Wind Fragility of Glass Windows with Tape and Film Reinforcement

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Abstract

Damages caused by strong winds are not restricted to main load-bearing structural elements such as beams and columns. Most damages are attributed to a breach in the envelope structures such as the roof, window, and door. In this study, the wind fragility of the glass used in residential apartment windows was developed based on the results of a window aerodynamic performance test report from the Korea National Disaster Management Research Institute. Four types of window glass systems were tested, which included 16 mm and 5 mm glass without attachments, 16 mm glass with tape reinforcement, and 5 mm glass with film reinforcement. Furthermore, to simulate the usage of these glasses in apartment windows, two simplified 5- and 10-storey building models were created to represent low-rise and high-rise buildings, respectively. Both building models consisted of one glass window on each floor. Subsequently, the Monte Carlo simulation method was used to generate random wind on the glass window surface, and the probabilities of failure as well as analytical fragilities were determined. A comparison between the glass windows in each building model and that between the different glass reinforcements was conducted. The fragility parameters showed a failure wind speed similar to the values determined in the experiment. However, the probabilistic results had more potential to precisely explain the performance of glass windows in terms of the expected failure probability, compared with the deterministic results that had only two explanations, i.e., the glass breaks or does not break at a specific wind speed.

Key words : Apartment Glass Window, Glass Reinforcement Method, Monte Carlo Simulation, Wind Fragility

요 지

강풍에 의한 손상은 보나 기둥 등 주구조요소에 대한 피해보다는 대부분의 손상피해가 지붕, 창문 등의 비구조요소에 주로 발생한다. 본 연구에서는 국립방재연구원에서 수행한 창호내풍성능시험 결과를 토대로 아파트 창호에 사용된 유리부재의 보강방법에 따른 취약성 평가를 연구하였다. 성능시험에서는 16mm 두께의 유리와 5mm 두께의 유리, 테이프로 보강된 16mm 두께의 유리, 필름으로 보강된 5mm 두께의 유리 등 총 4종류의 창호 내 유리 시험체에 대하여 내풍성능을 실험하였으며 이들 결과를 토대로 5층 및 10층 아파트 시공 시 각각 강풍 취약도 평가를 수행하였다. 다양한 내풍조건을 모사하기 위하여 몬테카를로 시뮬레이션 기법을 적용하여 유리창 표면에 발생 가능한 풍속을 생성하였으며 이후 유리의 보강성능에 따라 각각의 확률론적 강풍 취약성을 평가하였다. 본 연구를 통하여 도출된 결과는 강풍 발생 시 시공된 유리의 보강방법에 따라 예상되는 손상확률을 결과적으로 제시하였다.

핵심용어 : 아파트 창호, 창호 보강대책, 몬테카를로 시뮬레이션, 강풍 취약도

1. Introduction

Damages to structure due to natural disaster event are reported to be steadily on the rise because of the deterioration of climate stability and the growing frequency of natural disasters globally. Lee et al. (2017) made the estimation for the cost of maximum yearly damage due to natural disasters through 2060 in South Korea to be around 20.9 billion United

States dollar, which equivalent to 1.03% of future Korean GDP. Additionally, the damages due to typhoon not just limited to the devastating loss of economy, but also exposed the safety of human life to the danger due to failure of structure or the secondary effect from their failure. The recent increase of high intensity typhoon in the Pacific Ocean has emphasized the necessity of risk assessment for structure vulnerable to strong wind (Typhoon Committee, 2015).

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Wind fragility is a crucial component for the development of Probabilistic Risk Assessment (PRA) tool. PRA is a disaster management framework for natural disaster (FEMA, 2010) such as earthquake, typhoon, flood, etc. Wind fragility presents the probability of failure of structure or structural element in term of wind intensity. Several researchers have shown the development of wind fragility for various types of structure. Lee and Rosowsky (2006) and Ellingwood et al. (2004) show the analytical method to derive wind fragility for wood frame structure based on full-scale experiment of wood frame house. Additionally, Lee and Rosowsky (2005) also presented their study of wind fragility for roof sheathing. Likewise, Ham et al. (2009) and Lee et al. (2013), developed wind fragility for industrial building by using Monte Carlo Simulation method. In recent study for outdoor facilities, Choi and Jung (2017) evaluated the performance of soundproof/windproof wall installed on the road based on fragility assessment, Sim et al. (2018) and Kim and Jung (2018) applied Monte Carlo Simulation method in the development of wind fragility for anchor connection in the protruding advertisement sign structure used in Korea. For wind fragility of window glass in residential apartment building, Ham et al. (2014) present a paper on the assessment of extreme wind fragility for balcony windows installed in mid- and low-rise apartments. Their study can be used to estimate the potential damages of structure or structure's component in high wind regions.

