International Journal of Architectural, Civil and Construction Sciences
ISSN: 2415-1734
Vol:11, No:11, 2017

Wind Fragility for Soundproof Wall with the Variation of Section Shape of Frame

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***Abstract*—**Recently, damages due to typhoons and strong wind are on the rise. Considering this issue, we evaluated the performance of soundproofing walls based on the strong wind fragility by means of numerical analysis. Among the components of the soundproof wall, aluminum frame was the most vulnerable member, thus we have considered different section of aluminum frame in the determination of wind fragility. Wind load was randomly generated using Monte Carlo Simulation method. Moreover, limit state was based on the test standard of road construction soundproofing wall. In this study, the strong wind fragility was determined by considering the influence factors of wind exposure category, soundproof wall's installation position, and shape of aluminum frame section. Results of this study could be used to determine the section shape of the frame that has high resistance to the wind during construction of the soundproofing wall.

***Keywords*—**Aluminum frame soundproofing wall, Monte Carlo Simulation, numerical simulation, wind fragility.

I. Introduction

RECENT global warming has caused unusual climate phenomena all over the world. Among them, the damage of infrastructure facilities caused by typhoons and strong winds is increasing. As a result, there is a growing interest in countermeasures against wind disasters in Korea [1]. In the United States, Hazus-MH damage prediction system has been developed and used in disaster management field [2]. However, it is difficult to predict exact damage events in Korea considering the tool available.

Contributing to the development of probability risk assessment framework, in this study, we conducted a comparison of strong wind fragility according to the section shape of vulnerable members based on the previous study by Choi and Jung [3]. We evaluated the strong wind fragility according to wind intensity based on a stochastic evaluation method for the soundproofing walls installed in urban centers or expressways. For the target soundproofing walls model, the design criteria of the road construction sound barrier were considered. In addition, the structural test on the aluminum frame, which is a weak part of the soundproofing wall, was performed; and the soundproof wall finite element modeling and analysis was performed using the commercial analysis program ABAQUS. Finally, multiple wind fragilities of soundproof walls were derived using different shapes of the vulnerable member section, i.e. aluminum frame.

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Fig. 1 Failure of soundproof wall

II. Components and Modeling of Soundproofing Walls

A. Structural Performance of Soundproofing Walls Aluminum Frame

The soundproofing walls consisted of a soundproof plate (acrylic board), a soundproof plate reinforcement frame (aluminum frame), and a steel column (H-beam) as shown in Table I. The soundproofing walls [4] used in this study were the actual design of sound barrier applied to the Seoul–KwangMyeong Expressway, the diagram of this barrier was shown in Fig. 2.

TABLE I
Summary of Statistical Wind Load Parameters

Component	Elastic modulus (MPa)	ν	Density (g/cm³)
Acrylic board	2,350	0.26	1.20
H-beam	199,948	0.3	75.46
Aluminum frame	70,000	0.336	2.70

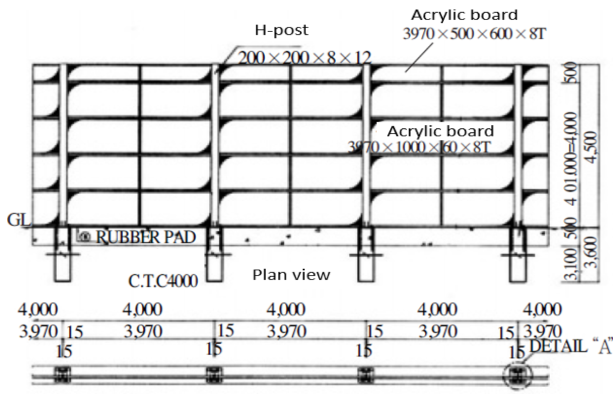

Fig. 2 Shape and specification of sound proof structure

In this study, a soundproofing walls reinforced aluminum frame was selected as a vulnerable member, and the wind fragility was determined based on the structural performance of this aluminum frame. In order to investigate the deflection and stiffness of aluminum frames, which used for reinforcing the soundproofing walls, three-point bending experimental study was performed. ABAQUS program [5] was used to model and analyze the frame. Finally, the two results were compared as shown in Fig. 3. It was observed that the experimental results were consistent with the analytical results; this outcome proved the reliability of the results.

