Quantitative Wind Risk Assessment for Low and Mid-Rise Apartment Buildings
Based on a Probabilistic Model

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Abstract
This study develops a risk assessment model and evaluates wind risk to predict typhoon-induced damage. A wind risk assessment model was developed using the convolution of a wind hazard model and a wind fragility model, and both models were developed using the Monte Carlo simulation based on probability theory. Wind risk was quantitatively evaluated using the window system and part of the exterior materials installed in low and mid-rise apartments. Wind risk was compared according to regional (namely Busan, Daegu, Daejeon, and Seoul), geomorphological (namely topographic factor and exposure category), and morphological factors of buildings (height, roof tilt angle, and number of housing units) in order to evaluate relative influence. By employing the risk assessment model this study compared 432 wind risks and found that the most influential factor was exposure category, followed by the topographic coefficient, building height, target site of assessment, roof tilt angle, and number of housing units (in that order). The wind risk assessment model in this study could be used as basic data for the estimation of damage driven by wind and for the establishment of damage reduction measures, combined with the economic value of apartment buildings’ exterior materials and interior contents.

Keywords: extreme wind risk; wind hazard; wind fragility; Monte Carlo simulation; probabilistic model

1. Introduction

In cases of residential building wind damage attributed to typhoons, public losses of both the economic and human nature are incurred, thus it is necessary to predict and/or mitigate wind damage. Risk assessment techniques against wind damage should be developed in order to estimate the wind damage inflicted on residential buildings. This study aims to develop a wind risk assessment model and quantitatively evaluate wind risk for low and mid-rise apartment buildings, the representative Korean housing type. This study calculated the wind risk model employing both a wind hazard model and a wind fragility model, based on a probabilistic method. Wind hazard was evaluated by applying the Monte Carlo simulation to past meteorological data on typhoons and then typhoon induced strong wind speeds were estimated (Lee et al., 2007a; MPSS, 2015). The wind fragility model was developed using and applying the Monte Carlo simulation to wind load and performance experiment data for apartment window systems (Ellingwood et al., 2004; Lee et al., 2013; Lee et al., 2005; Yun et al., 2015).

Since wind damage to low and mid-rise apartments is concentrated in the window system and part of the exterior materials, wind risk was evaluated based on the window system installed in the apartment balcony. Moreover, this study compared the relative influence that regional, geomorphological, and morphological factors of buildings would have on wind risk. The regional factor was addressed by evaluating four cities (Busan, Daegu, Daejeon, and Seoul), and the topographic factor and exposure category were reviewed under the umbrella of the geomorphological factor. Twelve baseline models were established according to building height, roof tilt angle, and housing unit to evaluate the morphologic effects of buildings.

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2. Theoretical Background

2.1 Wind Risk Assessment Model

The wind risk assessment model can be developed using the convolution of a wind hazard model referring to wind occurrence probabilities and a wind fragility model referring to the failure probability of the given window system. When probability models of wind hazard and wind fragility are independent events, the extreme wind risk model \( R(v) \) can be defined as Eq. (1) (Lee et al., 2013; Lee et al., 2011; Lee et al., 2005; Yun et al., 2015):

\[
R(v) = \int_{0}^{v} g_x(v) \cdot F_v(v)dv
\]

where \( g_x(v) \) denotes wind hazard and \( F_v(v) \) the wind fragility of the window system, respectively.

2.2 Development Method for the Wind Hazard Model

The wind hazard model is developed by constructing the probability distributions of the typhoon’s climatological characteristics and simulating typhoon using the Monte Carlo simulation and then representing a physical model (MPSS, 2015). In this study, past typhoon data from 1951 to 2013 was obtained from best track data from the RSMD (Regional Specialized Meteorological Center), the Tokyo-Typhoon Center. Probability distributions of climatological characteristics and a physical model can be applied as follows (Lee et al., 2011; Lee et al., 2007a; MPSS, 2015):

(1) Probability Distributions of a Typhoon’s Climatological Characteristics

In general, climatological characteristics of a typhoon can be categorized into central pressure depth, distance of closest approach, typhoon translation speed, typhoon translation heading, and the radius of maximum wind (MPSS, 2015).

