World Academy of Science, Engineering and Technology
International Journal of Civil and Environmental Engineering
Vol:10, No:12, 2016

Comparison of Wind Fragility for Window System in the Simplified 10 and 15-Story Building Considering Exposure Category

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***Abstract*—**Window system in high rise building is occasionally subjected to an excessive wind intensity, particularly during typhoon. The failure of window system did not affect overall safety of structural performance; however, it could endanger the safety of the residents. In this paper, comparison of fragility curves for window system of two residential buildings was studied. The probability of failure for individual window was determined with Monte Carlo Simulation method. Then, lognormal cumulative distribution function was used to represent the fragility. The results showed that windows located on the edge of leeward wall were more susceptible to wind load and the probability of failure for each window panel increased at higher floors.

***Keywords*—**Wind fragility, window system, high rise building.

I. Introduction

DURING the past two decades, the progress of concept design on probability-based limit states together with its increased utilization for various material and structural types have been of remarkable interest [1]. It has been widely recognized for probabilistic risk assessment (PRA) to be an effective tool to evaluate risk associated with every life-cycle aspect of structural and nonstructural component. Recent disasters around the world have highlighted the necessity of risk assessment tools for all types of structures after major consequence of economic losses and social disruption in prone areas such as high density regions or metropolitan areas.

Due to climate change, many typhoons have been yearly on the rise and has caused Korea to suffer from economic damage (equivalent to billions of dollars (USD) loss) during these recent years [2], [3] and demonstrated the increasing vulnerability of high rise residential buildings. Although, properly built structures can withstand major earthquakes and typhoons without collapse, the consequent economic losses and social disruptions are still unacceptable. Structural components such as ceiling, piping, windows, etc. were intensely damaged especially in densely built-up area. Thus, the risk and loss assessment tool was required to apply on both main load resistance and accessory components. Many studies use empirical method to derive the fragility function, which is a very important element for risk assessment study [4]. Empirical method uses historical damage data from post-disaster investigation to develop fragility function [5]-[7]. However, this approach is not practical for Korea, where limited post-disaster data exist.

Consequently, the objective of this study was to present a statistical approach to develop fragility for glass window system in high rise residential building. This statistical approach uses Monte Carlo Simulation (MCS) method to generate damage data based on statistical data of resistance capacity and wind loads on acting on window system. The geometry of structure and window system have been simplified to show the effect of building height and window location.

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II. Background of Structural Fragility Function

Fragility is a probability of exceeding any limit state (LS) of a structure, it can be defined as a conditional probability of failure of a structural member or system for a given set of input variables [1]:

$$P[LS] = \sum P[LS|D = x]P[D = x] \quad (1)$$

where D = a random demand on the system (e.g., 3-second gust wind speed, spectral acceleration, flood level), $P[LS|D=x]$ is the conditional probability of LS at given demand x. The hazard is defined by the probability, $P[D=x]$. The conditional probability, $P[LS|D=x]$ is the fragility. Equation (1) can also be expressed in convolution integral form if the hazard is a continuous function of demand x:

$$P[LS] = \int_0^\infty Fr(x)h_x(x)dx \quad (2)$$

where $Fr(x)$ = fragility function of demand x expressed in the form of a cumulative distribution function (CDF), and $h_x(x)$ = hazard function in the form of a probability density function (PDF).

The fragility of a structural system is commonly modeled by a lognormal cumulative distribution function (CDF) [8]:

$$Fr(x) = \Phi\left[\frac{ln(x)-\lambda_R}{\xi_R}\right] \quad (3)$$

TABLE I
DIMENSION AND CHARACTERISTICS OF BASELINE STRUCTURES

Properties	Type 1	Type 2
Plan dimension	10m × 5m	10m × 5m
No. of stories	10	15
Height per stories	3m	3m
Roof type	Flat	Flat
Window dimension	1m × 1m	1m × 1m