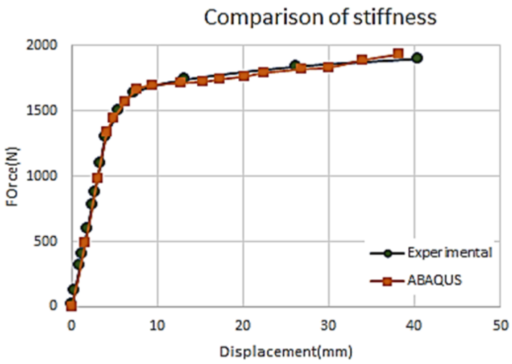

Fig. 3 Comparison of experimental and analytical result of aluminum frame

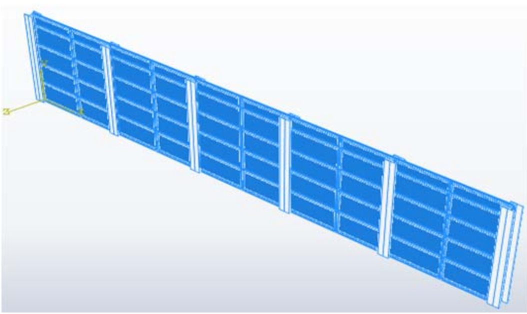

Fig. 4 Soundproof wall optimal model

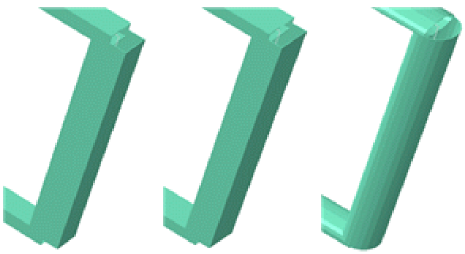

Fig. 5 Selected section shape of aluminum frame

B. Soundproofing Walls Modeling

In case of actual soundproofing walls, a large number soundproof panels were connected. However, in this study, the optimal model for analysis is composed of five panels of soundproof barrier [3]. The load of 3.0 kN/m was applied based on the design standards for road construction soundproofing walls. Also, the aluminum frame, the soundproof plate joint, the soundproofing wall frame, and the ground fixture were assumed to be completely fixed in place. The transparent soundproofing panel and the reinforcing frame were considered as complete elastic bodies. Three forms of aluminum section were selected for this study of wind fragility as shown in Fig. 5.

The analysis was performed by dividing the section shape of the aluminum frame into three types: rectangle, square, and circle. Furthermore, wind fragilities for soundproof wall with each section of aluminum frame were developed.

III. Estimation of Resistance Performance of Soundproofing Walls

In the same way as in the previous studies, the linear elastic analysis of the optimal design of the soundproof wall was carried out to estimate the resistance performance of the wall. As a result, the load – displacement relationship was obtained. The resistance capacity was determined based on the maximum permissible displacement of 50 mm, which is the test standard of the road construction of sound barrier. In this study, because of the elastic analysis, the result shows infinite load and displacement increment. It was assumed that the constituent elements of the soundproofing walls and the boundary conditions were completely elastic. In order to estimate a more reliable resistance performance, more accurate material properties and boundary conditions should be applied in the future study.

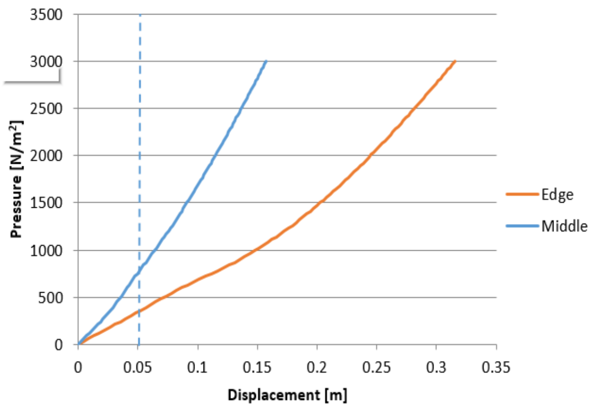

Fig. 6 Resistance capacity for edge and middle soundproof wall

IV. Evaluation of Soundproofing Walls Fragility

A. Wind Load Statistics

ASCE 7-10 [6] was used to determine wind load (W). Based on their performance, soundproof barriers were considered parts of the main wind-force resisting system. The total height of structure is 4.5 m, thus wind load pressure acting on this soundproof barrier structure can be calculated as:

$$W = q_h G C_f A_s \quad \text{(unit: } N\text{)} \tag{1}$$

where q_h = velocity pressure evaluated at height h, G = gust-effect factor, C_f = net force coefficient, and A_s = the gross area of the soundproof barrier.

The velocity pressure of wind loads calculated at height z is given by:

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

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

TABLE II
SUMMARY OF STATISTICAL WIND LOAD PARAMETERS

Parameters	Category	Mean	Standard Deviation	CDF
K_z	Exposure B	0.584	0.1110	Normal
	Exposure C	0.820	0.1148	Normal
	Exposure D	0.991	0.1388	Normal
K_d	MWFRS	0.890	0.1424	Normal
	Exposure B	0.770	0.0900	Normal
G	Exposure C	0.830	0.1000	Normal
	Exposure D	0.830	0.0700	Normal
C_f	Middle	Deterministic (1.35)		
	Edge	Deterministic (2.39		
K_{zt}	Deterministic (1.00)			

Nominal value of these coefficients could be found in ASCE 7-10 [7]. Additionally, based on Ellingwood and Tekkie [8] study, the statistical distribution, i.e. normal distribution, of these wind loads parameters could be determined. Accordingly, mean and standard deviation could be obtained. The mean and standard deviation of each wind loads parameters shown in Table II were used to generate random wind load describe in the next section.

Monte Carlo Simulation (MCS) method had been used to generate probabilistic wind load (W) acting on the soundproof wall with resistance capacity (R). As can be seen in Fig. 7, starting from the minimum wind speed, we generated 5,000 random K_z, K_d, and G by sampling from their normal distributions in Table II. Then, by comparing these random wind loads with the resistance capacity of soundproof wall, we can determine the failure of this wall when $f(V) = R - W \leq 0$ [9]. Therefore, by reiterating this step a large number of times, in this case 5000, a damage array at wind speed V was obtained. Consequently, probability of failure (P_f) could be calculated by dividing the total number of failure with the total number of iteration, i.e. 5000. Additionally, by repeating the damage array construction for different wind speed until total failure occurred (P_f = 1), a fragility curve in term of wind speed could be determined.

In the case of the soundproofing walls, it is difficult to define the exact failure limit state because the structural performance probability distribution analytical value of the structural member was insufficient. Therefore, following the previous study and design guideline, 50-mm displacement of soundproof wall was defined as the failure limit state. Moreover, wind load was evaluated according to the wind exposure category and the location of the sound barrier. Wind exposure category is a classification of surface roughness coefficients as can be seen in Fig. 8, which show the wind exposure category B, C, and D. The installation position was divided into two parts which are edge and the middle part of the overall wall.

