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Adaptation of residential houses to increasing wind hazard under climate change

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ABSTRACT: Adaptation of wind-resistant performance of residential houses to increasing wind hazard under climate change is considered in this paper. As wind risk reduction measures, "upgraded repair" undertaken after damage is considered in addition to usual renewal and retrofit, which is normally undertaken before damage. For the purpose to investigate the effectiveness of these measures, a recursive formula is proposed to compute the temporal changes of the distribution of the resistance and the probability of failure. The proposed formula can accommodate the mind of house owners toward upgrading repair after damage as well as the rate of renewal and retrofit. A simple example is presented to demonstrate the use of the formula considering the wind risk of residential houses in Japan focusing on damage to roofing, which is the most common type of wind damage in Japan.

1. INTRODUCTION

1.1. Background

Adaptation to climate change has become a central issue all over the world. Japan is facing increasing wind damage to residential houses due to the impacts of more frequent intensified typhoons, see Figure 1. However, the adaptation of residential houses is not straightforward because of multiple reasons: Nishijima et al. (2022) conducts a questionnaire survey after Typhoon Faxai (2019) and revealed several reasons. One of the reasons is that the damage to houses by wind in Japan typically do not extend to total or structural failures and thus the damaged houses are repaired to as those were; hence, no increase of wind-resistant performance is anticipated. Another reason is that wind damage in Japan rarely involves fatality, which may less motivate house owners to retrofit vulnerable houses. Other reason is that most of houses are insured, which less motivates owners to retrofit. Consequently, wind vulnerable houses tend to remain wind vulnerable.

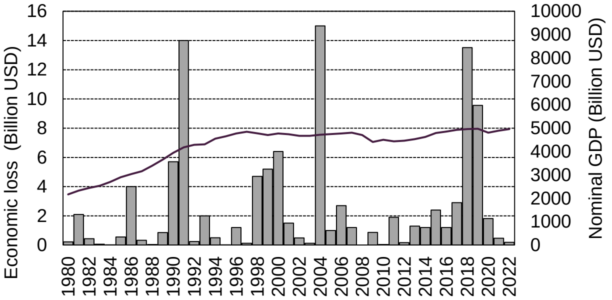

Figure 1: Economic losses due to typhoon in Japan (based on Munich Re until 2017, and The General Insurance Association of Japan thereafter.)

For the purpose to enhance the upgrading of wind vulnerable houses, the first author has proposed a "insurance" scheme and the group of the authors have investigated possibilities and challenges of the scheme. The proposed scheme is a strategy that supports upgrading of the building part that received damage. Hereafter, it is called "upgraded repair" strategy.

1.2. Objective and structure of this study

This study investigates the effectiveness of upgraded repair under various scenarios and conditions. Furthermore, effects of usual renewal and retrofit are considered.

The structure of this study is as follows: First, a recursive formula for computing temporal changes of the distribution of resistance and the probability of failure is proposed. Then, regional wind vulnerability models for residential houses are built based on existing literature on wind vulnerability as well as exposure data available; a simplified wind hazard model is developed based on the wind hazards implied in the design code of Japan and a wind pressure database. On these bases, assuming (a) several scenarios on the change of the wind hazard due to climate change, (b) the minds of the owners toward upgraded repair and (c) background renewal and retrofit of existing houses, the changes of the wind risk (the probability of failure) over time are calculated and the results are analyzed.

2. METHODOLOGY

2.1. Probability of failure

Typical wind damage of houses in Japan is damage to roofing. Therefore, this study considers only damage to roofing. The failure of roofing can be generally defined as:

$$M = R < S \tag{1}$$

where M is safety margin, R is resistance of roofing and S is wind load to roofing. Detachment of the roofing, which is a common failure mode in Japan, is considered here. The wind load is written as:

$$S = C_f \frac{1}{2}\rho(E_R V)^2 \tag{2}$$

where C_f is the absolute value of the negative peak wind force coefficient, ρ is air density ($\approx$1.2kg/m^3), V is the basic wind speed and E_R is the factor that converts the basic wind speed to the one considering surrounding conditions and building height. Note that the resistance and the wind load are dependent on the location (such as verge, eave etc.) in the roof; however, in this study, a representative resistance and a representative wind load are considered as defined later.