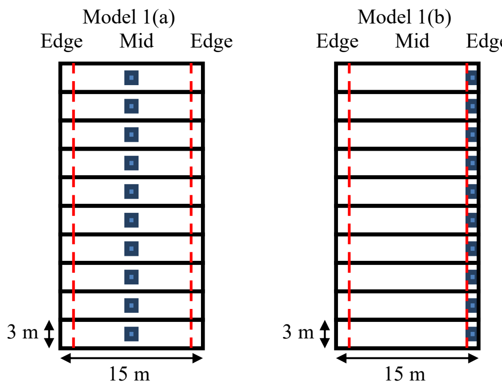

Fig. 1 Dimension and windows layout for 10 stories structure (a) windows in the middle of structure, and (b) windows at the edge zone [9] of structure

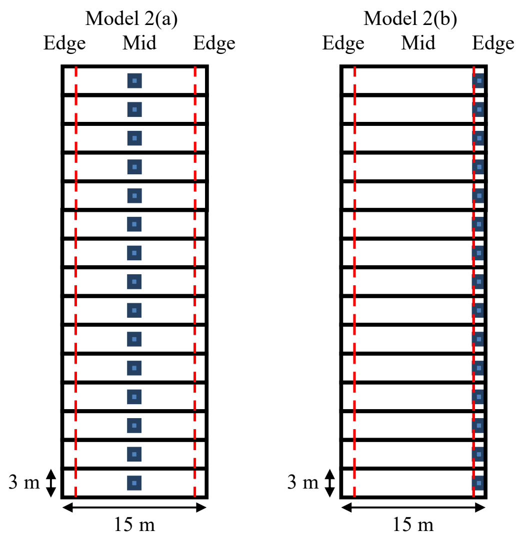

Fig. 2 Dimension and windows layout for 15 stories structure (a) windows in the middle of structure, and (b) windows at the edge zone [9] of structure

in which $\Phi(\cdot)$ = standard normal CDF, λ_R = logarithmic median of capacity R (in units that are dimensionally consistent with demand), and ξ_R = logarithmic standard deviation of capacity R.

III. WIND FRAGILITY FOR WINDOW SYSTEM

A. Baseline Structures Property and Resistance Capacity

Wind fragilities assessment were performed for two simplified residential buildings with an assumption that there was only one window per each floor. The use of these simplified structure was to compare the effect of window location and their height. The result of fragilities function will show these effects, which also depict their performance in the entire structure. Dimensions and detailed properties of structures were shown in Table I; in Figs. 1 and 2, the layouts of the two structure types are described with two different locations of window for each type of structure. These two window' locations have different pressure coefficient, according to ASCE 7 [9].

In this study, no frame failures were modeled, the entire performance of the window system is governed by statistical resistance capacity of glass panel with mean 2.25 kPa and COV 0.25, this probability distribution follows normal distribution function [10].

B. Wind Load Statistics

ASCE 7 [9] defines two types of structural elements subjected to wind load: (1) main wind-force resisting systems (MWFRS), and (2) components and cladding (C&C). For outside windows, they are part of the components and cladding. Wind load pressure acting on this C&C in building with height higher than 18.3 m is as:

$$W = q_z GC_p - q_h GC_{pi} \tag{4}$$

where q_z = velocity pressure evaluated at height z, q_h = velocity pressure evaluated at mean roof height h, GC_p = product of gust factor and external pressure coefficient, and GC_{pi} = product of gust factor and internal pressure coefficient. The velocity pressure evaluated at height z is given by:

$$q_z = 0.613 K_z K_{zt} K_d V^2 \quad \text{(unit: } N/m^2\text{)} \tag{5}$$

where K_z = the velocity pressure exposure factor, K_{zt} = the topographic factor, K_d = the wind directionality factor, V = the basic wind speed in *m/s*.

Table II shows statistical value of these wind load parameters based on [11]. To obtain mean value of this parameters, multiply the mean-to-nominal value with the nominal value in ASCE 7 [9]. COV is coefficient of variation which equal standard deviation value divided by mean value.