B. Calculation of Probability of Failure for Soundproof Wall

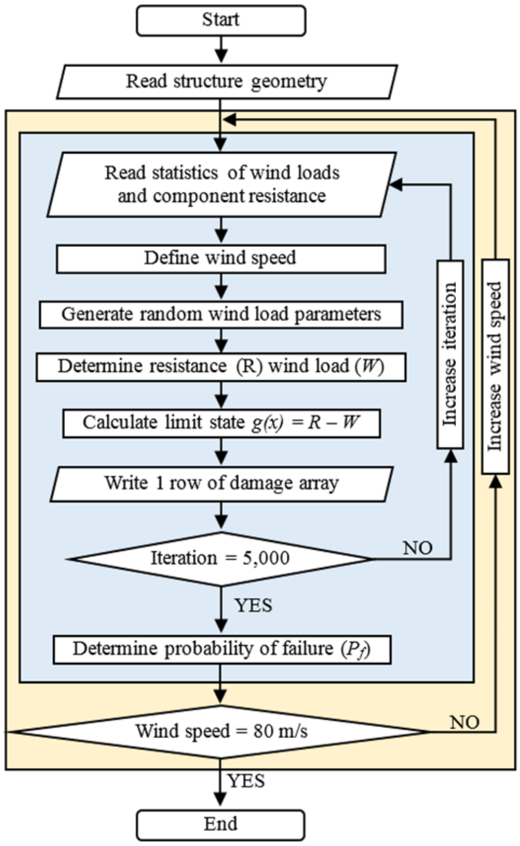

Fig. 7 Monte Carlo Simulation flowchart

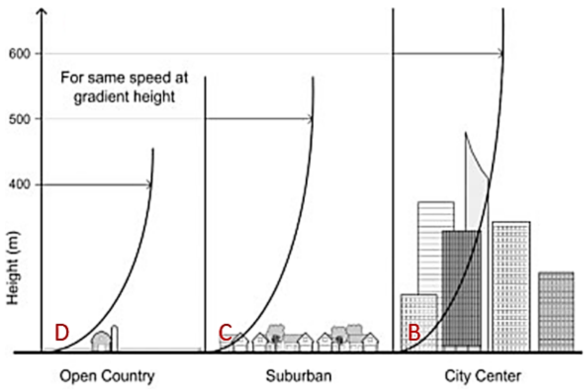

Fig. 8 Wind exposure category diagram

C. Evaluation of the Fragility According to the Section Shape of Aluminum Frame of Soundproofing Walls Installed at Edge

Figs. 9-11 and Table III show the wind fragility and distribution parameters according to section shape and wind exposure category for the soundproofing walls installed at edge of the entire panel. In case of soundproofing walls composed of a rectangular aluminum frame and wind exposure category D, the failure started when the wind velocity reached 14 m/s and the complete failure occurred at 23 m/s. For the square section, failure started at 16 m/s and complete failure occurred at 25 m/s.

In case of circular cross section, complete failure occurred at 24 m/s and the beginning of failure was at 15 m/s. Consequently, it can be concluded that it was considered safe in the order of square-circle-rectangle. Analysis of the wind fragility by the surface roughness classification shows that the initial wind speed which caused the failure decreased from 18 m/s to 14 m/s when the exposure category changed from B to D. This indicates that the level of vulnerability varied slightly depending on the surface roughness classification.

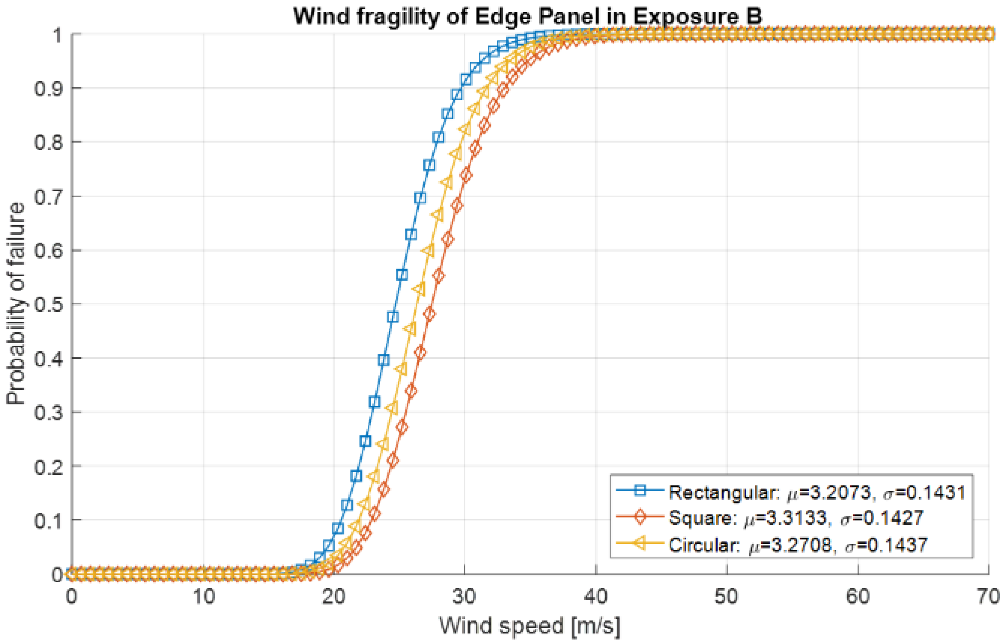

Fig. 9 Edge soundproof wall fragility curves for section shape (exposure B)