Improvement on these ongoing researches for the safety of window glass used in residential building, Disaster Research Laboratory (2012) performed full-scale experiment for window glass subjected to wind load in order to improve the

understanding of glass breakage mechanism and to determine the effectiveness of self-measurement window breakage prevention methods. These self-measurement methods consisted of tape and film attachment to the glass surface to reinforce the window during strong wind. Accordingly, these experimental results can be used to develop wind fragility and evaluate the performance of glass window in the probabilistic perspective. Probabilistic is derived from probability which in general is based on randomness in the occurrence of events. Therefore, by combining the deterministic results of window component and probabilistic models of wind load, this study showed the development of wind fragility for glass window in residential building, as well as, comparison of multiple scenarios based on the differences of building models and glass surface reinforcement methods.

2. Glass Window Experiment

The full-scale glass window experiment was performed by Disaster Research Laboratory (2012) under the support of Korea National Disaster Management Research Institute. The experiment was conducted for various thickness, reinforcement and installation condition. However, in this paper, only four types were considered. The results of the experiment were shown in Table 1. The experiment was conducted by using pressurized chamber as can be seen in Figs. 1 and 2. In these figures, the before and after breakage of the glasses were shown. Moreover, the tape reinforcement can be seen on the left glass picture in Fig. 2. Fig. 3 show the safety assessment of film reinforcement on the 5 mm glass.

Fig. 1. P16S Before and After Breakage (Disaster Research Laboratory, 2012)

Fig. 2. P16T Before and After Breakage (Disaster Research Laboratory, 2012)

Fig. 3. Safety Assessment of Film on P5F After Breakage (Disaster Research Laboratory, 2012)

Table 1. Glass Resistance Performance of Pressurize Test Results (Disaster Research Laboratory, 2012)

Sample name	Glass thickness	Glass reinforcement method	Fracture load		
			Pa (N/m ²)	Kgf/m ²	Wind speed (m/s)*
P16S	16 mm Pair Glass	None	7350	750	109.5
P16T	5 mm	None	4263	435	83.4
P5S	16 mm Pair Glass	Tape (* pattern)	7644	780	111.7
P5F	5 mm	Film (inside and outside)	2920	298	69.1

* Conversion of pressure to wind speed by $V = 4 \times \sqrt{q}$, where $q = \text{kgf/m}^2$

3. Wind Fragility for Glass Window

Wind fragility for glass window presents the probability that the glass reaches its fracture load or resistance capacity in function of wind speed. This probability of failure was determined with Monte Carlo Simulation (MCS) method by the following equation:

$$P_f(v) = \frac{\sum_{i=1}^N (LS | V=v)}{N} \quad (1)$$

where, V is uncertain wind speed, v is a specific value of V (no uncertainty). Hence, $\sum_{i=1}^N (LS | V=v)$ is the sum of glass reaching limit state (LS) when wind speed equals v , and N is the number of MCS.

The probabilities of failure at all wind speed v were fitted to lognormal cumulative distribution which is a widely-used model to present fragility (Porter, 2015). Lognormal cumulative distribution function (CDF) has the following form:

$$Fr(V) = \Phi\left(\frac{\ln(V/\mu)}{\sigma}\right) \quad (2)$$

where, $\Phi(\cdot)$ is a standard normal CDF, μ is median capacity of the glass window to resist damage, and σ is standard

deviation of the natural logarithm of the capacity of the glass window to resist damage. Parameters μ and σ were used to present the wind fragility for glass window because it can be used to integrate with the existing wind related PRA framework to provide factual basis for disaster management and decision making, as was shown by Vickery et al. (2006).