TABLE II
SUMMARY OF STATISTICAL WIND LOAD PARAMETERS

Parameters	Category	Mean-to-Nominal	COV	CDF
K_z	Exposure B	1.01	0.19	Normal
	Exposure C	0.96	0.14	Normal
	Exposure D	0.96	0.14	Normal
K_d	C & C	1.05	0.16	Normal
GC_{pi}	Enclosed	0.83	0.33	Normal
	Partially Enclosed	0.92	0.33	Normal
GC_p	Zone 4 (Mid)	0.95	0.12	Normal
	Zone 5 (Edge)	0.95	0.12	Normal
K_{zt}	Deterministic (1)			

C. LS

Failure of window due to wind loads occurs when the combination of internal and external pressures acting on a panel exceed their resistance capacity. The LS function for one window at any floor level could be written in terms of the basic random variables as:

$$f(x) = R - W \quad (6)$$

where R = resistance capacity of glass panel, and W = wind loads acting on the window. Probability of failure of this panel can be defined as:

$$P_f = P(f(x) < 0) \quad (7)$$

where x is velocity of wind used to determine wind loads W in (5) and (6). Hence, the probability of failure is a function of the basic wind speed V squared.

System LS were defined in this study to correspond to four levels of damage: DS1, DS2, DS3, and DS4, it was shown in Table III. Two different cases of window location were considered in this study: (1) middle of structure, and (2) edge of structure, as can be seen in Figs. 1 and 2.

TABLE III
DEFINITION OF DAMAGE STATES

Damage states (DS)	Damage level	Percentage of windows fail
1	Minor	≥ one window
2	Moderate	≥ 10%
3	Severe	≥ 20%
4	Destructive	≥ 33%

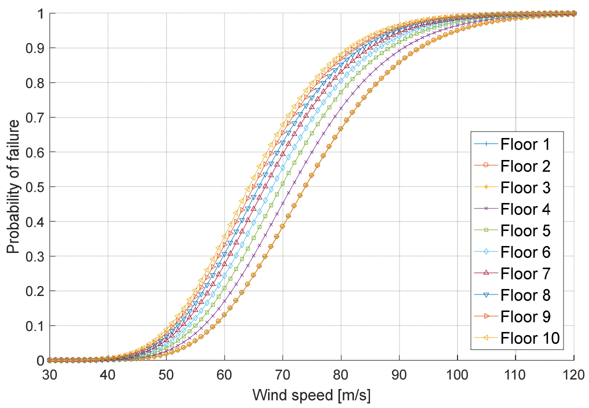

Fig. 3 Probability of failure for window in Model 1(a) structures

D. Calculation of Probability of Failure for a Window at Each Floor

Probability of failure for a window is given by (7). MCS method had been used to simulate probabilistic wind loads (W) and window resistance capacity (R). At each step of wind speed, we generated 10,000 random K_z, K_d, GC_{pi}, GC_p, and glass resistances capacity by sampling from their normal distributions in Table II. Then, we could determine and compare 10,000 different wind loads (W) and window resistance capacities (R). From these 10,000 comparisons, we could determine probability of failure for a window panel. Each windows probability of failure was independent from one to another. Fig. 3 shows this probability of failure for a 10 stories structure where the window' location was in the middle of the building and it was in the windward direction in Exposure B category. It could be observing that window located at higher floor level had the probability of failure increase. This is due to the fact that the parameters K_z in (5) is height dependent [9]. In Fig. 3, from 1st floor to 3rd floor, they had the same probability of failure, because the same value of K_z.

In Fig. 3, a fully enclosed structure was assumed; the structure became partially enclosed when the first window panel failure occurs. The individual window fragility curves were used in the next section to calculate the fragility for complete window system.

E. Calculation of Window System Failure Probabilities

From Fig. 3, a simple system reliability concepts were utilized to construct fragility curves for LS defined by failure of multiple windows in the structure. Assumed statistically independent panel failures, the fragility for the case of less than j windows failure conditioned on wind speed can be written as [1]:

$$F_{system}(N_f \le j|V) = \sum_{i=0}^{j} F_{system}(N_f = i|V) \quad (8)$$

where V = wind speed, N_f = number of failed windows, and $F_{system}(N_f=i|V)$ = failure of i numbers of window and safety of total windows $(n) - i$.

Model 1 and Model 2 had 10 and 15 total windows, respectively. The failure of an individual window at each floor was calculated using the procedure in the previous section (Section III.D.) and then using (8), the system failure probability for each LS at a given wind speed was determined. This procedure repeated for wind speed ranging from 30m/s to 120m/s. Two assumptions were required in this system analysis:

1) Window failure are statistically independent.
2) The internal pressure condition is assumed to be an "enclosed" before the failure of the first window, and "partially enclosed" after the first window fails.

