Risk-Based Design Load on Buildings With Predetermined Service Life

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ABSTRACT: The possibility that a short-term building meets a rare event is lower than that of an ordinary building. Because strong wind and snow can be predicted relatively accurately, the design load can be reduced provided that preliminary preventive care (PPC) is executed by the building safety manager. When conducting PPC, the safety level should be kept equivalent to that of an ordinary building. The object of this research is to discuss the optimum design load that minimizes the total expected cost. Then, simple formulae to determine the optimum design load are proposed.

1. Introduction

In recent years, global environmental issues have been one of the main concerns among societies and buildings with longer service lives than ordinary ones are considered one of the solutions (Kimura, 2013). On the other hand, the social needs of buildings with limited service lives have been increasing for the purpose of efficient use of land leasehold, experimental verification of new construction methods, etc. However, in the current Building Standards Act of Japan, a building with a service life longer than a year is designed in principle as an ordinary building. Because the possibility that a building with a service life shorter than that of an ordinary building meets a rare event during its service life is lower, the design load can be reduced.

In order to meet such social needs, a "Kigen-tsuki Building" has been proposed and Recommendations for design of such buildings was published (AIJ., 2013). According to the recommendations, a Kigen-tsuki Building is designed with a predetermined service life and conditions of use, and is, in principle, disassembled after the expiration of the period of the predetermined service life. The primary mission of buildings including Kigen-tsuki Buildings is to protect human life from loads such as strong winds, heavy snow, and earthquakes. Therefore, the safety level of a Kigen-tsuki Building shall be equivalent to that of a ordinary building. On the contrary, exceeding the serviceability limit state can be compensated economically. Because strong winds and snowfall can be predicted relatively accurately, the serviceability performance level of a Kigen-tsuki Building can be adjusted provided that preliminary preventive care (PPC) such as installation of temporary supports is surely executed by building safety manager. By reducing the design load, the initial cost can be reduced. However, new risks arise such as the trouble and failure of conducting PPC. The degree of such risk depends on the design load and the trigger level (the forecast level at which PPC is conducted). In order to implement the design of a Kigen-tsuki Building in a practical manner, simple guidelines for the design load and the trigger level are needed.

The objective of this research is to propose simple formulae to determine the optimum design wind load, snow load, and trigger level of a Kigen-tsuki Building by taking into account the variability in the annual maximum value of wind speed, ground snow weight, service life, the cost to conduct PPC, the cost of failure in serviceability, and the slope of the initial cost. To achieve this objective, an evaluation method of the limit state probability of a Kigen-tsuki Building is developed by first taking into account the posterior distribution of the daily maximum wind speed and ground snow weight in consideration of PPC as a function of the accuracy of the forecast of the wind speed and ground snow weight. The method also takes into account the possibility of the failure of conducting PPC owing to uncertainty in the forecast. Then, the optimum design load and trigger level on a Kigen-tsuki Building that minimizes the total expected cost are discussed.

2. Risks associated with load reduction and expected total cost

Risks associated with the reduction of design loads on a Kigen-tsuki Building are classified into the following three types (Mori et al., 2012).

- C_{tr}: Cost of PPC including loss owing to limited use of the building (per time),
- C_{f1}: Loss of failure owing to improperly conducting PPC,
- C_{f2}: Loss owing to the occurrence of load exceeding the design load of ordinary buildings

Since it is difficult to treat C_{f1} and C_{f2} with clear distinctions, they are treated together as $C_f = C_{f1} + C_{f2}$. Then, the expected total cost, C_T, can be expressed as the sum of the initial cost, the expected cost associated with PPC, and the expected cost of failure in serviceability and safety.

$$C_T = C_I + C_{fS} \cdot P_{fS} \cdot t_L + C_{fU} \cdot P_{fU} + C_{tr} \cdot E[N_{tr}] \quad (1)$$

where t_L is the pre-determined service life (year), C_I is the initial cost, C_{fS} and C_{fU} are losses owing to the exceedance of the serviceability limit state and ultimate limit state, respectively, P_{fS} and P_{fU} are the serviceability limit state probability and ultimate limit state probability, respectively, N_{tr} is the number of times that PPC is conducted during t_L, and $E[\bullet]$ is the expectation operator. The reference period of P_{fS} is set to be 1 year, while that of P_{fU} is set to t_L years. According to the principle of minimizing the total expected cost, the design load that minimizes C_T in Eq.(1) is optimal.