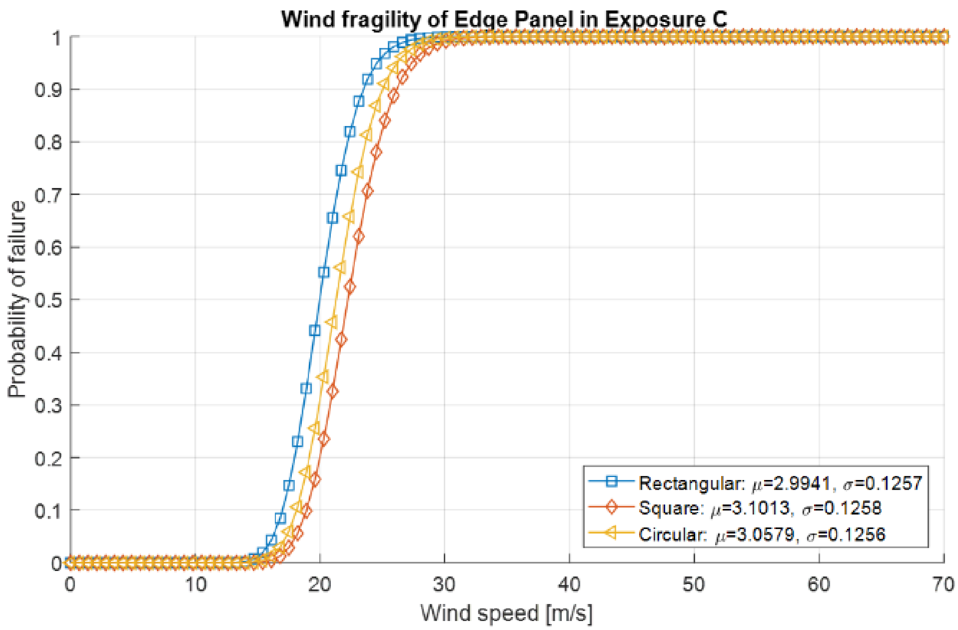

Fig. 10 Edge soundproof wall fragility curves for section shape (exposure C)

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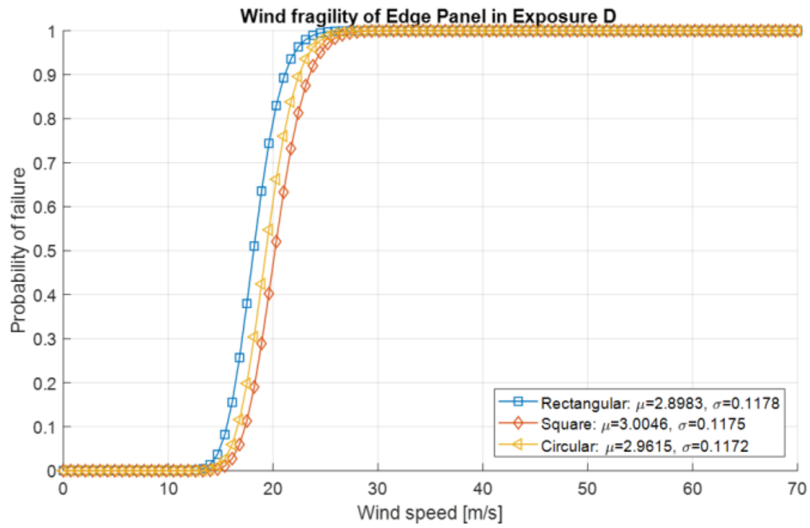

Fig. 11 Edge soundproof wall fragility curves for section shape (exposure D)