Numerically simulation has been used to facilitate the analysis.

IV. Results

After determining window system failure probability for each step of wind speed from 30 m/s to 120 m/s, Fig. 4 shows that the lognormal CDF from (3) provided a good fit for these fragilities. In the figure, symbols represented the calculated fragility curves while dash-lines were used to represent the lognormal CDFs obtained by maximum likelihood fitting analysis. For the case of Model 1, fragility for DS1 and DS2 had the same result, this was due to 10% of total ten windows was equal to one window, which was the case of DS1. The results for damage state 1 fragility of window system was shown in Table IV.

Fig. 5 shows the comparison of window system fragilities located in the middle of windward wall at different exposure category in damage state 3 (DS3). In ASCE 7-2010, the product of gust factor and external pressure coefficient (GC_p) is depended on location of the component and cladding, in windward wall this coefficient has the same value which resulted in the overlap of blue (square) and red (triangle) line in Fig. 6. However, on the leeward wall, this coefficient does not have the same value which resulted in different probability of failure for yellow (circle) and purple (reverse triangle) line. Moreover, from Fig. 6, windows located in leeward wall are more susceptible to failure than those located on the other side, especially for windows on the edge of the building (purple line). Windward wall is the wall facing where the wind is coming from, and leeward wall is the wall on the downwind side.

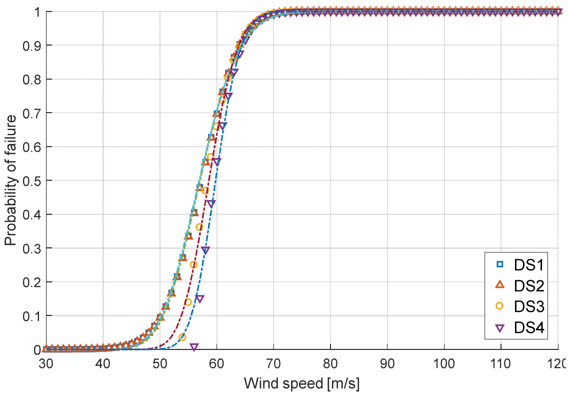

Fig. 4 Lognormal fitted window system fragilities (Model 1 / Exposure B / Middle / Windward)

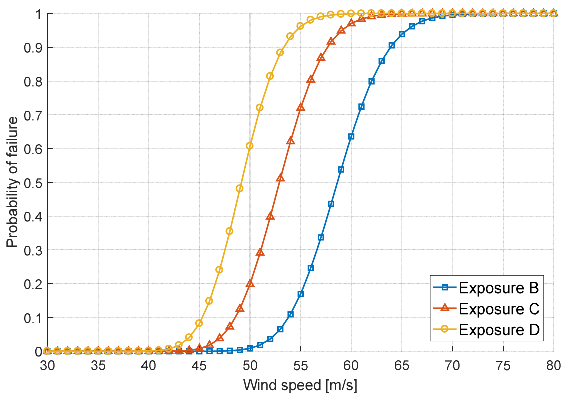

Fig. 5 Comparison window system fragilities for different exposures categories (Model 1 / Middle / Windward / DS3)

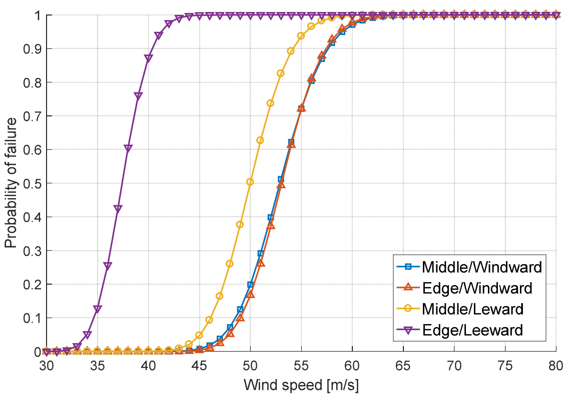

Fig. 6 Comparison of window system fragilities for different window locations (Model 1 / Exposure C / DS3)