3. Design load and trigger level

3.1. Evaluation method

3.1.1. PPC and Posterior probability distribution of wind speed and ground snow weight

Since the duration of strong winds and ground snow weight in general areas occurs from half a day to one day, it is assumed that PPC is applied on a daily basis when the weather forecast value exceeds the trigger level. Because of errors in forecasting, PPC cannot always be conducted even if the actual daily maximum wind speed or the ground snow weight, X_e, exceeds the trigger level. Here, it is assumed that the probability of conducting PPC when the trigger level is set to X_{tr} given $X_e = x$ can be expressed as

$$\begin{aligned} F_{tr}(x;x_{tr}) &= P[\text{triggered}|X_e = x] \\ &= \Phi\left(\frac{x - x_{tr}}{V_{tr} \cdot x_{tr}}\right) \end{aligned} \quad (2)$$

where $\Phi(\bullet)$ is the standard normal probability distribution function (CDF), and V_{tr} is the accuracy of the weather forecast expressed by its standard error divided by the actual value, corresponding to its coefficient of variation (COV). According to the theorem of total probability, the probability that PPC is triggered on a certain day, p_{tr}, can be expressed as

$$p_{tr} = \int_0^\infty F_{tr}(x;x_{tr}) f_{X_e}(x)dx \quad (3)$$

where $f_{X_e}(x)$ is the probability density function of the daily maximum value, X_e. Then $E[N_{tr}]$ in Eq.(1) can be expressed as

$$E[N_{tr}] = r_d \cdot t_L \cdot p_{tr} \quad (4)$$

where r_d is the number of days that a trigger may take during a year. The posterior CDF of X_e given that PPC is triggered can be expressed as

$$\begin{aligned} F_{X_{e_{tr}}}(x) &= P[X_e \leq x|\text{triggered}] \\ &= \frac{\int_0^x P[\text{triggered}|X_e = x] \cdot f_{X_e}(x)dx}{p_{tr}} \\ &= \frac{\int_0^x F_{tr}(x;x_{tr}) \cdot f_{X_e}(x)dx}{p_{tr}} \end{aligned} \quad (5)$$

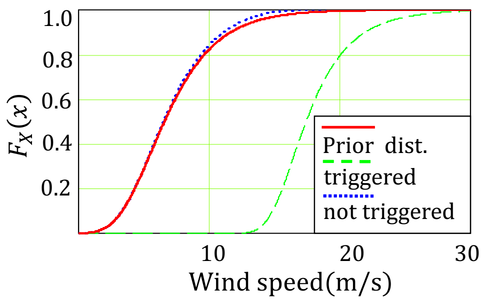


Figure 1: Prior and posterior CDF of daily maximum wind speed.

Likewise, the posterior CDF of X_e given that PPC is **not** triggered can be expressed as

$$\begin{aligned} F_{X_{e_{ntr}}}(x) &= P[X_n \leq x|\text{not triggered}] \\ &= \frac{\int_0^x \{1 - F_{tr}(x;x_{tr})\} f_{X_e}(x)dx}{1 - P[\text{triggered}]} \\ &= \frac{F_{X_e}(x) - \int_0^x F_{tr}(x;x_{tr}) \cdot f_{X_e}(x)dx}{1 - p_{tr}} \end{aligned} \tag{6}$$

Fig.1 shows the prior (solid line) and posterior CDF of the daily maximum wind speed given that PPC is triggered (dashed line) or not triggered (dotted line). It is assumed that x_{tr} =16 m/s, V_{tr} = 0.1 and the daily maximum wind speed is described by a Gumbel distribution with mean equal to 7.1 m/s and COV equal to 0.48.