Distribution of central pressure depth \( \Delta \rho \) can be represented as Weibull distribution as provided in Eq. (2) (Lee et al., 2011; Lee et al., 2007a; MPSS, 2015):

\[
F(\Delta \rho | a, b) = 1 - \exp \left\{ -\left( \frac{\Delta \rho}{a} \right)^b \right\}
\]  

where \( a \) and \( b \) denote the parameters of Weibull distribution which are dependent on the location of interest. For Seoul, -221.7 and 231.7 are obtained as \( a \) and \( b \), while -235.0 and 242.9 are computed for Busan.

Typhoon translation speed \( s \) can be represented as Gamma distribution as provided in Eq. (4) (Lee et al., 2011; Lee et al., 2007a; MPSS, 2015):

\[
F(s|a, b) = \frac{1}{b^a\Gamma(a)} \int_{0}^{s} t^{b-1}e^{-\frac{t}{b}}dt
\]

where \( a \) and \( b \) denote parameters of Gamma distribution, which are 8.9 and 1.1 for Seoul, and 6.1 and 1.7 for Busan.

Typhoon translation heading \( \beta \) can be represented as Extreme Value distribution as provided in Eq. (5) (Lee et al., 2011; Lee et al., 2007a):

\[
F(\beta|\mu, \sigma) = 1 - \exp \left\{ -\exp \left( \frac{\beta - \mu}{\sigma} \right) \right\}
\]

where \( \mu \) and \( \sigma \) denote parameters of Extreme Value distribution, which are 232.8 and 38.0 for Seoul, and 230.1 and 38.3 for Busan.

\( R_{max} \), radius of maximum wind, can be represented as provided in Eq. (6) which shows the relationship of central pressure depth and radius of maximum wind (Lee et al., 2011; MPSS, 2015):

\[
R_{max} = -66.19 \ln \Delta \rho + 335.18 \text{ (km)}
\]

where \( \Delta \rho \) is central pressure depth.

(2) Physical Model

This physical model is distinguished as a wind field model and a central pressure model. A wind field model for a typhoon affecting the Korean Peninsula can be evaluated using an extended wind field model of the Batt’s model (Batts et al., 1980; Lee et al., 2007b). The maximum gradient wind speed in the wind field is represented as Eq. (7) (Lee et al., 2011; Lee et al., 2007b; MPSS, 2015):

\[
V_{gx} = K \sqrt{\Delta \rho} - \frac{R_{max}F}{2}
\]

where \( K = \left[ R_{max} \alpha/\rho \right]^{1/2} \) while \( a \) is a coefficient provided in \( dp/dn = \alpha \Delta \rho \), \( \rho \) is the density of atmosphere, \( R_{max} \) is the radius of maximum wind, and \( f \) is the Coriolis parameter, respectively.

At a radius of maximum wind of 10m sea level, the relationship of 10-min average wind speeds and maximum gradient wind speed can be assumed as Eq. (8) (Lee et al., 2011; Lee et al., 2007b; MPSS, 2015):

\[
V(z = 10, r = R_{max}) = 0.865V_{gx} + 0.5s
\]

where \( V_{gx} \) denotes maximum gradient wind speed, and \( s \) is the translation speed of a typhoon.

\( V(z = 10, r) \) represents 10-min average wind speeds at 10m height of sea level at the distance of \( r \), from the typhoon center on the line which is 115° clockwise from the translation heading of a typhoon (MPSS, 2015). \( V(z = 10, r, \theta) \) represents 10-min average wind speed.
speeds at 10m height of sea level at the distance of \( r \), from the typhoon center, on the line which is \( \theta \) away from the line which is 115° clockwise from the translation heading of a typhoon. Therefore, the relationship of \( V(z=10, r), V(z=10, r, \theta) \), and translation heading of typhoon \( s \) can be assumed to be equal to Eq. (9) (Lee et al., 2007b):

\[
V(z=10, r, \theta) = V(z=10, r) - 0.5s(1 - \cos \theta)
\]

where \( s \) denotes typhoon translation speed, and \( \theta \) is the angle from the line which is 115° clockwise from the typhoon translation heading.