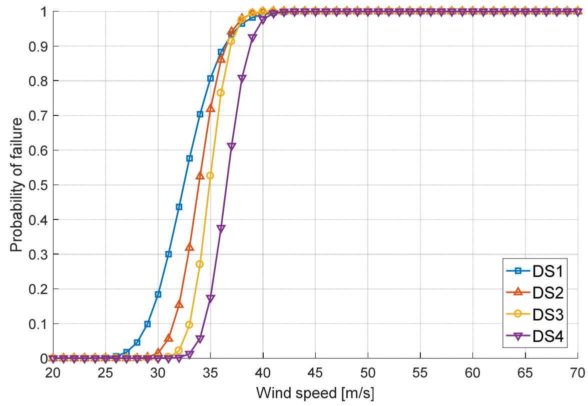

Fig. 7 Comparison window system fragilities for different damage states (Model 2 / Exposure C / Edge / Leeward)

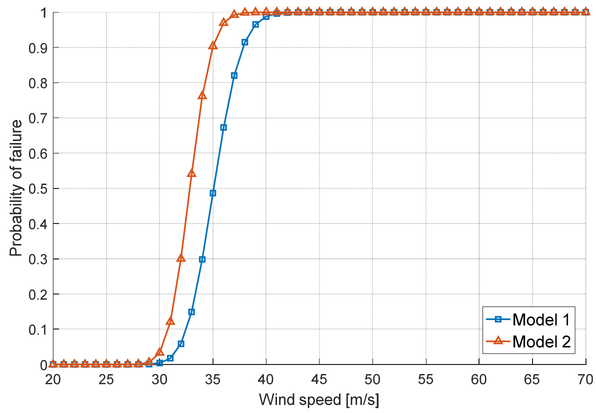

Fig. 8 Comparison window system fragilities for different structure model (Exposure D / Edge / Leeward / DS 3)

TABLE IV
SUMMARY OF LOGNORMAL PARAMETER FOR WINDOW SYSTEM FRAGILITIES

Model	Exposure	Windward		Leeward	
		λ_R	ξ_R	λ_R	ξ_R
1(a)	B	4.040	0.0964	3.972	0.0950
	C	3.942	0.0919	3.881	0.0909
	D	3.867	0.0920	3.816	0.0913
1(b)	B	4.043	0.0946	3.662	0.0959
	C	3.941	0.0919	3.574	0.0905
	D	3.866	0.0926	3.509	0.0905
2(a)	B	3.940	0.0902	3.864	0.0896
	C	3.854	0.0886	3.788	0.0885
	D	3.786	0.0876	3.730	0.0878
2(b)	B	3.940	0.0922	3.554	0.0901
	C	3.852	0.0882	3.481	0.0883
	D	3.785	0.0880	3.424	0.0854

In Model 2, the fragility for DS1 and DS2 showed distinct value (cf. Fig. 7). The effect of structure height was shown in Fig. 8, in this figure the comparison between window system fragilities of Model 1 and Model 2 structure was shown. The window system was located in the leeward wall and at the edge of structure, which was the most critical. In this figure, it could be seen that as the structure get higher they become more vulnerable to wind loads. This is due to the height dependence of parameter K_z, this parameter increased proportionally with the height of structure.

V. Conclusions

This paper shows the development of fragilities for window system in simplified high rise residential building built in high wind region. Two model of structures were studied to comprehend the effect of structure height on their fragility curves. While the geometry of structures was assumed, the methodology in this study could be used for further study to improve the risk assessment framework.

A MCS method had been use for generating wind loads and resistance capacities to determine the probability of failure for each window in an individual floor. Then, the fragilities for window system on the entire building could be calculated by depending on predefined damage states. The result showed that:

1) Windows located at higher floor were more vulnerable to wind loads.
2) Windows located on leeward wall had higher probability of failure, especially windows located on the edge of building.
3) Fragilities for window system for Model 2 (higher building) had higher probabilities of failure than those in Model 1 (lower building), this is due to the combination of higher vulnerable windows (as stated in 1) and higher number of failure possibility.

Acknowledgment

This research was supported by a grant [MPSS-NH-2015-79] through the Disaster and Safety Management Institute funded by Ministry of Public Safety and Security of Korea government.

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