3.1.2. *Wind load model*

The wind load W (N) can be expressed as

$$W = \frac{1}{2}\rho(XE_H)^2 C_D G_D A \tag{7}$$

where X (m/s) is the 10min average wind speed at 10 (m) above the ground, ρ is the air density, which is equal to 1.22 kg/m^3, E_H is the vertical profile coefficient, C_D is the wind force coefficient, G_D is the gust response factor, and A is the projected area (m^2). Eq.(7) can be rewritten as

$$W = aBX^2 \tag{8}$$

where a is a normalization coefficient making the median of B equal to unity. Then B can be expressed as

$$B = \frac{1}{2a}\rho E_H^2 C_D G_D A \tag{9}$$

Assuming that A is a deterministic value, and that ρ, E_H, C_D, and G_D are lognormally distributed, B, as the product of lognormal random variables, is also lognormally distributed. Its logarithmic standard deviation, $\sigma_{\ln B}$, is expressed as

$$\sigma_{\ln B} = \sqrt{\sigma_{\ln \rho}^2 + 2\sigma_{\ln E_H}^2 + \sigma_{\ln C_D}^2 + \sigma_{\ln G_D}^2} \tag{10}$$

3.1.3. *Snow load model*

The snow load S (N/m^2) can be expressed as

$$S = X \cdot \mu_0 \cdot R_{env} \tag{11}$$

where X is the ground snow weight (N/m^2), μ_0 is the roof shape coefficient, and R_{env} is the environmental coefficient. Similar to Eq.(8), Eq.(11) can be rewritten as

$$S = aBX \tag{12}$$

where

$$B = \mu_0 \cdot R_{env} \tag{13}$$

The logarithmic standard deviation of B can be expressed as

$$\sigma_{\ln B} = \sqrt{\sigma_{\ln \mu_0}^2 + \sigma_{\ln R_{env}}^2} \tag{14}$$

The forecasted ground snow weight is evaluated by multiplying the forecasted ground snow depth with the unit snow weight.

3.1.4. *Strength model*

The safety of ordinary buildings in Japan is in general ensured not by ultimate strength design but by allowable stress design (ASD). Considering such situations, the probability characteristics of strength for the serviceability limit state and the ultimate limit state are modeled as follows:

The allowable stress for short term loading, R_n, is expressed as

$$R_n = D_n + L_n + P_n \tag{15}$$

where D_n, L_n and P_n are the design dead load, design live load and design wind (or snow) load considered in ASD. In a steel structure in Japan, R_n is the smaller between the nominal yield strength, R_S, and 70% of the nominal tensile strength, R_U. Here, it is assumed that R_n is the 5% quantile value of

R_S that is considered as the strength for the serviceability limit state. Then the strength for the ultimate limit state is modeled as

$$R_U = \frac{R_S}{0.7} \tag{16}$$

Assuming that R_S is lognormal distributed with a COV equal to V_R, then the mean of R_S, μ_{R_S}, can be expressed as

$$\mu_{R_S} = \alpha_R \cdot R_n \tag{17}$$

where

$$\alpha_R = \frac{\sqrt{1+V_R{}^2}}{\exp\left\{\Phi^{-1}(0.05)\sqrt{\ln(1+V_R{}^2)}\right\}} \tag{18}$$

From Eqs.(15), (17) and (18)

$$\mu_{R_S} = \alpha_R\left(\frac{D_n}{\mu_D} + \frac{L_n}{\mu_L}\frac{\mu_L}{\mu_D} + \frac{P_n}{\mu_{Pa}}\frac{\mu_{Pa}}{\mu_D}\right)\mu_D \tag{19}$$

where μ_D and μ_L are the means of D and L, respectively, and μ_{Pa} is the mean of the annual maximum of the wind load or snow load. It is assumed that the design load formulae in ASD of an ordinary building is based on the 50 year recurrence value of the wind speed or ground snow weight. Because the wind load is proportional to the square of the design wind speed, the design wind load on a Kigen-tsuki Building, P_n, can be expressed as

$$P_n = W_{n50}\cdot\left(\frac{x_r}{x_{50}}\right)^2 \tag{20}$$

where x_r is the r-year recurrence wind speed and W_{n50} is the wind load based on x_{50}.

