Fig. 4 Example transmission tower

2) the probability distribution function of wind load $F_Q(q)$ for each loading pulse (thunderstorm). This may be obtained from statistical analysis of the meteorological records within the reference area; 3) the path length b. With these parameters known, the upcrossing rate can be computed using Eq. (12) by substituting Eq. (5)

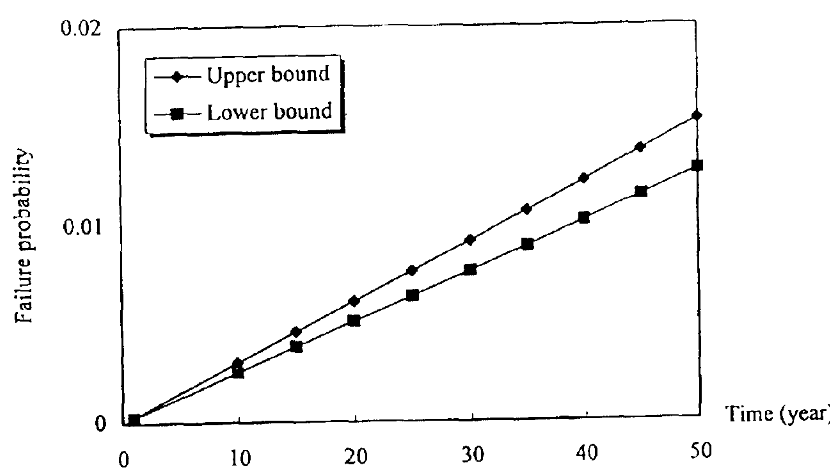

Fig. 5 Time-variant failure probability

$$\nu_{cj} = \frac{1}{L} \cdot G_{sj}\,(r_j) \cdot \lambda \cdot \mu_b \tag{17}$$

It should be noted that for different reference areas the parameters used in the model may have different values. It is obvious that the availability and accuracy of data for the parameters of Eq. (17) are essential to the risk assessment of transmission line structures. Herein data from Moree station (Table 2) are used for illustration, i.e., λ=0.7, μ_b=54.06 km, L =100 km.

For the computation of time-variant failure probability, a transmission tower from Haldar (1986), shown in Fig. 4, is taken as a simple example. From the statistical analysis of meteorological data of Moree area, the wind load follows a Gumbel distribution. Since a linear structural analysis is used the load effects (axial force) in structural components (legs) are also of Gumbel. The wind load Q has a mean of 30 (kN) and standard deviation of 5. For simplicity, the structural resistance (buckling capacity) is assumed to be deterministic with $R_{1,2}$=180, $R_{3,4}$=150, $R_{5,6}$=120 so that Eq. (17) could be used directly. If structural resistance is a random variable, Eq. (17) needs to be modified to take into account the uncertainty of structural resistance. In this case, a simulation algorithm may be employed (see, e.g., Li and Melchers 1994).

The failure of the structure is defined as a series system, i.e., failure of any one of leg members 1 to 6 results in the failure of the tower. So that Eq. (15) is used for computation of failure probability of structural system. For each leg member, Eqs. (10) and (12) are used to calculate the failure probability, assuming $p_f(0)$=0. Typical results are shown in Fig. 5. As can be seen the failure probability of the transmission tower is linearly proportional to the upcrossing rate over time (i.e., Eq. (12)). Therefore the accuracy of the risk assessment is largely dependent on the accuracy of the thunderstorm model developed, in particular, the availability of the parameters of the model. That is why stochastic models are essential to risk analysis of transmission line structures subject to natural hazards like thunderstorms. This conclusion is consistent with other investigations of transmission line structures, such as a study on tornado risk by Milford and Goliger (1995), whereby accuracy of the tornado model is important. Also, the computed failure probabilities using Cornell upper and lower bounds are very close.

7. Conclusions

A stochastic model for severe thunderstorm winds has been proposed and necessary parameters required in the model has been studied. The validity of the proposed model has been checked using available data from a meteorological station. Based on the thunderstorm model, the risk of transmission line structures under severe thunderstorms has been assessed numerically based on the computed failure probability of the structure. The major advantage of the model is that the size effect of thunderstorms on wind load intensity has been taken into account.

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