The probability of failure is calculated as:

$$P_F = P[M < 0] = P[R < S] \tag{3}$$

Due to deterioration and renewal/retrofit of roofing materials and climate change, the resistance, the wind load and hence the probability of failure are time dependent. In order to signify this, the subscript t is used in the following where relevant. Taking the wind speed V as annual maximum wind speed, P_F corresponds to the annual probability of failure and the unit of the time t is thus year.

2.2. Temporal change of resistance distribution

In case where the entire roofing is replaced with a new roofing after partial/entire damage to the roofing, the distribution of the resistance of roofing generally changes over time. The change of the distribution is expressed as:

$$F_{R,t+1}(r) = \widetilde{F_R}(r)P_{F,t} + F_{R,t}(r)\left(1 - P_{F,t}\right) \tag{4}$$

Here, $F_{R,t}(r)$ is the cumulative distribution function of the resistance R at time t. $\widetilde{F_R}(r)$ is the cumulative distribution function of the resistance of the new roofing. Given that the rate of the upgrading of roofing after damage is α, the cumulative distribution function of the resistance at R at time $t+1$ is written as:

$$F_{R,t+1}(r) = \left\{\alpha\widetilde{F_R}(r) + (1-\alpha)F_{R,t}(r)\right\}P_{F,t} + F_{R,t}(r)\left(1 - P_{F,t}\right) \tag{5}$$

2.3. Deterioration of resistance

Assuming the deterioration rate of the resistance is β, the cumulative distribution function of the resistance R in case of no roofing damage; i.e., no replacement, is expressed as:

$$F_{R,t+1}(r) = F_{R,t}\left(\frac{r}{1-\beta}\right) \tag{6}$$

Thus, equation (5) describing the temporal change of the resistance distribution is revised as follows:

$$F_{R,t+1}(r) = \left\{\alpha\widetilde{F_R}(r) + (1-\alpha)F_{R,t}\left(\frac{r}{1-\beta}\right)\right\} \times P_{F,t} + F_{R,t}\left(\tfrac{r}{1-\beta}\right)\left(1-P_{F,t}\right) \tag{7}$$

2.4. Background renewal and retrofit

Renewal due to obsolescence and retrofit before wind damage are assumed to take place in accordance with the current resistance of roofing. Namely, the renewal/retrofit rate is assumed to be modeled depending on the resistance r as:

$$g(r) = exp\left(-\tfrac{r}{\delta}\right) \tag{8}$$

where the parameter δ represents the difference of the renewal/retrofit rate for different resistance. The fraction ϵ_t of the house stock that is renewed or retrofitted at time t is calculated as:

$$\epsilon_t = \int_0^\infty g(x)f_{R,t}(x)dx \tag{9}$$

where $f_{R,t}(r)$ is the probability density function of the resistance R at time t and is equal to $dF_{R,t}(r)/dr$. The cumulative distribution function of the resistance of the renewed or retrofitted roofing is denoted by $\widehat{F_R}(r)$. Finally, the temporal change of the distribution of the resistance is obtained by revising equation (7) as:

$$F_{R,t+1}(r) = \left\{\alpha\widetilde{F_R}(r) + (1-\alpha)F_{R,t}\left(\frac{r}{1-\beta}\right)\right\} \times P_{F,t} + \left\{\epsilon_t\widehat{F_R}(r) + \int_0^r (1-g(x))f_{R,t}(x)dx\right\} \times \left(1-P_{F,t}\right) \tag{10}$$

2.5. Increase of wind load due to climate change

Assuming the increase rate of the annual maximum wind speed is γ, the temporal change of the cumulative distribution function of the annual maximum wind speed V is written as:

$$F_{V,t+1}(v) = F_{V,t}\left(\tfrac{v}{1+\gamma}\right) \tag{11}$$

Note that the cumulative distribution function of the wind load S is obtained as:

$$F_S(s) = F_V\left(\sqrt{\tfrac{2s}{C_f\rho}}/E_R\right) \tag{12}$$

Based on the above formulation, it is possible to compute the temporal change of the annual probability of failure of a representative house due to wind, which can be translated into the expected number of houses with roofing damage to total number of house stock.