As the snow load is proportional to the ground snow weight, the design snow load on a Kigen-tsuki Building, P_n, can be expressed as

$$P_n = S_{n50}\cdot\left(\frac{x_r}{x_{50}}\right) \tag{21}$$

where x_r is the r-year recurrence ground snow weight, and W_{n50} is the ground snow weight based on x_{50}.

3.1.5. *Exceedance Probability*

The limit state probability of a structural member, P_f, can be expressed as

$$P_f = 1 - P\left[\bigcap_{i=1}^{r_d} R^* - (D+L+P_i) > 0\right] \tag{22}$$

where r_d is the reference period (day), R^* is the strength when either PPC is conducted, R, or not conducted, R_0. P_i is the load owing to the i-th day maximum wind speed or ground snow weight. By substituting Eqs.(8) and (12) into Eq.(22) and assuming that the daily maximum wind speed or ground snow weight are statistically independent of each other, P_f can be expressed as

$$\begin{aligned} P_f &= 1 - P\left(\bigcap_{i=1}^{r_d} R^* - [D+L+W(or\ S)] > 0\right) \\ &= 1 - \int\cdots\int \{F_{X_e}[g(r^*,d,l,b,a)]\}^{r_d}\cdot f_{\mathbf{R}}(\mathbf{r})\,d\mathbf{r} \end{aligned} \tag{23}$$

where $f_{\mathbf{R}}(\mathbf{r})$ is the joint probability density function of R, R_0, D, L, and B. $g(r,d,l,b,a)$ is expressed as follows:

For wind load

$$g(r,d,l,b,a) = \exp\left[\frac{\ln(r-d-l) - \ln b - \ln a}{2}\right] \tag{24}$$

For snow load

$$g(r,d,l,b,a) = \exp\left[\ln(r-d-l) - \ln b - \ln a\right] \tag{25}$$

$F_{X_e}[g(r^*,d,l,b,a)]$ can be estimated using its posterior CDF expressed by Eqs.(5) and (6) and the theorem of total probability as

$$\begin{aligned} F_{X_e}[g(r^*,d,l,b,a)] &= F_{Xe_{tr}}[g(r_0,d,l,b,a)]\cdot p_{tr} \\ &+ F_{Xe_{ntr}}[g(r,d,l,b,a)]\cdot(1-p_{tr}) \end{aligned} \tag{26}$$

where r_0 and r are realized values of R_0 and R, respectively. Eq.(23) can be estimated by using a hybrid Monte Carlo simulation, in which samples of R, R_0, D, L, and B are generated and the sample mean of $(F_{Xd})^{rd}$ is calculated. This makes it possible to evaluate P_f with a smaller number of samples than a simple Monte Carlo simulation.

Table 1: Probability model of wind speed and ground snow weight

	CDF	COV (V_X)
Annual max of wind speed	Gumbel or Frechet	0.10, 0.20, or 0.30
Annual max of ground snow weight	Gumbel	0.80, 1.00, or 1.20

Table 2: Parameters related to wind and snow load

	COV
Air density ρ	0.10
Vertical profile coefficient E_H	0.10
Wind force coefficient C_D	0.15
Gust response factor G_D	0.15
Roof shape coefficient μ_0	0.15
Environment coefficient R_{env}	0.10

Table 3: Probability model of loads and resistance

	CDF	nominal / mean	mean	COV
D	Normal	1.00	μ_D	0.10
L	LN	0.40	0.75 μ_D	0.40
R	LN	5% lower limit	Eq.(19)	0.10

Table 4: Cost model

C_I	1.0
C_{Ia}	0.01, 0.03, 0.05, or 0.1
C_{fS}	0.1 or 0.3
C_{fU}	2.0
C_{tr}	0.001, 0.004, or 0.007