In this paper, LS was the breakage of glass determined based on the experiment results shown in Table 1. In addition, wind load applied on the glass surface was simulated with MCS based on ASCE-7 (ASCE, 2010). The guideline in ASCE-7 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 pressure acting on the window can be calculated as the following:

- Building with height less than 18.3 m

$$W = q_h [GC_p - GC_{pi}] \quad (3)$$

- Building with height greater than 18.3 m

$$W = q_z GC_p - q_h GC_{pi} \quad (4)$$

where q_z is velocity pressure evaluated at height z , q_h is velocity pressure evaluated at mean roof height h , GC_p is product of gust factor and external pressure coefficient, and GC_{pi} is product of gust factor and internal pressure coefficient. The velocity pressure q_z (N/m^2) evaluated at height z is given by:

$$q_z = 0.613K_zK_{zt}K_dV^2 \quad (5)$$

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

Wind load parameters were modeled with Normal distribution function. The two parameters present these Normal distribution models were determined by Ellingwood and Tekie (1999) through Delphi questionnaire. The statistical wind load parameters used in this study were derived by combining the Normal distribution models of wind load parameters with nominal wind load parameters in ASCE-7. Table 2 presents the mean and standard deviation value of the statistical wind load parameters used. Parameter K_z was shown in range to account for all building floor and model.

Fig. 4. Simplified Building (a) Model 1: five-story building (15 m) and (b) Model 2: ten-story building (30 m)

Table 3. Dimensions and Characteristics of Simplify Building Model

Properties	Model 1	Model 2
Plan dimension	15 m × 6 m	15 m × 6 m
No. of stories	5	10
Height per story	3 m	3 m
Roof type	Flat	Flat

Two simplified building models were assumed in this study. Each model had a 1m × 1m window in the middle of each floors as can be seen in Fig. 4. The dimensions and characteristics of the building model used in this paper were shown in Table 3.

4. Results and Discussion

By combining all conditions of building model, glass type and wind exposure category; there were a total of 180 wind fragilities. For Model 1, there were five wind fragilities, one for window at each floor; however, these fragilities had the same parameters, as can be seen in Fig. 5, since the wind load of low-rise structure was considered at the height of building roof, i.e. the maximum wind load. Thus, only one fragility was used to present each conditions of Model 1 building. For Model 2, the fragilities in floor 1-3 had the same parameters; but starting from Floor 4, their parameters had difference value, as shown in Fig. 6. This was due to the velocity pressure exposure factor parameter K_z which had the same distribution for structure lower than 9.1 m in wind exposure category B region. The most critical fragility curve, at Floor 10, will be used to present Model 2 wind fragility, unless state otherwise, to simplify the comparison process.

Table 2. Statistical Wind Load Parameters

Parameters	Category	Mean	Standard deviation	Distribution
K_z	Exposure B	0.7096 ~ 0.9978	0.1348 ~ 0.1896	Normal
	Exposure C	0.8200 ~ 1.2113	0.1148 ~ 0.1696	Normal
	Exposure D	0.9913 ~ 1.3797	0.1388 ~ 0.1932	Normal
K_d	1.0000			
GC_{pi}	Enclosed	0.1500	0.0500	Normal
	Partially enclosed	0.4583	0.1528	Normal
GC_p	Model 1 (5 story)	0.8550	0.1026	Normal
	Model 2 (10 story)	0.9500	0.1140	Normal
K_{zt}	1.0000

Fig. 5. Wind Fragility for Model 1 Building with P5F Glass in Exposure B

Fig. 6. Wind Fragility for Model 2 Building with P5F Glass in Exposure B

A notable observation in Figs. 5 and 6 was the differences of wind fragility parameters for the same floor (height of the glass window). This is due to the external pressure coefficient parameter C_p . As explained in ASCE 7 (ASCE, 2010), external surfaces of building are subject to “flowing” air which resulted in the considerably varying of pressure on the building surface depending on structural configuration and direction of the wind. For the same condition of wind direction in Model 1 and Model 2, although the window located at the same height (15 m), the total height (structural configuration) of the two buildings was difference which resulted in the difference value of parameter C_p . Consequently, the wind load generated for these two models also had difference pressure.

