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RELIABILITY OF A STRUCTURE STRICKEN BY A TORNADO

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Abstract. A tornado may become a very dangerous climatic action for any structure, depending on the tornado intensity and extent of the structure. The origin of a tornado, its range and further activity appear to be unpredictable and completely random. The strike of a tornado to a structure depends on the tornado movement and the structure extent. The tornado intensity is specified by the wind speed, following observed damages and consequences. The probability of a tornado strike on a structure depends on the extent of the structure itself, on the tornado range, and the extent of the considered reference area, for which data concerning tornado appearance are available. The probability of failure of a structure is given by the product of the probability of contact of a tornado with the structure and the probability of exceeding the design speed of the tornado wind. The probability of exceeding the design wind speed depends on the assumed distribution of wind speed and the frequency of tornadoes during the required lifetime of the structure. The target failure probability of common structures presented in available documents is 10^{-6} per year, and 10^{-7} per year of structures in power plants. However, it is not clear how these criteria have been derived. Further development of reliability theory of tornado-stricken structures is recommended to be focused on the risk analysis of appropriate systems, of which the considered structures are elements, on the target failure probability, on detailed analysis of the probability distribution of tornado wind speed and their frequency during the required lifetime of the structures.

Keywords: Design wind speed, power plant, probability, structure, target failure probability, tornado.

1. Introduction

Reliability analysis of a structure stricken by a tornado is treated in several documents and prescriptions [1–3] that are focused primarily on nuclear power plants. Recent document [2] provides detailed recommendations for reliability verification of power plants using probabilistic methods considering random properties of structures and tornado effects. All the available documents include analysis of two inseparable factors of tornado action affecting the reliability of a structure:

(1) tornado strike on structure,

(2) the intensity of tornado effects.

Both factors have random character depending on several local circumstances and conditions that are often assessed based on observed consequences and available experience.

The factor (1) depends on the frequencies of the tornado in the reference territory where the tornado actions are observed. Specification of such a territory depends on social and economic aspects, on longtime observation of tornado, and empirical meteorological information. Tornado strike on the considered structure depends surface area of the reference territory. It is a random variable that can be only assessed.

The factor (2) the intensity of tornado effects is commonly described by wind speed in the air twirl. The wind speed is again a random variable having a large variability of unknown parameters that can be assessed based on observed destructive consequences of tornado action. The design value of the wind speed can be estimated assuming usually Weibull distribution and approximate parameters. Because of uncertain parameters (including the skewness) the estimated design wind speed may be imprecise.

The tornado intensity is usually classified using graduated tables for ground wind speeds. Two scales indicated in Table 1 are commonly applied: Fuji and TORRO scales. Fuji scale (having 6 grades) is primarily used in USA, TORRO scale (refine Fuji scale having 10 grades) is used in Europe. The lowest grade of both scales starts with the wind speed of 17 m/s, the highest grade from 121 m/s.

2. Probability of structural failure

The probability of structural failure p_f due to tornado action can be assessed considering probability pA of tornado strike on a given structure, and simultaneous exceedance of wind speed of the design value vd, when the structure may fail with the probability p_v. The resulting failure probability p_f is therefore given as the product of two probabilities:

$$p_f = p_A \times p_v \quad (1)$$

Probability p_A of tornado strike depends [2] on area of reference territory A_0, for which records of tornado actions are available for n years, on extend of structure A_k and also on the total tornado extent A_tor. Above