3.2. Numerical analysis

3.2.1. Probability model

Through a statistical analysis of the data during the past n years of the daily maximum wind speed, it was found that the wind speed in Tokyo and Sapporo can be described by a Gumbel distribution, while in Naha it can be described by a Frechet distribution (Mori et al., 2012). In cities such as Nagoya and Kanazawa, the daily maximum wind speed can be described by a combination of three different distributions (JMA, 2014), which can be obtained by dividing a year into three periods considering the season of typhoons. Yet, considering only the upper 1/3 values of the samples, which are of concern in structural design, it can eventually be described by either a Gumbel or Frechet distribution. Thus, it is assumed that the daily maximum wind speed is described by either a Gumbel or Frechet distribution, and the statistics listed in Table 1 are considered here.

According to statistical data from 1961 to 2015, it snows more than 5 cm above the ground for 1.5 days on average in ordinary area such as Nagoya, Tokyo, and Yokohama from December to February (JMA, 2014). Then, it is assumed here that the events of snow can be modeled by a Poisson process with mean occurrence rate, λ equal to 1.5/90. Then, the CDF of the r_d day maximum ground snow weight can be expressed as

$$\begin{aligned} F_{X_0}(x) &= \sum_{i=1}^{\infty} (F_{X_S}(x))^i \cdot \frac{(\lambda r_d)^i e^{-\lambda r_d}}{i!} \\ &= \exp[-\lambda \cdot r_d \cdot (1 - F_{X_S}(x))] \end{aligned} \tag{27}$$

where $F_{X_S}(x)$ is the CDF of the ground snow weight when it snows more than 5 cm. It is assumed that all snow melts after the end of each snowfall. The 90 day (1 year) maximum ground snow weight generally has a Gumbel distribution and is expressed as

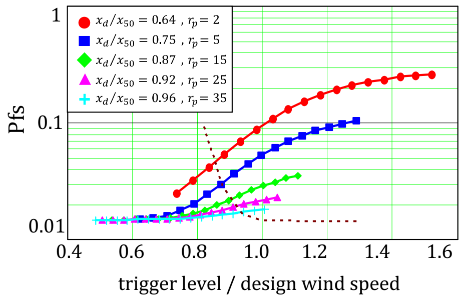
$$\begin{aligned} F_X(x) &= \exp[-\lambda \cdot 90 \cdot (1 - F_{X_S}(x))] \\ &= \exp[-\exp(-\alpha(x-u))] \end{aligned} \tag{28}$$

From Eq.(28), $F_{X_S}(x)$ can be expressed as

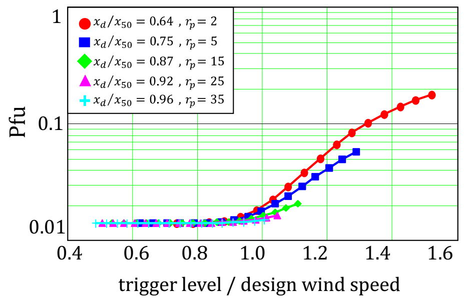
$$F_{X_S}(x) = 1 - \frac{\exp[-\alpha(x-u)]}{\lambda \cdot 90} \tag{29}$$

Parameters in Eqs.(7) and (11) other than wind speed and ground snow weight are listed in Table 2. It is assumed that the parameters are lognormally distributed with a median equal to unity (AIJ., 2015).