A central pressure model can adopt a rising central pressure model by applying the rising effects of central pressure when a typhoon lands at the shore as provided in Eq. (10) (Fujii, 1998; Lee et al., 2007b):

\[
\Delta p(t) = \Delta p_0 \exp(-\alpha_p t)
\]

where \( \Delta p_0 \) denotes central pressure depth at the time of landing, and \( \alpha_p \) is the coefficient representing the rate of rising central pressure, which was -0.065 (Fujii, 1998), and \( t \) is hours in time.

(3) Wind Hazard Caused by Typhoon

Wind speed, calculated by applying typhoon climatological characteristics to the Monte Carlo simulation and thus reflecting the physical model, is represented by Weibull distribution as provided in Eq. (11) (Lee et al., 2011; Lee et al., 2007b), and is evaluated according to return periods as provided in Eq. (12) (MPSS, 2015; Lee et al., 2011). The model of wind hazard accompanying a typhoon, \( g_z(v) \), with the use of Monte Carlo simulation, is calculated as provided in Eq. (13), which is a probabilistic density function of Eq. (11) as follows (Lee et al., 2011; MPSS, 2015):

\[
F(v|a, b) = 1 - \exp\left(-\frac{v^a}{b}\right)
\]

\[
v_T = b[-\ln 1/T]^{1/a}
\]

\[
g_z(v) = \left(a \frac{v^{a-1}}{b^a}\right) \exp\left(-\frac{v^a}{b}\right)
\]

where \( a \) and \( b \) denote parameters of Weibull distribution, and \( T \) denotes return period (Lee et al., 2011; MPSS, 2015).

2.3 The Development Method of Wind Fragility

(1) Establishment of Wind Fragility Functions using the Monte Carlo Simulation

A wind fragility model for a window system with the use of the Monte Carlo simulation is developed by identifying probability distributions of wind load and a window system’s resistance and with repetitive comparison using limit state equation as provided in Eq. (14) (Ellingwood et al., 2004; Lee et al., 2013; Schultz et al., 2010; Yun et al., 2015):

\[
Z = R_w - L_w
\]

where \( Z \) is the margin of safety, \( R_w \) is a window system's probability distribution of resistance performance against wind load, and \( L_w \) is a probability distribution of wind load. This study included failure caused by wind pressure alone and excluded debris-induced destruction. In Eq. (14), \( Z < 0 \) denotes the failure state of a window system. The flow chart for applying Monte Carlo Simulation is shown in Fig. 1.

Since values are selected at random in the probability distributions, the selection results of a high value of wind load and a low value of resistance performance could be analyzed as system failure, but a low value of wind load and a high value of resistance performance could likely be selected in the following analysis, resulting in an increase in uncertainty associated with the inherent randomness of the process. Therefore, the probability of window system failure should be assessed by conducting repetitive comparisons. In this study, 5,000 analyses were performed at a specific wind speed to assess the wind fragility of the window system, as seen in Fig. 1.

Fig. 1. Flow Chart for Monte Carlo Simulation

Apartment window system wind fragility should be evaluated according to a damage state as seen in Table 1. (FEMA, 2010). In Table 1, “%” denotes the percent of the number of destroyed window systems against the total number of window systems in the whole apartment.

Wind fragility, calculated in the form of discrete function, can be a curve fitting in the form of a continuous function by applying log-normal cumulative distribution functions as provided in Eq. (15) (Ellingwood et al., 2004; Lee et al., 2013) and can be built in the database using the parameters of this
probability distribution Eq. (15) and is expressed by:

$$F_r(v) = \Phi \left[ \frac{\ln v - m} {\zeta_R} \right]$$  (15)

where $\Phi$ denotes the standard normal distribution function, $v$ is wind speed, $m$ is the population mean, and $\zeta_R$ is the standard deviation. $m$ and $\zeta_R$ were calculated using the least square method estimating parameters with the least error values through repetitive calculations.