Fuji	TORRO	Damage	Wind	Detailed description of damage
F0	T0 T1	Slight damage	17-24 m/s 25-32 m/s	Accidentally demolished chimneys and wooden fences, minor damage to the roofing, damaged advertisements and road signs next to roads, broken tree branches, sporadically uprooted trees with shallow roots, traces of a tornado are visible in the field.
F1	T2 T3	Moderate damage	33-41 m/s 42-51 m/s	Partially destroyed roofing, moving cars are pushed off the roads, mobile homes are shifted from the foundations, overturned or heavily damaged, flimsier buildings and shelters are badly damaged to destroyed, larger trees with stronger roots are sporadically uprooted and broken
F2	T4 T5	Moderate damage	52-61 m/s 62-72 m/s	The roofs of less rigidly built buildings are completely torn down, mobile homes and flimsier structures are completely destroyed, in brick and stronger wooden houses, the side and front walls are not yet seriously damaged. Light cars float, small and light debris become projectiles, most isolated large trees are uprooted or broken.
F3	T6 T7	Significant damage	73-83 m/s 84-95 m/s	Roofs and some walls are completely torn from the structure even in well-built buildings, heavier cars are buoyed, trains and locomotives are overturned, most trees in continuous forests are uprooted and broken, standing trees and tree stumps are partially debarked by flying debris.
F4	T8 T9	Severe damage	96-107 m/s 108-120 m/s	Reinforced concrete buildings are significantly damaged, brick (brick) and stone buildings are severely (mostly irreparably) damaged, less solid buildings are completely levelled, the ruins of flimsy buildings are scattered at considerable distances from their foundations, cars are drifted by the air (just above the ground).) or towed over long distances, large and heavy "projectiles" are formed from flying debris, tree stumps are completely stripped of bark.
F5	T10	Complete destruction	> 121 m/s	Reinforced concrete buildings are badly damaged, other buildings are completely destroyed, cars are carried through the air like projectiles over considerable distances, fields are completely devoid of vegetation, crops are mostly torn out even with roots.

TABLE 1. Tornado intensity scales of Fuji and Torro.

mentioned variables A_0, A_{tor} and A_{k} are random variables of considerable variability that require statistical and probabilistic analysis. In addition, tornado extent A_{tor} may be assessed as product of the length L and width w ($A_{\mathrm{tor}} \approx L \times w$) [2].

Assuming that the tornado actions occur within the reference territory A_0 uniformly, then the probability p_A for one year can be estimated from the mean values of involved variables A_{k}, A_{tor} and A_0 using the formula:

$$p_A \approx (A_{\mathrm{k}} + A_{\mathrm{tor}})/A_0/n, \qquad (2)$$

where n denotes the number of years when tornados are observed in the reference territory A_0. More detailed probabilistic analysis concerning the specific location of a structure can be provided on the basis of the local conditions within the reference territory A_0.

An example. The probability p_A of a tornado strike per year is strongly dependent on the extent of reference area A_0. In South Moravian region $A_0 = 7188\,\mathrm{km}^2$ and area $A_{\mathrm{k}} + A_{\mathrm{tor}} = Ak + L \times w = 1 + 4 \times 0,5 = 3\,\mathrm{km}^2$. Then the probability p_A determined from one observation is about $\approx 3/7188 \approx 4 \times 10^{-4}$. However, when A_0 is considered as a circle with the centre at the structure and the radius of 100 km, then $A_0 \approx 31400\,\mathrm{km}^2$, and $p_A \approx 3/31400 \approx 1 \times 10^{-4}$.

Parameters	v_{inf} [m/s]	μ [m/s]	σ [m/s]	α	Design values v_d [m/s] for p_v 10^{-5}	10^{-6}	10^{-7}
WEIBMIN	30 [m/s]	42	10	1,5	127	142	157
WEIBMIN	7 [m/s]	42	10	1,0	108	118	127
WEIBMIN	21 [m/s]	42	10	0,5	92	98	104
WEIBMIN	10 [m/s]	42	10	0	80	84	87
NORMAL	± INF	42	10	0	85	90	94

TABLE 2. Design values of wind speed v_d for given skewness α and exceedance probability p_v.

3. Design wind speed

The design value vd of the wind speed v is defined for the specified exceedance probability p_v when the structural failure may occur, so:

$$p_v \approx P(v > v_d), \tag{3}$$

Weibull distribution of wind speed v is considered in available documents [1–3]. It is the lower bound limited distribution characterized by three parameters: the mean μ, standard deviation σ a and skewness α. In the professional literature and software products (MATHCAD, EXCEL, EasyFit) another three parameters are also used: for example c_1 (also α or b), c_2 (also b or a) and the lower bound v_{inf} (for standardized variables u_{inf}).