Probability models of the strength and dead load and live load are shown in Table 3. Considering low-rise steel structures, which are often candidates for a Kigen-tsuki Building, it is further assumed that the ratio of μ_D to μ_L equal to 0.75 and the ratio of μ_W to μ_D+μ_L equal to 1.0 (Itoda et al., 2004). It should be noted that the ratio of μ_W to μ_D+μ_L was separately examined in the range of 0.8 to 2.0, and



(a) Serviceability



(b) Ultimate

Figure 2: Effect of trigger level on P_f

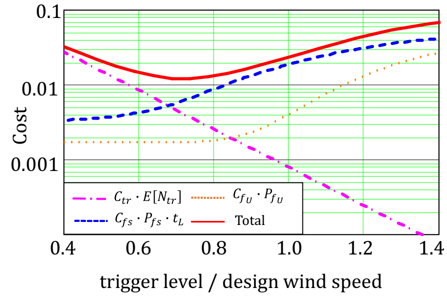


Figure 3: Optimum trigger level

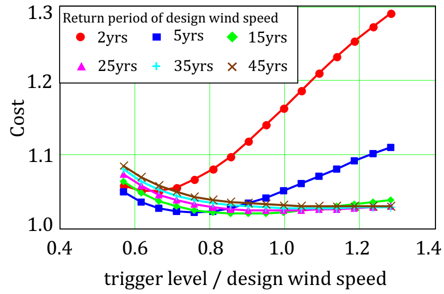


Figure 4: Total expected cost, C_T

it was confirmed that the influence of the ratio on the following conclusions is very low.

The design wind load and snow load are determined on the basis of the return period of wind speed or ground snow weight, r_p, equal to either 2, 3, 5, 10, 15, 20, 25, 30, 35, 45 or 50 years. The design load for PPC is determined on the basis of r_p = 50 years. In the actual calculation, the 50 year recurrence wind speed is set to 32 m/s, while the 50 year recurrence ground snow weight is set to 600 N/m^2, which corresponds to about 30 cm of snow depth. It is also assumed that the accuracy of the weather forecast, V_{tr}, for the wind speed and snow depth is 0.1 or 0.2 (Shimizu and Omasa, 2006).

3.2.2. Cost model

Because the initial cost, C_I, is approximately a linear function of the design load (Kanda, 2008), the following initial cost model is assumed.

$$C_I = C_{Ia} \cdot \frac{P_d}{P_{50}} + C_{Ib} \tag{30}$$

where P_d and P_{50} are the design load on a Kigentsuki Building and an ordinary building, respectively. Assuming that costs are estimated in practice by structural engineers, here the dimensionless cost models shown in Table 4 are considered.

3.2.3. Results

Fig.2 shows an example of the dependence of (a)P_{fS} and (b)P_{fU} on the ratio of the trigger level, x_{tr}, to the design wind speed, x_d, which is determined on the basis of a return period equal to 2, 5, 15, 25, or 35 years. The design wind speed, x_d, normalized by the 50-year recurrence wind speed, x_{50}, is also presented in the figure. Here, it is assumed that the annual maximum wind speed is described by a Gumbel distribution with a COV equal to 0.2, V_R =0.2, V_{tr} = 0.1, and t_L =10 years. When x_{tr} is sufficiently smaller than the design wind speed, P_{fS} and P_{fU} are nearly constant; however, it starts to increase at a certain value of x_{tr}/x_d. The value of the ratio where P_{fS} starts to increase varies depending on x_d, and it decreases as x_d becomes smaller. By contrast, the value where P_{fU} starts to increase is not significantly dependent on x_d. In order to ensure the same safety level with a ordinary building, PPC must be conducted before P_{fU} rises. The dotted line in Fig.2(a) shows the upper limit of x_{tr}/x_d where P_{fU} is nearly constant in Fig.2(b).

Fig.3 shows the dependence of $C_{tr} \cdot E[N_{tr}]$ (dotted-dashed line), $C_{fS} \cdot P_{fS} \cdot t_L$ (dashed line), $C_{fU} \cdot P_{fU}$ (dotted line), and their sum (solid line) on the ratio (x_{tr}/x_d). Then the same probability model considered in Fig.2 and the design wind speed is