(2) The Evaluation Method of Wind Load Probability Distribution

A probability distribution of wind load, which would be used for the Monte Carlo simulation, was calculated using the revised wind load provision for exterior materials in ASCE 7-10 from which wind load coefficients in Eq. (16) can be obtained (ASCE, 2010; Cope, 2004; Ellingwood et al., 1999; Lee et al., 2013).

$$L_w = \alpha [q_z(GC_p) - q_b(GC_p)] (N/m^2)$$  (16)

where $\alpha$ denotes the removal coefficients of safety factor applied in ASCE 7-10 (ASCE, 2010; Cope, 2004; Lee et al., 2013), $q_z$ is velocity pressure at a certain height ($z$) as provided in Eq. (17), $q_b$ is velocity pressure at mean roof height, $GC_p$ is external pressure coefficient, and $GC_{pi}$ is internal pressure coefficient.

$$q_z = 0.613 K_z K_{zt} K_v V^2 (N/m^2)$$  (17)

where $K_z$ is velocity pressure exposure coefficient, $K_{zt}$ is topographic factor, $K_v$ is wind directionality factor, and $V$ is basic wind speed (ASCE, 2010).

(3) The Evaluation Method for Probability Distribution of a Window System's Resistance Performance

A window system consists of components including glass, metal-bar, metal bracket, and anchor bolt (Kim et al., 2015a; MPSS, 2015). A probability distribution on the window system's resistance performance can be calculated using resistance performance statistics obtained from the component test for each component. However, there is a high level of uncertainty in the prediction of the whole window system's resistance performance directly from the resistance performance statistics of each component.

In this study, statistics of a window system's resistance performance and probability distributions were identified from structural tests on components and mock-ups tests under the KS F 3117 regulation (Kim et al., 2015b) as shown in Fig.2.

3. Assessment Model for Wind Risk

3.1 Assessment Model for Wind Hazard

This study selected four coastal and inland metropolitan cities in Korea – Busan, Daegu, Daejeon, and Seoul – as target sites for a wind hazard assessment. In the four regions, the probability distribution and parameters of wind hazard ($q(v)$) were evaluated based on the use of models for the wind field and central pressure of the typhoon based on the Monte Carlo simulation, as presented in Fig.3. As noted in Fig.3., a higher mode value and wind speed of more than 25m/s occurred more often in Busan than Daegu, Daejeon, and Seoul. Moreover, it is inferred that the wind speed in southern regions (Busan, Daegu, and Daejeon) where typhoons frequently pass through is higher than in Seoul.
The results of the mock-up experiment for obtaining the statistics of resistance of window systems showed that window glass was broken after metal bars were deformed at a yield point. For this reason, this study regarded the yield point of a metal bar at which a window system lost its functionality as the moment of destruction of the window system (Kim et al., 2015a; Kim et al., 2015b). The resistance of a window system was calculated by considering the yield point capacity of a vertical metal bar (displacement of a vertical metal bar: 29.76 mm) as a final wind resistance. The mean value of resistance at the yield point of a window system and the coefficient of variation were 1.22 kPa and 0.11, each, and these statistics were applied to calculation of the resistance probability distribution. The probability distribution of a window system was assumed as a normal distribution. Although the mock-up test results were produced using limited specimens, it may be considered valid to assume that the probability distribution of resistance performance is a normal distribution using the methodologies and results of preceding studies (Lee and Rosowsky, 2005; Ellingwood et al., 2004), as well as the central limit theorem, a statistical theory (Cope, 2004).

The deformation of the vertical metal bars at the yield point in the mock-up test was considered as the state of failure of the window systems in this study. Since it was assumed that the window systems installed in every story of the baseline models were identical, the failure state of the window system was also considered to be the same.

(3) Wind Fragility

The wind fragility developed with the use of Monte Carlo simulation is shown in Fig. 4. The values referred to as symbols ("□", "■", "○", "×") in Fig. 4 represent fragility evaluated using discrete functions by

![Fig.4. Fragility Curves of Baseline Model 5 (Exposure C, Kzt=1.26)](image-url)
increasing the wind speed of 1-80 m/s by 1 m/s on the basis of Monte Carlo simulation. The solid lines were obtained by curve fitting using parameters of the log-normal cumulative distribution function in Eq. (15).