TABLE III
SUMMARY OF STATISTICAL WIND LOAD PARAMETERS

Component	profile	Category	μ_R	ζ_R
Edge	Rectangle	Exposure B	3.2073	0.1431
		Exposure C	2.9941	0.1257
		Exposure D	2.8983	0.1178
	Square	Exposure B	3.3133	0.1427
		Exposure C	3.1013	0.1258
		Exposure D	3.0046	0.1175
	Circle	Exposure B	3.2708	0.1437
		Exposure C	3.0579	0.1256
		Exposure D	2.9615	0.1172

D.Evaluation of the Fragility According to the Section Shape of Aluminum Frame of Soundproofing Walls Installed at Middle

Figs. 12-14 and Table IV show the strong wind fragility and distribution parameters according section shape and wind exposure category for the soundproofing walls situated at the middle section. In the case of a soundproofing walls with middle, the level of safety was significantly higher than the soundproofing walls located at both ends of the edges. Based on wind exposure category D, the wind velocity causing the initial failure was about 28 m/s and complete failure occurred at about 45 m/s. The fragility according to the section shape of the aluminum frame was considered safe in the order of square-circle-rectangle like the edge soundproofing walls. Also, it can be seen that the wind speed causing the initial failure decreased slightly from 33 m/s to 28 m/s when the wind exposure category altered from B to D.

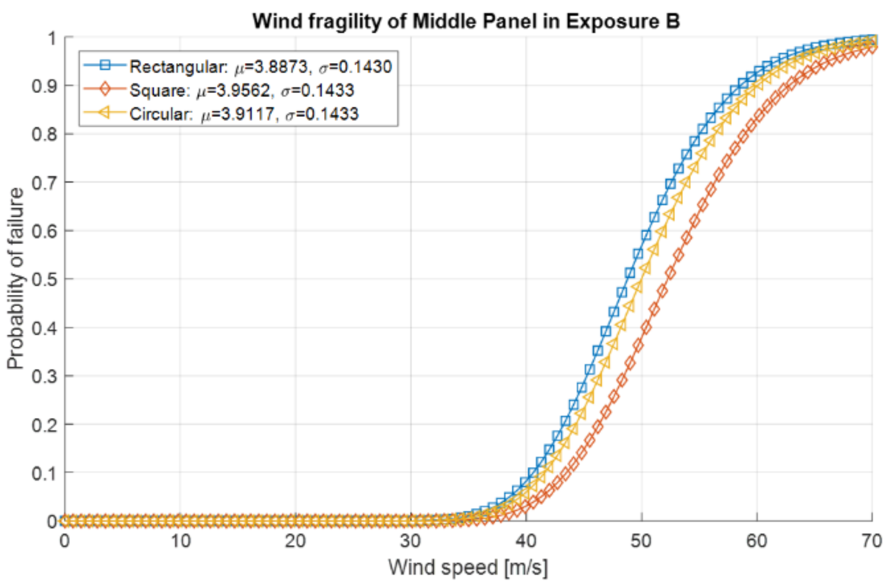

Fig. 12 Middle soundproof wall fragility curves for section shape (exposure B)

