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ORIGINAL CONTRIBUTION

Extreme Wind Fragility Assessment for Window System Failure in Lightweight Steel Frame Structure in Korea

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***Abstract*— The small-scale residential facilities have already reached a high level of damage as the resultant of a clear increase in the number of recent natural disasters. Therefore, disaster prevention, which refers to safety assessment, is extremely important. The new wave of research focuses on the need of enhancing durability and resistance to strong wind of small-scale residential facilities, which requires the safety assessment of their roof, door, and window components. Hence, in this research, we concentrate on defining the initial step in the framework of probability risk assessment of wind loads by developing wind fragility on small-scale residential facilities in South Korea, i.e., the window system installed in a lightweight steel frame house. The study was to develop fragility model using random variables according to the wind loads parameters and the resistance capacity of the window system. Design- and material-based experimental results in typical residential facilities in South Korea provided capacity parameters, i.e., resistance capacity of the window system, which allow us to obtain the failure probability of the window system under various limit conditions and consequently be used to evaluate the vulnerability of windows in this small residential steel house. The study has successfully proved that the most vulnerable is the leeward windows, i.e., opposite to the wind direction.**

***Index Terms*— Light Weight Steel Frame, Monte Carlo Simulation, Wind Fragility**

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I. INTRODUCTION

The construction of lightweight small scale steel frame house in South Korea has remarkably augmented. Within the existing buildings, since the 2000s, approximately 55% was accounted for the small-scale frame structures. Facing extremely rare events, which include earthquake, typhoon, and other disasters, was not generally considered by the contractors in their customary design criteria for these structures. However, it can be seen that the increasing typhoon frequency yearly is now inevitable [1]. In response to this detrimental effect of climate change, the urgency for adaptation and significance of risk assessment subjected to high wind disaster were published in the previous studies. [2] developed statistical wind loads' parameters by means of Delphi questionnaire aimed at enabling a panel of experts in the field to reach consensus [3]. Moreover, the statistical parameters have been extensively used; such as [4], [5], [6] used the parameters in conjunction with design loads guideline [7] to develop wind and seismic fragility for wood frame structure. Furthermore, [8], [9], developed wind fragility for South Korea's structure; their focus was on industrial building and residential apartment type. Consequently, fragility has emerged as a key component of Probability Risk Assessment (PRA) framework and increasingly become one of popular analysis tools over the past decade. In order to evaluate risks associated with every life-cycle aspect of structural and nonstructural components, PRA was utilized as a systematic and comprehensive methodology. Fragility analysis integrated with regional typhoon hazard models can be merged to estimate failure probabilities and develop predictive models for pre- and post-disaster management. In South Korea, to date there has been very limited number of studies on small-scale steel frame structure contrary to the case of high rise and industrial buildings. Despite the fact that properly designed building can withstand extreme events, i.e., typhoon, their components such as windows, doors, and roof cladding will damage and cause leakage or loss of building function. Hence, the aim of this research was to focus on the damage to the component of lightweight small-scale steel frame house, i.e., window system, under the wind pressure acting on the window glass panel [17]. This paper presents a study on the prediction of the wind-induced damage using probabilistic approach. Moreover, this approach used Monte Carlo Simulation (MCS) method that generates damage information for structural window component. To define probability of failure over a range of assigned wind speed, the simulation compares probabilistic wind loads and resistance strength of glass window using the experimental test data performed by [9]. Subsequently, Maximum Likelihood Estimation (MLE) was employed to estimate the fragility parameters, which follows the log normal cumulative distribution function [10]. This approach was highly applicable and recommended for structure with few or non-existing record of failure data.

II. BASELINE STRUCTURE MODEL

A small-scale two-storey steel frame structure used for the study was shown in Fig. 1. The window system was configured into two models:

- Model 1: window only located on south and east sides (10 windows)

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- Model 2: window located on all four sides (20 windows)

Capacity of this window was based on the resistance of glass panel which was derived from experimental data by [9] and design guide [11]. Dimensions of window are 2.1 m × 3.3 m and the statistical resistance capacity following Normal distribution function with the mean value 2.25 kPa and coefficient of variation 0.25.

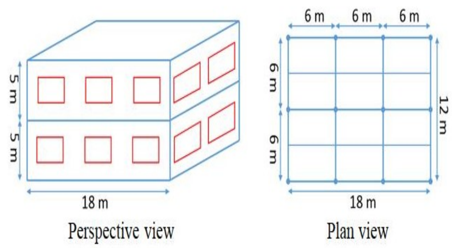

Fig. 1. Dimensions of steel frame structure

III. FRAGILITY ANALYSIS FOR WINDOW SYSTEM

A. Definition of Fragility Function

Wind fragility function shows the relationship between wind intensity, i.e. wind speed, and their corresponding probability of failure. Moreover, based on their development method, there are three types of fragility, which are empirical, analytical, and expert judgement. In this study, the development of fragility was based on analytical method by means of MCS method and based on resistance capacity data and statistical wind loads' data shown in the next section. Generally, the fragility function can be defined as a mathematical function of probability whose variation generated by external excitation reached or exceeded a specified limit state. It is commonly described by lognormal distribution as following [12]:

$$Fr(x) = \phi\left[\frac{In(x) - \mu_R}{\sigma_R}\right] \quad (1)$$

in which, $\Phi(\cdot)$ = standard normal cumulative distribution function, μ_R = logarithmic median of capacity R (in units that are dimensionally consistent with demand), and σ_R = logarithmic standard deviation of capacity R.