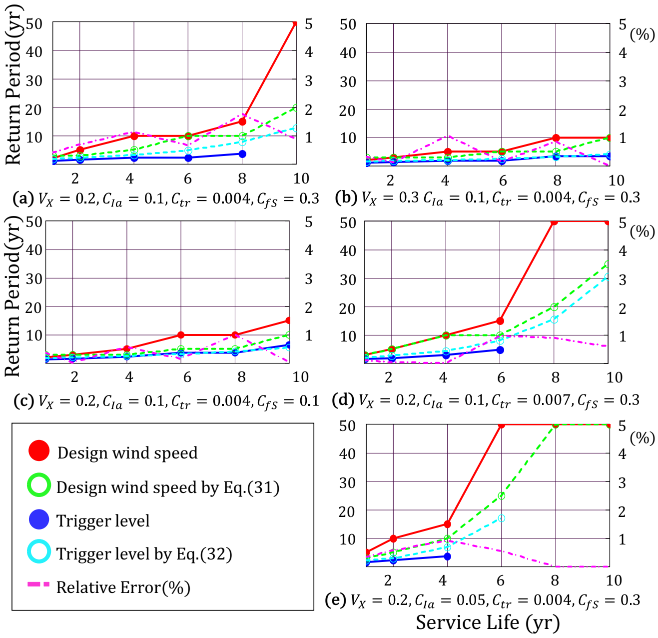


Figure 5: Optimum design wind speed and trigger level (Gumbel dist.)

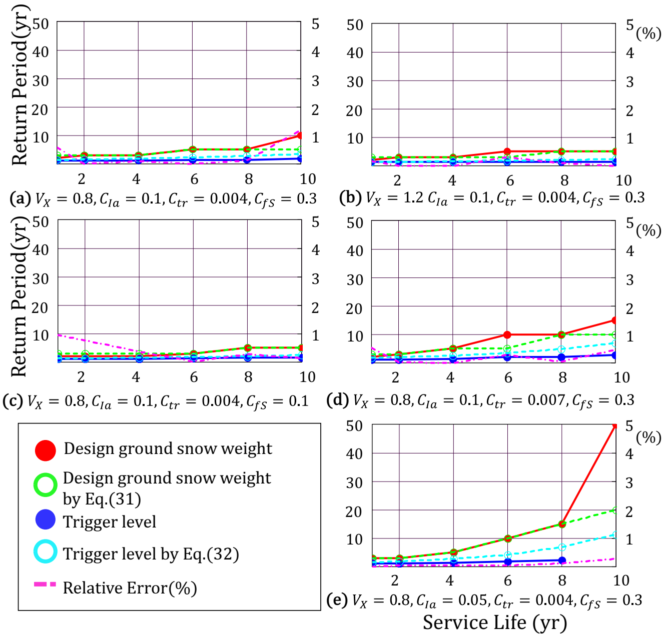


Figure 6: Optimum design ground snow weight and trigger level (Gumbel dist.)

determined on the basis of $r_p = 5$ years, $t_L = 1$ year, $C_{fS} = 0.3$, and $C_{tr} = 0.001$. When x_{tr}/x_d is up to 0.8, $C_{fU} \cdot P_{fU}$ is nearly constant, indicating that the same safety level as that of an ordinary building is achieved. By contrast, $C_{fS} \cdot P_{fS}$ starts to increase when x_{tr}/x_d is about 0.6. Because C_I is constant, x_{tr} that minimizes the sum of these three costs yields the minimum expected total cost. The optimum x_{tr} in this example is about 70% of x_d.

Fig.4 shows the expected total cost, C_T, using the same probability model considered in Fig.3 but with various design wind speeds, which are determined on the basis of r_p = 2, 5, 15, 25, 35, or 45 years. C_{Ia} for the initial cost is assumed to be 0.1. It can be found in the figure that a design wind speed of $r_p = 15$ years and a trigger level of $x_{tr} = 0.85x_d$ yield the minimum total expected cost.