In the following sections individual modeling is explained and the parameter values assumed in this study is summarized in Table 1 in Section 6.

3. WIND HAZARD MODELING

The wind load is modeled according to equation (2). The annual maximum wind speed is modeled for each of 47 prefectures in Japan in order to take into account the difference of the wind hazard. The Building Standard Law of Japan (BSLJ) specifies a basic wind speed in terms of 10-minute sustained wind speed at 10-meter height for a standard surrounding condition, which approximately corresponds to 50-year return period wind speed. Assuming that 500-year return period wind speed is 1.25 times of the 50-year return period wind speed and the annual maximum wind speed follows the Gumbel distribution, the cumulative distribution function $F_S(s)$ is determined. In order to account for the impact of possible climate change on wind hazard, the parameter γ is introduced in equation (11). In this study, three scenarios are considered to investigate the sensitivity of the wind hazard change on the future wind risk; i.e., $\gamma = 0, 0.001, 0.002$.

The basic wind speed is converted into the wind speed for residential houses considered in this study. The considered houses in this study is assumed to locate in urban areas, which is categorized as surface roughness category III of BSLJ and the height of the houses is assumed to be 7 m. Thus, $E_R = 0.74$ according to BSLJ.

The wind force coefficient C_f is a characteristic wind pressure normalized with a reference wind velocity pressure, and is generally a random variable; however, often a deterministic value is used in wind resistant design and risk analysis. In this study, a deterministic value is assumed. The wind force coefficient depends on roof shape (hip, gable etc.) and differs at different locations on a roof. To simplify the analysis, this study assumes a representative peak wind force coefficient, and $C_f = 2.5$. Note the corresponding wind speed used for calculating wind velocity pressure is 10-minute sustained wind speed.

4. VULNERABILITY MODELING

The resistance of roofing depends, among others, on roofing material, construction method, and construction year. The distributions of the resistances of roofing are evaluated for different combinations of the abovementioned parameters by Okada and Kikitsu (2005). The ratios of the roofing materials used differ in different areas of Japan. The detailed statistics of the ratios appear not available. Therefore, this study relies on the statistics on the ratios obtained through a survey by Japan Housing Finance Agency (1999), which is based on questionnaire survey to house owners who used loan provided by Japan Housing Finance Agency. Combining these two, the distributions of the resistances in different prefectures are estimated in terms of distribution $F'_R(r)$. It should be noted that the distributions obtained in this manner have significant probabilities at lower tails, which is not realistic. Therefore, the distribution is truncated at $r = r^*$, and the probability in $r \leq r^*$ is redistributed to $r > r^*$; i.e.

$$F_{R,1}(r) = \begin{cases} 0, & r \leq r^* \\ \frac{F'_R(r) - F'_R(r^*)}{1 - F'_R(r^*)} & r > r^* \end{cases} \tag{13}$$

Here, $r^* = 500$ [Pa] is assumed. $F_{R,1}(r)$ is adopted as the initial distribution of the resistance in the simulation.

Deterioration rate β differs for different types of roofing materials, construction quality etc., and is difficult to estimate. In this study, $\beta = 0, 0.01$ is assumed.

5. ADAPTATION STRATEGY

The rate α of the upgrading of roofing after damage reflects the mind of house owners toward the upgraded repair. In this study, four scenarios with respect to the rate are considered, i.e., $\alpha = 0, 0.1, 0.5, 1$. The cumulative distribution function $\widetilde{F_R}(r)$ of the resistance after upgrading repair is assumed to follow the lognormal distribution with the median of 3500 [Pa], which roughly corresponds to the resistance in case up-to-date roofing construction methods are adopted. The coefficient of the variation is assumed to be 0.3.