To compare the relative effects of regional, geomorphological, and buildings' morphological wind risk factors, wind fragility was limited to damage state 2. Table 4. presents the parameters of log-normal cumulative distribution across variables of damage state 2 for 12 baseline models. In Table 4., the numbers in brackets refer to the values of baseline models 7-12.

4. Assessment of Wind Risk

Figs.5.-8. show wind risk by regional, geomorphological, and buildings' morphological factors, evaluated by computing the convolution of wind hazard and fragility. In Figs.5.-8., "dot (•)" refers to the risk of wind speed with a return period of 100 years.

The representative graph presented in the wind risk assessment by factor (namely, region, topography, exposure category, and building morphology) indicated in the following section represents the results of only one wind risk assessment by the relevant factor.

Although a total of 432 risk models were analyzed in this study, producing the assessment findings by every $K_{zt}$ and damage state as seen in Fig.8., only part of the results was presented due to lack of space. However, as for the relative comparison on the effects influencing wind risk by factor (as seen in Table 5. in the paper), the three different values of $K_{zt}$ were applied to analyze the regional, and morphological factors of buildings, by comparing all the findings from 432 risk calculations.

4.1 Assessment of Wind Risk by Regional Factor

To assess wind risk according to regional factors, this study selected four cities, Busan, Daegu, Daejeon, and Seoul, and compared the wind risk of each region. To that end, the wind fragility model was used at the condition of baseline model 3, exposure C, and $K_{zt}$ of 1.02.

As shown in Fig.5., the maximum values of wind risk are 1.9%, 1.1%, 0.7%, and 0.5% in Busan, Daejeon, Daegu, and Seoul, respectively. Fig.5. suggests that the wind risk in Busan, which has a higher wind speed distribution than others, is about 3.8 times, 2.7 times, and 1.7 times higher than in Seoul, Daegu, and Daejeon.

4.2 Assessment of Wind Risk by Geomorphological Factors

Fig.6. presents wind risk influenced by wind speed-up resulting from changes in the topographic factor ($K_{zt}$) of 1.00, 1.02, and 1.26. The wind fragility based on baseline model 6 and exposure D was applied to the assessment of wind risk by topographic factors, in which the wind hazard of Daejeon was used. According to Fig.6., the topographic factor of 1.26 involves the maximum strong wind risk of about 4.1%, 2.7 times higher than 1.5% when the topographic factor is 1.00. When the factor is changed from 1.00 to 1.02, the maximum wind risk increases by 1.1 times to about 1.7%. It is inferred that since the rise in a topographic factor results in a higher wind load, this increases the risk level of wind.
Fig.7. shows the comparison of wind risk according to exposure category. The wind fragility applied to this assessment was based on baseline model 11 and $K_z$ of 1.26, and the wind hazard of Daegu was used. Fig.7. shows that the maximum risk was 0.5% at exposure B.

The risk increased 4.6 times to 2.3% and 8.2 times to 4.1% at exposure C and D. This means that the change from B to C through D of exposure category leads to higher wind load, thereby increasing wind risk.

4.3 Assessment of Wind Risk by Buildings’ Morphological Factors

Morphological factors of buildings were classified into building height, roof tilt angle, and number of housing units. For want of space, this section covers the assessment findings according to building height, the most influential among the three factors. The effects of roof tilt angle and number of housing units are described in Section 4.4.

Fig.8. shows the comparison of wind risk by building height. Baseline models 7-9, exposure C, and $K_z$ of 1.02 were applied to this risk assessment, and the wind hazard in Busan was used. As noted in Fig.8., maximum risk varies depending on building height, showing 2.9%, 2.3%, and 1.2% for 15-story, 12-story, and 5-story buildings, respectively. It can be seen that the wind risk for 12-story and 15-story apartments is 1.9 times and 2.4 times higher than in a 5-story apartment.

Such a change in wind risk is caused by wind load, which increases as the velocity pressure exposure coefficient, proportional to building height, rises.