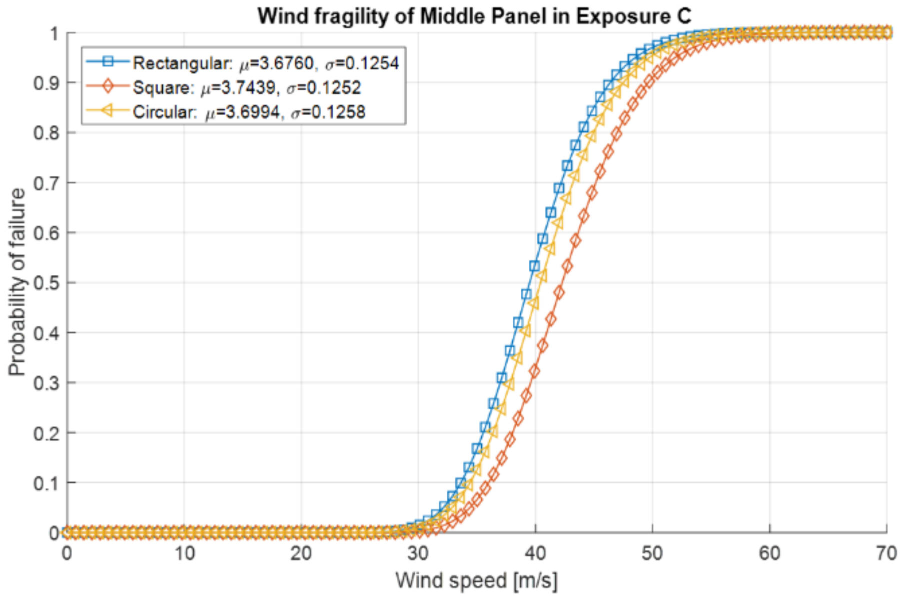

Fig. 13 Middle soundproof wall fragility curves for section shape (exposure C)

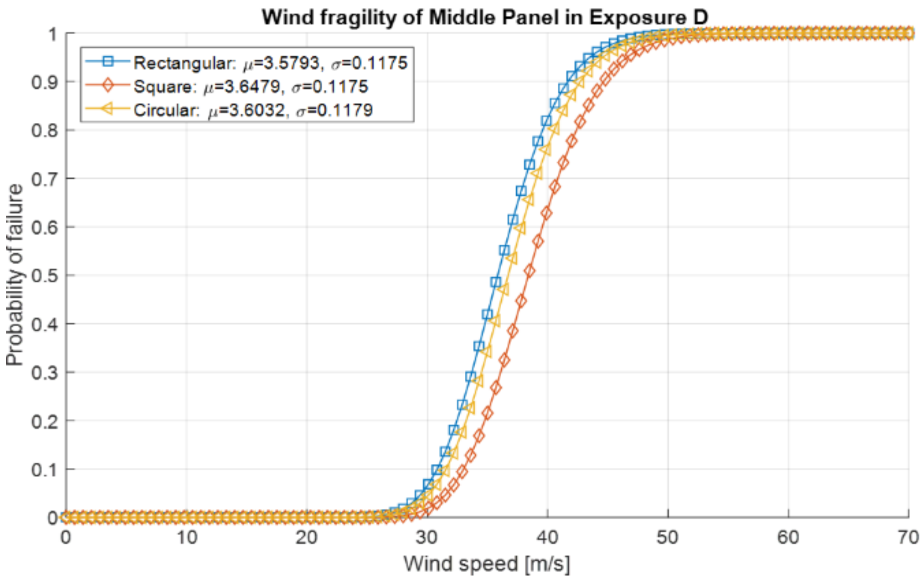

Fig. 14 Middle soundproof wall fragility curves for section shape (exposure D)

TABLE IV
SUMMARY OF STATISTICAL WIND LOAD PARAMETERS

Component	profile	Category	μ_R	ζ_R
		Exposure B	3.8873	0.1430
	Rectangle	Exposure C	3.6760	0.1254
		Exposure D	3.5793	0.1175
		Exposure B	3.9562	0.1433
Middle	Square	Exposure C	3.7439	0.1252
		Exposure D	3.6479	0.1175
		Exposure B	3.9117	0.1433
	Circle	Exposure C	3.6994	0.1258
		Exposure D	3.6032	0.1179

V. CONCLUSIONS

This study was conducted to evaluate wind fragility according to section shapes of the vulnerable members, i.e. aluminum frame, of the soundproofing walls installed on domestic roads. Three different sections of aluminum frame, which were rectangular, square, and circular shape, were evaluated to determine the vulnerability to strong winds. As a result, the order of section with square-circle-rectangle shape was more resistant to wind pressure. Moreover, it was concluded that, it was necessary to consider the design and construction conditions according to wind exposure category and location of installed panels. Additionally, more reliable results could be obtained by developing various prediction models through securing and analyzing structural performance data according to the shape of soundproof walls installed in the future.

Acknowledgment

This research was supported by a grant [MOIS-DP-2015-05] through the Disaster and Safety Management Institute funded by Ministry of the Interior and Safety of Korean government.

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