The parameter c_1 depends solely on the skewness α, the parameter c_2 depends on the parameter c_1 (skewness α) and standard deviation σ, the lower bound of the standardized variable u_{inf} depends only on the parameter c_1 (on skewness α), the lower bound of the real variable v_{inf} depends on three parameters: on the mean μ, standard deviation σ and also on the skewness α (on parameter c_1) [4].

The skewness α affects therefore the lower bound v_{inf} and shape of the distribution for a given mean and standard deviation σ, and significantly affects resulting probability of tornado effect. Appendix provides a copy of MATHCAD sheet enabling application of the Weibull distribution. An example of determining the design values of wind speed v_{d} for given skewness α and exceedance probability p_v is indicated in Table 2.

It follows from Table 1 and Figure 1 that the relatively high skewness $\alpha = 1,5$ leads to high design values v_d of wind speed, by 50 % greater than for the skewness $\alpha = 0$ (normal distribution). However, it is not clear how the actual skewness α can be determined from available data. It may be also recommended to utilize experience from the distribution of usual wind speed or the information concerning lower bound v_{inf} indicated in Table 1.

4. Number of tornado strikes

During the required lifetime of a structure several tornados, in general, say N, may occur [3]. If the distribution function of a singular tornado is $\Phi(x, 1)$, then the overall distribution function of all N tornados is given by power function $\Phi(x, 1)^N$ [4, 5]:

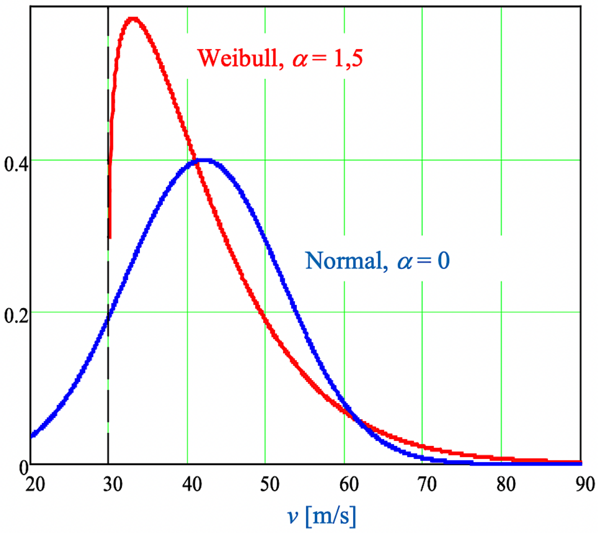

FIGURE 1. Weibull and normal distribution for $\mu = 42$ m/s and $\sigma = 10$ m/s.

$$\Phi(x, N) = \Phi(x, 1)^N \tag{4}$$

Then the design value (upper fractile) $v_{d,N}$ of the distribution function $\Phi(x, 1)^N$ may be greater the design value determined from a single distribution $\Phi(x, 1)$. The occurrence number N may be in the case of less frequent tornados equal to the number of years n used in Equation 2.

Variation of the design value $v_{d,N}$ of tornados for given exceedance probabilities with the occurrence number N is indicated in Table 2. Probability density functions and partly distribution functions for occurrence numbers $N = 1$ and 10 are shown in Figure 3.

An example. Table 3 demonstrates that the resulting design values $v_{\text{d},N}$ for given number of tornados $N > 1$ are greater than the values for one tornado $N = 1$. With increasing N the design value increases up to 35 %. Consequently, when designing a structure the number of tornados N during the assumed lifetime is necessary to consider.

When during the assumed lifetime of a structure the number of tornados is N, then the probability $p_{v,N}$, that the wind speed v_N exceeds the design values v_{d} with the probability:

$$p_{v,N} = \text{P}(v_N > v_d) \tag{5}$$

Occurrence number of tornados N	Lower bound v_{inf} [m/s]	Mean value μ [m/s]	Standard deviation σ [m/s]	Skewness α	Design value $v_{d,N}$ for exceedance probability 10^{-5}	10^{-6}	10^{-7}
1	30	42	10	1,5	127	142	157
10	30	61	10	1	142	157	172
100	30	80	10	1	157	172	187
1000	30	98	10	1	172	187	201

Table 3. Variation of the design value $v_{\text{d},N}$ of tornados with the occurrence number N.