Figs.5 and 6 show the optimum design wind speed and ground snow weight, respectively on a Kigen-tsuki Building with a service life, t_L. The associated trigger levels are also presented in the figures. Here, it is assumed that the COV of the annual wind speed is equal to 0.2 or 0.3, the COV of the annual ground snow weight is equal to 0.8 or 1.2, $V_R = 0.1$, $V_{tr} = 0.1$, $C_{Ia} = 0.1$ or 0.05, $C_{tr} = 0.004$ or 0.007, and $C_{fs} = 0.1$ or 0.3. x_d and x_{tr} are expressed in the corresponding return period (years) and indicated by ● and ■, respectively. Because PPC is not conducted when the optimum design load is based on the 50-year recurrence value, the optimum trigger level is not shown. Compared with the basic case in Figs.5(a) and 6(a), the optimum design load decreases when V_X is large [Figs.5(b) and 6(b)] or C_{fS} is small [Figs.5(c) and 6(c)]. By contrast, when C_{tr} is large [Figs.5(d) and 6(d)], not only the optimum design load but also the trigger level increases. This is because the priority here to reduce the cost of PPC than the risk of exceeding serviceability limit state. When C_{Ia} is small [Figs.5(e) and 6(e)], the optimum design load increases, because C_I can not be reduced significantly even if the design load is reduced. In the case of the snow load in Fig.6, the design load reduction rate is larger than the wind load because the COV of the ground snow weight is larger than that of the wind speed and the period during snowfall is as short as 90 days.

4. FORMULAE OF OPTIMAL DESIGN LOAD AND TRIGGER LEVEL

In order to determine the optimum design wind load and snow load, it is necessary to estimate the limit state probability, which is not an easy task for ordinary structural engineers. On the basis of the results presented in Section.3.2.3, the following approximation formulae are proposed to evaluate the return period of the design wind speed or ground snow weight, $\widehat{r}_p$ and that of the trigger level, $\widehat{r}_{p_{tr}}$.

$$\widehat{r}_p = \exp\left(\frac{\ln 50 - 1}{k} \cdot t_L + 1\right) \tag{31}$$

$$\widehat{r}_{p_{tr}} = k_{tr} \cdot \widehat{r}_p \tag{32}$$

where

$$k = \exp(a) \cdot V_X^b \cdot \exp(cV_{tr}) \cdot C_{tr}^d \cdot C_{fS}^e \cdot C_{Ia}^f \tag{33}$$

$$k_{tr} = 0.85 + \exp(-8V_X - 0.8) - \exp(-327C_{tr} - 1.34) \tag{34}$$

where a, b, c, d, e, and f are parameters shown in Table 5, which depend on the type of distribution of the annual maximum values and type of load. The design load and trigger level estimated by Eqs.(31) and (32) are indicated by ○ and □, respectively, in Figs.5 and 6. The resulting error in the expected total cost using Eqs.(31) and (32), $\widehat{C}_T$, defined by the following equation is indicated in the figures by a dashed-dotted line using the axis on the right.

$$\varepsilon = \frac{\widehat{C}_T}{C_T} - 1 \tag{35}$$

where C_T is the expected total cost by a rigorous analysis. Although the optimum design load largely varies depending on the cost model and the probability characteristics of the wind speed and ground snow weight, in any case, the error in the estimation of the total expected cost is about 1% or lower.

5. CONCLUSION

The evaluation method of the limit state probability of a Kigen-tsuki Building when minimizing the expected total cost was presented. Simple formulae were proposed to determine the optimum design wind speed, ground snow weight, and trigger level as a function of the variability in wind speed, ground snow weight, service life, cost of PPC, losses owing to the exceedance of the serviceability limit state and the slope of the initial cost. The error in the expected total cost estimated using the proposed formulae was within 1%. By using this method, it is possible for structural engineers to plan Kigen-tsuki Buildings at an appropriate performance level without complicated probability calculations.

Table 5: Parameters of Eq.(33)

Load	cdf	a	b	c	d	e	f
Wind	Gumbel	4	1.5	-3.6	-0.5	-0.4	0.9
	Frechet	5.2	1.9	-3.6	-0.4	-0.5	0.9
Snow	Gumbel	1.5	0.8	-1.5	-0.7	-0.3	1

6. REFERENCES

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