B. Limit States

When the applied wind loads exceed the resistance capacity of glass, the failure of window occurs. This is the limit state considered in this study which can be seen below:

$$g(x) = R–W \quad (2)$$

Where, R = resistance capacity of the glass panel, W = combination of internal and external wind pressure projected on window surface. Failure of each window can be defined as a condition where $g(x) < 0$. Additionally, to account for the system of window in each configuration model, four damage states corresponding to the number of window failures were defined as shown in Table I as per recommendations by [13, 14, 15, 16]. These damage states considered the probability of failure from each window and made a random combination to determine probability of failure for all possible failure combinations per percentage of window failure in each damage state.

TABLE I
DEFINITION OF DAMAGE STATES

Damage State (DS)	Damage Level	Percentage of Windows Fail
1	Minor	≥ one window
2	Moderate	≥ 10%
3	Severe	≥ 20%
4	Destructive	≥ 33%

C. Wind Load Statistics

Window or wall subjected to wind loads follow the provision of [7] design guideline for component and cladding. In this case of study, low rise provision was followed, wind pressure can be determined as below:

$$F = q_h(GC_p\text{-}GC_{pi}) \qquad (unit : N/m^2) \quad (3)$$

where, q_h = velocity pressure evaluated at mean roof height h, GCp = external pressure coefficient, and $GCpi$ = internal pressure coefficient. The velocity pressure evaluated at height z in ASCE 7 (2010) (Eq. 4) is given by:

$$q_z = 0.613K_zK_{zt}K_dV^2 \qquad (unit : N/m^2) \quad (4)$$

where, q_h is equivalent to q_z at height h, K_z = velocity pressure exposure factor, K_{zt} = topographic factor, K_d = wind directionality factor, and V = basic wind speed in (m/s) (3-second gust wind speed at 10m and in open terrain).

Summary of wind loads statistics used in this study was shown in Table II. The statistics of K_z, GC_{pi}, and GC_p were obtained from previous Delphi study of wind parameters [2], [4]. The information was used to calculate mean-to-nominal and COV; sequentially, used for determining mean and Standard Deviation (SD) of each parameter from nominal value in [7].

TABLE II
SUMMARY OF WIND LOAD PARAMETERS' STATISTICS

Parameter	Category	Mean-to-Nominal	COV	Nominal	Mean	SD
k_z	Exposure B	1.01	0.19	0.72	0.73	0.14
	Exposure C	0.96	0.14	1.00	0.96	0.13
	Exposure D	0.97	0.14	1.18	1.14	0.16
k$_d$	C&C		deterministic (1.0)			
k$_{zt}$		deterministic (1.0)				
GC$_{pi}$	Enclosed	0.83	0.33	0.18	0.15	0.05
	Partially Enclosed	0.92	0.33	0.55	0.46	0.15
GC$_p$	Zone 4	0.95	0.12	-1.1	1.05	0.13

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IV. RESULTS AND DISCUSSION

A. Probability of Failure for each Window

MCS 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, GC_{pi}, GC_p, and glass resistance capacity by sampling from their normal distributions. Therefore, we could determine and compare 10,000 different wind loads (W) and window resistance capacities (R) following the limit state in Eq. 2. Thus, probability of failure was obtained for a window panel. Each window's probability of failure was independent from one to another. Fig. 2 and Fig. 3 show fragility curve for window in first and second floors located on the windward and leeward wall, respectively. Windward and leeward walls mean a wall on the side facing the wind and a wall on the side sheltered or away from the wind, respectively. Furthermore, it could be observed that windows located on the leeward wall were more critical as can be seen from the parameters representing the fragility curve μ and σ [12].

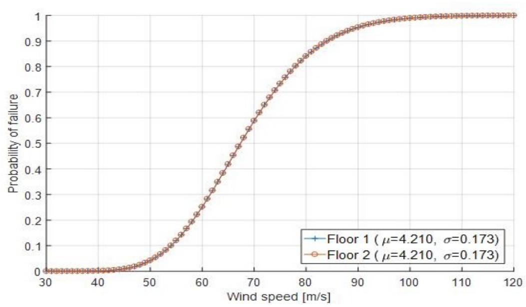

Fig. 2. Fragility curve of each window in windward wall

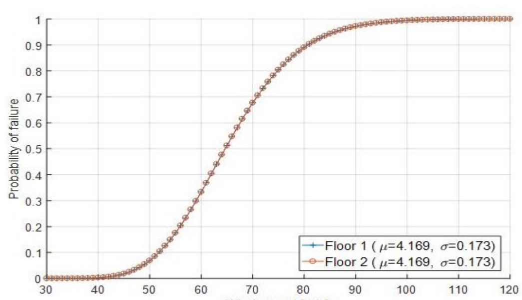

Fig. 3. Fragility curve of each window in leeward wall

B. Fragility for Window System

Following the result from each window panel probability of failure in the previous section and damage states defined above, fragility for each configuration model was determined following Eq. 5 below [4]:

$$F_{system}(N_f \leq j|V) = \sum_{i=0}^{j} F_{system}(N_f = i|V) \qquad (5)$$

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

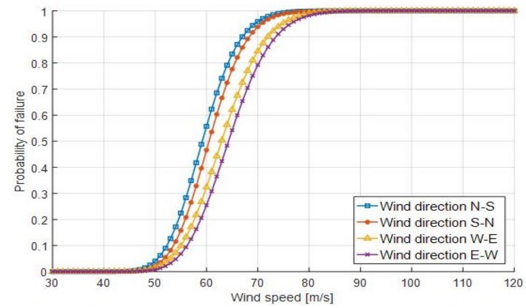

Fig. 4. Model 1 window system fragility in DS1 and exposure B with different wind direction

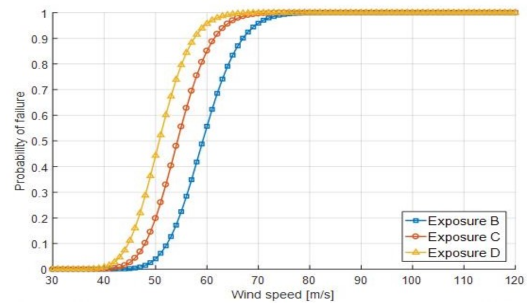

Fig. 5. Model 1 window system fragility in DS1 and wind direction N-S with different exposure category

Fig. 4 shows the result for window system fragility with at least one window fail in exposure B, which is urban area, for different wind direction. Since Model 1 was not symmetry, window only located on south and east sides. Thus, the change of wind direction results in different projected area of wall facing the wind. Wind from North to South (blue line) resulted in window system situated at leeward wall, away from wind, which was more critical. Same situation for East side window system, which resulted in West to East direction, became more critical (yellow curve). Furthermore, the effect of nearby building can be seen in Fig. 5, where different exposure category was shown for Model 1 window system fragility in DS1 and wind direction North to South. Exposure category was determined based on ground surface roughness from natural topography, vegetation, and constructed facilities. Exposure B is typical residential subdivision or wooden area, Exposure C is open terrain or hurricane prone shorelines, and Exposure D is flat and unobstructed area within ¼ mile of an inland lake at least one mile across. Hence, in Fig. 5, the building situated in Exposure D was the most prone to failure. This is expected due to the wind loads parameters [7].

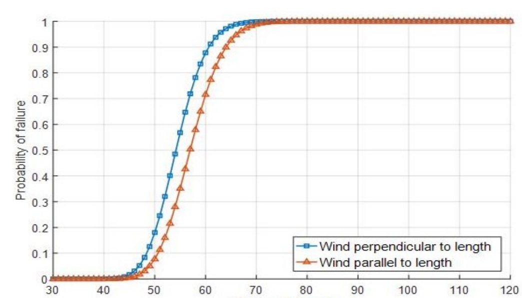

Fig. 6. Model 2 window system fragility in DS2 and exposure B with different wind direction

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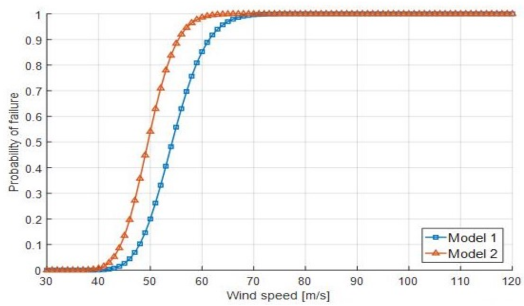

Fig. 7. Window system fragility in DS2 with wind direction N-S and exposure C for different window model

Model 2 window system configuration was symmetry for windward and leeward wall; thus, in Fig. 6, there were only direction perpendicular and parallel to the long dimension of building. Additionally, there were more windows on the North and South sides of building, so it resulted in higher probability of failure as compared to the other two sides. Lastly, the comparison between Model 1 and Model 2 was shown in Fig. 7. With twice the number of windows in Model 2, their possible combination is also higher which shows in red curve a more vulnerable system.

V. CONCLUSION

This paper proposes a case study of lightweight steel frame structure with two window configuration models and the development of fragility of its window system. Results obtained from fragility of window system showed that window situated at the leeward wall had higher probability of failure for both individual window and as a system of windows, which was around 10%. Similarly, it can be predicted that with higher number of window panels, the failure probability is expected to be increased for the system, as can be seen for North and South window systems. In conclusion, usage of this methodology could lead to a more predictable structure performance and facilitate the introduction of performance-based design guidelines for this component of building. Fragilities such as those presented here also can be convolved with wind hazard curves to develop a risk assessment tool, which can evaluate the potential impact of a natural hazard in public planning and mitigate the consequent economic losses and social disruption. Further study should focus on experiment of various types of glass that could be used to improve the resistance of window to high wind disaster.

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