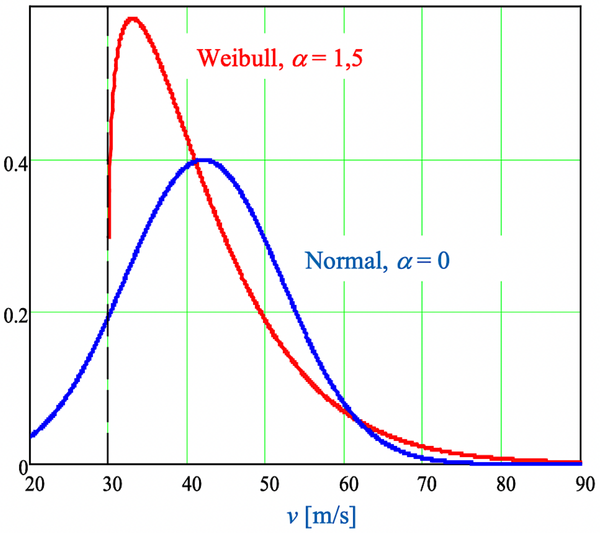

Figure 2. Distributions of tornado wind speed for $N = 1$ and 10.

Table 4 indicates the probability $\mathrm{P}(v_N > v_d)$ for design values v_d determined for a single tornado ($N = 1$) when structural failure may occur. Design values v_d are determined as before for the probabilities 10^{-5}, 10^{-6} a 10^{-7}.

The probability $\mathrm{P}(v_N > v_\text{d})$ for the design value v_d determined from one observation ($N = 1$) is therefore increased by the order of tornado occurrence N.

5. Failure probability

Failure probability of a structure due to tornado strike is generally given by Equation1 1 as the product of the probability p_A, of tornado strike, and the probability p_v, that wind speed exceeds design value vd when structural failure may occur. In the case of one isolated tornado the failure probability $p_{f,1}$ is given as:

$$p_{f,1} = p_A \times p_v = \mathrm{P}(A_0, A_\text{k}, A_\text{tor}) \times \mathrm{P}(v > v_d) \quad (6)$$

In the case of N tornados during the required lifetime the failure probability $p_{f,N}$ is given by the product:

$$p_{f,N} = p_A \times p_{v,N} = \mathrm{P}(A_0, A_\text{k}, A_\text{tor}) \times \mathrm{P}(v_N > v_d) \quad (7)$$

It is obvious that when several tornados ($N > 1$) are assumed, the failure probability is greater than when only one tornado ($N = 1$) is considered.

An example. Consider as before the reference area $A_0 = 7188$ km2 and extent $A_\text{k} + A_\text{tor} = 2 + 1 = 3\,\text{km}^2$. Then the probability pA was determined from one observation $\approx 3/7188 \approx 4 \times 10^{-4}$. When the structure is design assuming the probability $\mathrm{P}(v > v_d) = 10^{-5}$, then the expected probability is $\approx p_{f,1} \approx p_A \times p_v = 4 \times 10^{-9}$. However, when during the assumed lifetime number of tornados is $N = 10$, then the failure probability is about $\approx p_{f,N} = p_A \times p_{v,N} \approx 4 \times 10^{-8}$. Thus, it is the failure probability ten times greater.