The renewal/retrofit rate δ reflects macroscopic conditions such as economy and technological development as well as microscopic conditions such as deterioration degree or construction quality of individual houses. The renewal/retrofit rate δ can also be, to certain degree, controlled by political interventions such as subsidies to retrofit. In this study, $\delta = 500$ is considered. Also, the case of no renewal/retrofit (i.e., $\delta \to 0$) is considered as reference. The cumulative distribution function $\widehat{F_R}(r)$ of the resistance after renewal or retrofit is assumed to have the same distribution as the one after the upgraded repair; i.e., $\widehat{F_R}(r)$ is identical to $\widetilde{F_R}(r)$.

6. SIMULATION OF FUTURE WIND RISK

6.1 Simulation condition and cases

Future wind risk is simulated in terms of probability of failure for each of the prefectures in Japan except for Hokkaido and Okinawa. The distributions of wind load and resistance are different in different prefectures due to e.g. different frequencies of impact of typhoons and different practices of roofing construction methods. In this paper, the results are shown for prefectures (A: Aomori, B: Osaka and C: Kagoshima). These three prefectures have different characteristics both in wind hazard and resistance. The wind hazard is same in Aomori and Osaka (34 m/s) according to BSLJ, and is higher in Kagoshima (38 m/s). The resistance is in overall higher in Aomori, reflecting that majority of the roofing is either slate or metal. The parameters assumed in the simulation are listed in Table 1.

The initial cumulative distributions $F_{R,1}(r)$ of the resistances at time $t = 1$ for three prefectures (Aomori, Osaka and Kagoshima) are illustrated in Figure 2. In Figure 2, the renewal/retrofit rates $g(r)$ are also illustrated in case of $\delta = 500$. The fractions ϵ_t of the house stock that is renewed or retrofitted at $t = 1$ are calculated as 0.0043, 0.035 and 0.055 respectively. The initial cumulative distributions $F_{S,1}(s)$ as well as its change over time are illustrated in Figure 3.

Temporal change of the cumulative distribution function of a representative residential house is computed based on equation (9). Then, temporal change of the probability of failure of the house is computed together with the distribution of the increasing wind load represented by equations (10) and (11).

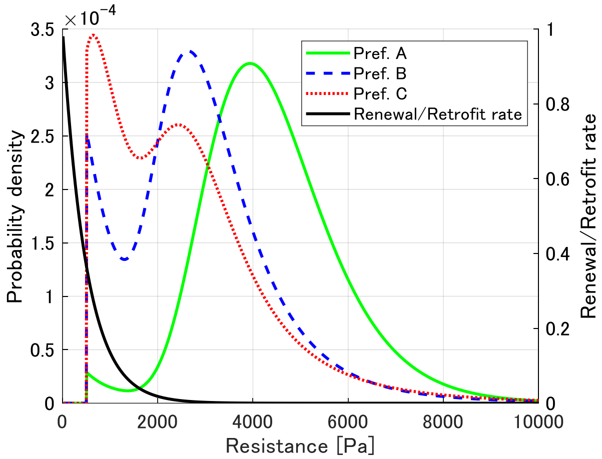

Figure 2: Initial distributions of resistance for three prefectures and renewal/retrofit rate.

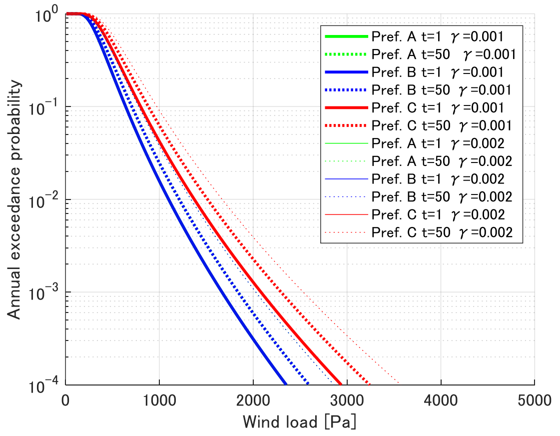

Figure 3: Distributions of wind load at $t = 1, 50$ year for three prefectures in case of γ =0.001,0.002.