For 16 mm glass without reinforcement, the comparison between Model 1’s wind fragility and the most critical wind fragility of Model 2 was shown in Fig. 7. It can be seen in Fig. 7 that the median wind speeds of the glass to resist wind damage were 101.7 m/s and 95.0 m/s for Model 1 and Model 2, respectively. This median failure wind speed was comparable to the fracture load value for P16S glass determined by Disaster Research Laboratory (2012), which was 109.5

m/s. These similarities could also be seen in Fig. 8, which shows the first floor’s wind fragility of Model 2 building. As can be seen in Fig. 8, the median failure wind speed was 105.5 m/s, 80.4 m/s, 107.6 m/s and 66.6 m/s for glass type P16S, P5S, P16T and P5F, respectively. Furthermore, with the fragility parameters shown in Fig. 8, the probability of failure based on wind speed determined by Disaster Research Laboratory (2012) was found to be 61% for all glass types. Compare with the median failure wind speed, it showed that the deterministic results from the experiment were more conservative, i.e. higher capacity. Identical to the experimental result, the reinforcement of tape on the 16 mm glass increased their resistance to wind load by 2.1 m/s. For the 5 mm glass with film reinforcement, the test was conducted in a state where the sealing material between the PVC frame and the glass on the pressure side was less firm which resulted in lower fracture strength than the P5S sample. However, the glass scattering prevention effect due to the film reinforcement was confirmed. In term of probabilistic result, the median failure wind speed difference between the non-reinforced and reinforced 5 mm glass was 13.8 m/s.

Fig. 7. Wind Fragility for Model 1 and Model 2 Building with P16S Glass in Exposure B

Fig. 8. Wind Fragility for First Floor of Model 2 Building with all Glass Type in Exposure B

The effect of wind exposure categories on the performance of glass window were shown in Fig. 9. Wind fragilities for exposure category B, C and D were shown with their respective median failure wind speeds of 77.4 m/s, 68.2 m/s and 63.1 m/s. If the wind speed value of 83.4 m/s, from Table 1, was used to determine the probability of failure at each exposure category, the results would be 69%, 94% and 98% for exposure B, C and D, respectively. Thus, it alleged that the fragility parameters presented here had more potential to precisely explain the performance of glass window, in the form of expected failure probability, compare to the deterministic result which only have two explaining, i.e. glass break or glass not break.

Fig. 9. Wind Fragility for Model 1 Building with P5S Glass in All Exposure Categories

5. Summary and Conclusions

This paper showed the development of wind fragility for glass window based on the pressurize chamber experiment result of four glass types. Two different glass thickness and two types of reinforcement for each glass were considered in the experiment. To simulate the low- and high-rise residential building, two simplified building models were assumed. Thus, including three different wind categories defined in ASCE-7, a total of 180 wind fragilities were determined. While the building models were assumed, the probabilistic concept and method applied in this study could be flexibly updated or replaced with actual structure model to improve the risk assessment framework for wind disaster management.

MCS method was employed to generate random wind load; then the loading was compared with the glass fracture strength from the experiment to determine the probability of failure at each wind speed. Subsequently, the probabilities of failure at all wind speed were fitted to lognormal CDF

to determine wind fragility parameters μ and σ . These parameters can be integrated with a larger PRA database to improve the disaster management tool and decision making.

Results of this study showed that:

- Individual glass window became more vulnerable as they located at higher floor of the building. This is due to the increase of wind pressure at higher altitude. As can be seen from Model 2 building with P5F glass window type in exposure B, the median failure wind speed decrease from 66.6 m/s in the first floor to 59.9 m/s in the top floor.
- The deterministic wind speed from the experiment showed a more conservative result when combine with the fragility parameters. The probability of failure based on the deterministic wind speed from the experiment had over 50% failure probability.
- The probabilistic result had more flexibility for the explanation of glass window performance. It can be used to estimate the failure probability, whereas the deterministic result can only give two explaining, i.e. glass break or not break.

The failure of glass for window in building not only cause economic loss, but also causes harm and disruption to people's lives. More full-scale experiment for difference type of glass should be increased to improve the safety of glass usage and update the safety guideline for common resident. With more experimental results, the reliability in the probabilistic prediction of glass window performance could be greatly improved.

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