4.4 Assessment of Effects of Each Factor on Wind Risk

This study evaluated the relative effects of regional, geomorphological, and morphological factors of buildings on the maximum wind risk with the use of average values of the maximum risk from the findings of a total of 432 wind risk estimations. Fig.9. shows the assessment findings concerning the maximum wind risk according to regional and buildings’ morphological factors where $K_z$ was 1.26. For want of space, only the findings derived when $K_z$ was 1.26 are presented. Wind risk in the event that $K_z$ is 1.00 or 1.02 can be assessed using the same methods in this study.

Table 5. shows a relative comparison of average of maximum risk by regional, geomorphological, and

![Graph 1: Effects of Building Height on Wind Risk](image)

![Graph 2: Assessment of Maximum Wind Risk for Baseline Models Corresponding to Site and Exposure (Damage State 2, $K_z = 1.26$)](image)
morphological factors of buildings. As noted in Table 5., it was confirmed that exposure category influences the greatest effects on wind risk, which varies depending on regional, topographic, and buildings' morphological factors. The elements with the next greatest effect are listed in the following order: topographic factor, building height, target site of assessment, roof tilt angle, and number of housing units.

While the average maximum wind risk went up by 10.7 times when exposure increased by one level from B to D, it was 4 times higher when $K_e$ was 1.00 than when the value was 1.26. Also, it increased by 3.3 times when a building's height rose to 15 stories from 5 stories, and Busan showed 3.2 times higher average maximum risk than Seoul with the lowest wind risk. Gable roofs have 1.7 times higher average maximum risk than flat roofs. Given that the maximum risk was just 1.1 times higher when the number of housing units was reduced from 8 to 4, it is inferred that the effect of the factor is relatively slight compared to others.

Table 5. Relative Risks Corresponding to Variations of Factors

<table>
<thead>
<tr>
<th>Variation of Factor</th>
<th>Relative risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exposure Category</td>
<td></td>
</tr>
<tr>
<td>B → D</td>
<td>10.7</td>
</tr>
<tr>
<td>B → C</td>
<td>5.3</td>
</tr>
<tr>
<td>C → D</td>
<td>2.1</td>
</tr>
<tr>
<td>Topographic Factor</td>
<td></td>
</tr>
<tr>
<td>1.00 → 1.26</td>
<td>4</td>
</tr>
<tr>
<td>1.00 → 1.02</td>
<td>1.2</td>
</tr>
<tr>
<td>Building Height</td>
<td></td>
</tr>
<tr>
<td>5 → 15</td>
<td>3.3</td>
</tr>
<tr>
<td>5 → 12</td>
<td>2.2</td>
</tr>
<tr>
<td>Site</td>
<td></td>
</tr>
<tr>
<td>Busan</td>
<td>3.2</td>
</tr>
<tr>
<td>Daejeon</td>
<td>1.9</td>
</tr>
<tr>
<td>Daegu</td>
<td>1.5</td>
</tr>
<tr>
<td>Roof Tilt Angle</td>
<td></td>
</tr>
<tr>
<td>0° → 10°</td>
<td>1.7</td>
</tr>
<tr>
<td>Unit per Story</td>
<td></td>
</tr>
<tr>
<td>8 → 4</td>
<td>1.1</td>
</tr>
</tbody>
</table>

5. Conclusions

This study developed a model for assessing wind risk for the window systems of low and mid-rise apartments, an assessment model that has been urgently needed in Korea, with the use of Monte Carlo simulation based on probability theory. This risk assessment model was designed by computing the convolution of wind hazard and wind fragility. From this study, it was confirmed that wind risk can be evaluated quantitatively with use of the developed assessment model. A total of 432 wind risk estimations based on consideration of regional, geomorphological, and buildings' morphological factors were conducted through the newly-developed assessment model, and the relative effects of each variable on wind risk were compared quantitatively. As a result, exposure category, topographic coefficient, building height, target site of assessment, roof tilt angle, and number of housing units were listed in order of influence.

It is considered that the wind risk assessment model in this study can be used as basic data for the purpose of estimating damage caused by wind and establishing damage reduction measures, combined with the economic value of apartment buildings' exterior materials and interior contents. Finally, this study suggests the need to verify this newly developed risk assessment model by comparing it with post-disaster survey data in the future. Also, it is necessary to estimate the impact on a variety of exterior configurations of buildings in future research.

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