Table 1: Parameters assumed in simulation.

Rate of upgrading	$\alpha = 0, 0.1, 0.5, 1$
Wind hazard change	$\gamma = 0, 0.001, 0.002$
Conversion factor	$E_R = 0.74$
Wind force coefficient	$C_f = 2.5$
Lower bound of resistance	$r^* = 500\ [Pa]$
Deterioration rate	$\beta = 0, 0.01$
Renewal/retrofit parameter	$\delta = 500\ [Pa]$ $\delta \to +0\ [Pa]$

6.2 Simulation results and discussion

The case of $\gamma = 0$, i.e. no wind hazard increase due to climate change, is first considered. The sensitivity of the three parameters α, γ and δ on the temporal change of the probability of failure is analyzed. The reference case is: $\alpha = 0.5$, $\beta = 0$, $\delta \to +0$.

The sensitivity of house owner mind toward upgraded repair on the temporal change of the probability of failure is illustrated in Figure 4, i.e., cases of $\alpha = 0, 0.1, 0.5, 1$ are shown. The probability of failure is, for all over the period, highest at Kagoshima reflecting the assumed highest wind hazard and lowest resistance. At the same time, the upgraded repair is more effective at Kagoshima and the probability of failure is reduced approximately by half after 50 years. On the other hand, the upgraded repair has almost no effect on the probability of failure at Aomori. This is due to that the chances of upgraded repair are rarer due to the original small probability of failure. As expected, the reduction of the probability of failure is higher for larger value of α; however, the rate of the reduction is smaller for the prefectures whose probability of failure is smaller.

The sensitivity of the deterioration of the resistance on the temporal change of the probability of failure is illustrated in Figure 5, i.e., β =0,0.01. As can be seen in the figure, the effect of the deterioration rate on the temporal change of the probability of failure is of minor.

The impact of the assumed renewal/retrofit on the temporal change of the probability of failure is illustrated in Figure 6. The impact of the renewal/retrofit is significant: The probability of failure is reduced by the order of the magnitude of 10^2 after 50 years. However, in order to achieve such renewal/retrofit accompanies significant cost. As an example, the expected fraction of the number of houses with the upgraded repair in Osaka at $t = 1$ is equal to $P_{F,1} \times \alpha = 8.5 \times 10^{-3} \times 0.5 = 4.25 \times 10^{-3}$. On the other hand, the expected fraction of them with the renewal/retrofit is equal to $\left(1 - P_{F,1}\right) \times \epsilon_1 \approx 1 \times 0.035 = 3.5 \times 10^{-2}$, which is approximately eight times higher; consequently, the total cost is eight times higher, assuming that the cost for upgraded repair and the cost for renewal/retrofit are identical.

Finally, the cases of $\gamma = 0.001, 0.002$, i.e., wind hazard increase due to climate change, are analyzed. Figure 7 shows the temporal change of the probability of failure at Kagoshima for $\gamma = 0.001, 0.002$. For reference, the case of $\gamma = 0.001$ is also shown. All the three cases of γ with $\alpha = 0.5$ results in the reduction of the probability of failure over time. However, the cases of $\gamma = 0.001, 0.002$ with $\alpha = 0.1$ results in the increase of the probability of failure. Under the assumptions made in this study, it is demonstrated that the upgraded repair strategy can adapt to the increase of the wind hazard due to climate change given that a certain ratio of house owners adopts the upgraded repair strategy.

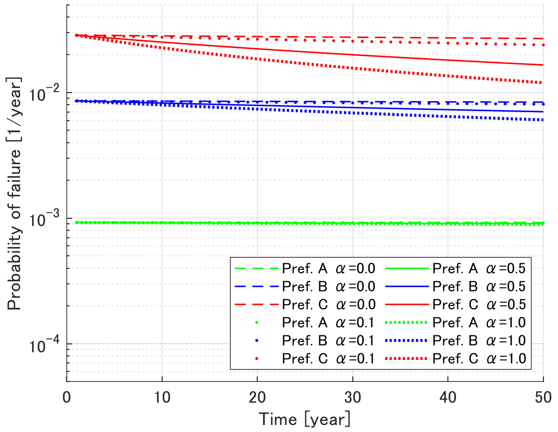

Figure 4: Effect of house owner mind toward upgraded repair on temporal change of the probability of failure at three prefectures.