6. Target probability of failure

Target probability of failure of a structure during the lifetime t denoted $p_{tar,t}$ can be specified based on probabilistic optimization (maximization) of structural utility (cost) $C_\text{tot}(t)$ during its lifetime t. This can be analyzed in a simplified way considering the total benefit of functioning structure $C_\text{ben}(t)$ during the lifetime t, and the possible losses $C_f(t)$ caused by structural failure (within the relevant system) with the target probability $p_{tar,t}$. The total utility $C_\text{tot}(t)$ can be then symbolically expressed as [4, 5]:

$$C_{\text{tot}(t)} = \max\{C_\text{ben}(t) - p_{tar,t} \times C_f(t)\}. \quad (8)$$

The cost $C_\text{ben}(t)$ includes all kind of benefits during the life time t. Consequences of structural failure $C_f(t)$ cover all the material, ecological and social losses caused by the structural failure. These losses $C_f(t)$ may be extremely large, and could be very difficult to assess. A detailed analysis is outside this contribution and it is recommended to accept a very small target probability, for example, $p_{tar,t} = 10^{-7}$ per year as indicated in documents [1–3].

Note that the target probability for common structures is usually accepted as $\approx 1.30 \times 10^{-6}$ for one year (that is reliability index $\approx 4,7$). This corresponds to $\approx 0,72 \times 10^{-4}$ per 50 years (and to the reliability index 3,83), per 100 years the target probability is $\approx 1,31 \times 10^{-4}$ and reliability index $\approx 3,65$. Variation of the target probabilities $p_{tar,t}$ with reference time t given in years for selected basic probabilities $p_{tar,1} = 10^{-5}$, 10^{-6} and 10^{-7} is shown in Figure 3.

Number of tornados N	Lower bound v_{inf} [m/s]	Mean value μ [m/s]	Standard deviation σ [m/s]	Skewness α	The probability $P(v_N > v_\text{d})$ for design value v_d 127	142	157
1	30	42	10	1,5	1.0×10^{-5}	1.0×10^{-6}	1.1×10^{-7}
10	30	61	10	1	9.4×10^{-5}	1.0×10^{-5}	1.1×10^{-6}
100	30	80	10	1	9.3×10^{-4}	1.0×10^{-4}	1.1×10^{-5}
1000	30	98	10	1	9.3×10^{-3}	1.0×10^{-3}	1.1×10^{-4}

TABLE 4. Probability $P(v_N > v_d)$ of exceedance the design values v_d.

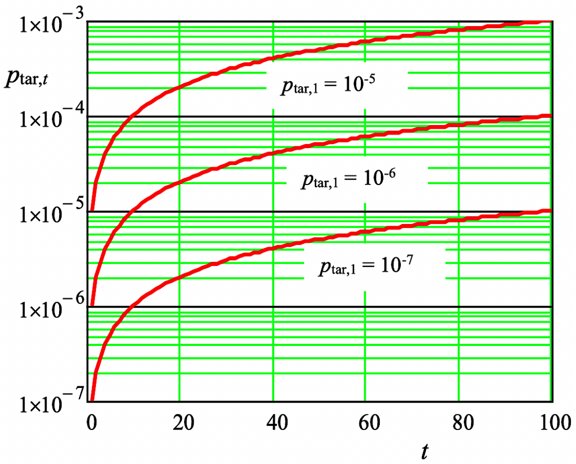

FIGURE 3. Variation of the target probabilities $p_{tar,t}$ with reference time t in years for basic probabilities for one year - $p_{tar,1} = 10^{-5}$, 10^{-6} and 10^{-7}.

7. CONCLUDING REMARKS

(1) A tornado may be for any structure very dangerous depending on the extent of the structure and tornado and its intensity. Tornado is unpredictable and of random time behaviour.

(2) The probability of a tornado strike can be assessed taking into account the extent of a structure and tornado and the extent of the reference territory where tornados are observed.

(3) Tornado intensity expressed by wind speed is determined after the tornado strike following observed consequences.

(4) Probability structural failure is given by a product of the probability of a tornado strike and the probability of wind speed exceedance of design value.

(5) Estimation of wind speed exceedance of design value is strongly dependent on assumed wind speed distribution and the number of tornado occurrences during the lifetime of the structure.

(6) Available documents provide for target probability for structural failure value 10-7 per year, however, it is unclear how this criterion has been derived.

(7) Further reliability analysis of structures stricken by tornados is to be focused on detailed analysis of tornado consequences, on wind speed distribution and the number of tornado occurrences during the lifetime of the structures.

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