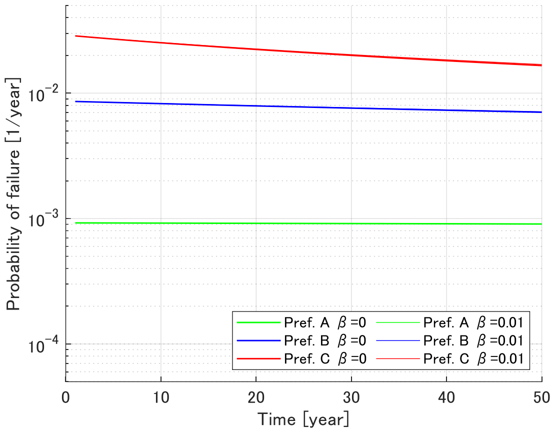

Figure 5: Effect of deterioration of resistance on temporal change of the probability of failure at three prefectures.

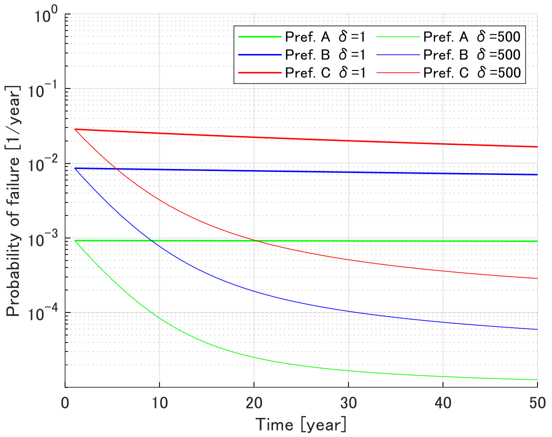

Figure 6: Impact of the assumed renewal/retrofit on temporal change of the probability of failure at three prefectures.

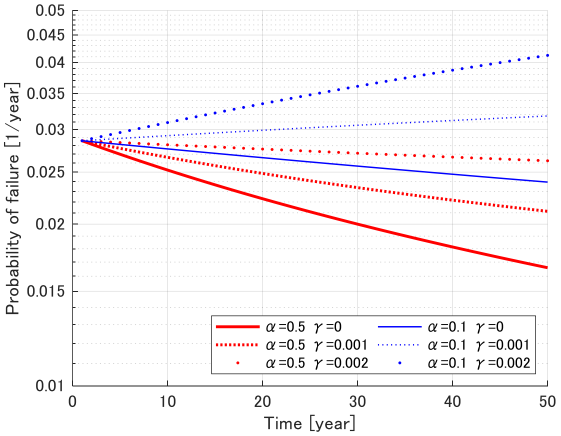

Figure 7: Effectiveness of upgraded repair under future climate change.

7. CONCLUSIONS

This paper considers effective measures for adaptation of residential houses against future increase of wind hazard due to climate change, focusing on damage to roofing. For this purpose, a recurrence formula for updating the distribution of the resistance as well as the probability of failure over time is proposed, considering renewal and retrofit before/after damage. Furthermore, an "insurance" option that covers the cost for not only repair but also upgrading roofing is proposed and its effectiveness is investigated using the proposed recurrent formula.

Under the assumptions made in this study, it is found that the upgraded repair strategy is effective in cases the resistance is low and the wind hazard is high; the probability of failure is reduced by approximately half over 50 years. Impact of the renewal and retrofit is significant; however, it is only possible with significant cost.

The results shown in the study are highly sensitive to the assumption, among others, on the lower tail of the distribution of the resistance. Therefore, it is required to further elaborate the modeling of the lower tail of the resistance in order to obtain a more reliable results on the temporal change of the probability of failure with different adaptation strategy.

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