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Optimal Section Design of Korean Agricultural Greenhouse Response to Climate Change Based on Monte Carlo Simulation

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Abstract: Rapid climate change has threatened the agricultural production infrastructure that was designed based on past weather conditions. A glass greenhouse structure is especially affected by the changing wind speed and snow. Therefore, it is necessary to update the standards for a greenhouse design to secure the appropriate safe standards for wind speed and snow depth according to the structure shape, cross-sectional shape, and size of the greenhouse. This study develops a structural optimal cross-section model to cope with climate change such as abnormal weather for Korean glass greenhouses. We programmed a model to calculate the probability of greenhouse failure and developed a sectional setting model for optimal failure probability by applying the concepts of a Monte Carlo simulation technique and simplex method. The main results showed that it is possible to reduce the probability of failure by about 80%, and the materials could be reduced by about 18% with the optimal cross-section setting of this study. Therefore, we propose that, with this cross-section, it is possible to build an economical greenhouse that still ensures safety against failure.

Keywords: factor of safety; probability of failure; Monte Carlo simulation; optimal section

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1. Introduction

Rapid climate change is becoming a climate crisis, which has a significant impact on agricultural yields. It also threatens the agricultural production infrastructure that was designed based on past weather conditions [1]. Since a greenhouse structure is greatly affected by wind speed and snow, it is necessary to update the design standards for the appropriate safe wind speed and snow depth in response to climate change based on the structure shape, cross-sectional shape, and size of the greenhouse [2].

Considering the recent changes in climate patterns and abnormal weather, it is necessary to update the greenhouse design standards. In Korea, a standard design for glass greenhouses was published in 1997 to meet the weather conditions at that time [3]. About 20 years later, glass greenhouses are still being built based on these standard designs. The area of glass greenhouses in Korea has continuously increased since the publication of the standard design. Specifically, it has increased by about 12 times from 345 ha in 2010 to 4010 ha in 2017 [4]. It is expected to increase to 7000 ha by 2022 with various government policy supports due to the trend toward smart farms in the era of the 4th Industrial Revolution [5]. There is also increased social damage when a greenhouse structure collapses due to recent strong typhoons and abnormal weather. According to the 6th IPCC report, the frequency of typhoons has more than doubled, and the maximum wind speed is expected to increase by about 20%, so the damage is likely to increase further [6]. Although the domestic storm and flood relief system can subsidize farmers for the damage, it is still not enough to adequately compensate for the damage [7]. In other words, greenhouses built based on design standards more than 20 years ago are likely to cause disasters due to climate change, and the damage will inevitably increase due to the insufficient funds for compensation.

One of the main purposes of a structural design is to ensure structural performance such as safety, usability, and function during the service life of the structure within the constraints of an economical design [8–10]. However, there is uncertainty about the main design variables required in the design process such as physical properties of materials, loads, and dimensional tolerances [11,12]. In the existing deterministic design approach, the structure is designed by assuming the main design variables are fixed values [13]. These assumptions have the disadvantage of ignoring the effect of the uncertainty of design variables on the objective function or constraint, so the result of the optimal design is lower than the probability of satisfying the constraint conditions [14]. Unlike the deterministic structural analysis methods, a probability-based reliability structural analysis technique quantitatively handles the uncertainty of variables, so the reliability technique can be a more reasonable to ensure the safety of structures in the design process [15]. In addition, since destruction or lack of safety in the structural system depends on the statistical characteristics of materials and loads under certain safety conditions, it is necessary to use a design method that is based on reliable analysis or design theory [16,17].

Some studies on greenhouse structures have been conducted based on the load and resistance factor design (LRFD), which introduces the concept of uncertainty as a load-increasing or strength-decreasing factor [18–20]. Reliability-based research in the field of structural analysis has recently increased [21–24]. Such reliability research has been conducted with methodologies such as the first order second moment (FOSM) and second order reliability method (SORM), which correspond to level-II. The main method for reliability analysis is reliability level II because it can be applied by converting a limit state function into a first or second approximation function when it is in the form of a nonlinear function, and by checking the sensitivity of each design variable, and obtaining results close to the true value [25]. However, this method has a disadvantage in that it cannot be applied when expressed as a negative function, and interpretation including the domain of the negative function is possible with level-III [26]. Level-III is the most basic simulation method that can directly calculate the probability of destruction of a structure. The Monte Carlo simulation (MCS) method is a representative method. The MCS is a convenient method for interpreting marginal state equations without approximating them. However, due to the characteristics of the simulation, it has a disadvantage in that it takes a long time to interpret. However, due to the recent rapid development of computing power, the processing speed of analysis is increasing. It is also a faster and more accurate reliability analysis method than the level-II method [27].

This study develops a structural optimal cross-section model to address climate change such as abnormal weather for Korean glass greenhouses. We analyzed the safety of the Korean standard glass greenhouse due to the external load. A structural reliability analysis of the glass greenhouse was performed using the simplex method-based Monte Carlo simulation (MCS). Finally, the optimal cross-section was set according to the probability of optimal failure by reliability.

2. Materials and Methods

2.1. Korean Agricultural Greenhouse

We conducted an optimal cross-section study for Korean glass greenhouses issued by the Korea Rural Community Corporation (KRC). In the early 1990s, Korea began a facility modernization project to generate profits and supply stable agricultural products in rural areas. Accordingly, in 1991, the KRC published 10 standard designs for farm supply automation houses, including single- and multi-span pipe houses. Later, the KRC published a standard design for Korean glass greenhouses in 1997 [28].

Since 2000, the standard design of a farmhouse distribution-type automation house has been updated by customizing crops through various studies, but the existing standard design has been used for glass greenhouses. We performed an analysis on the wide-span type glass greenhouse, which is the most common standard design (Figure 1).

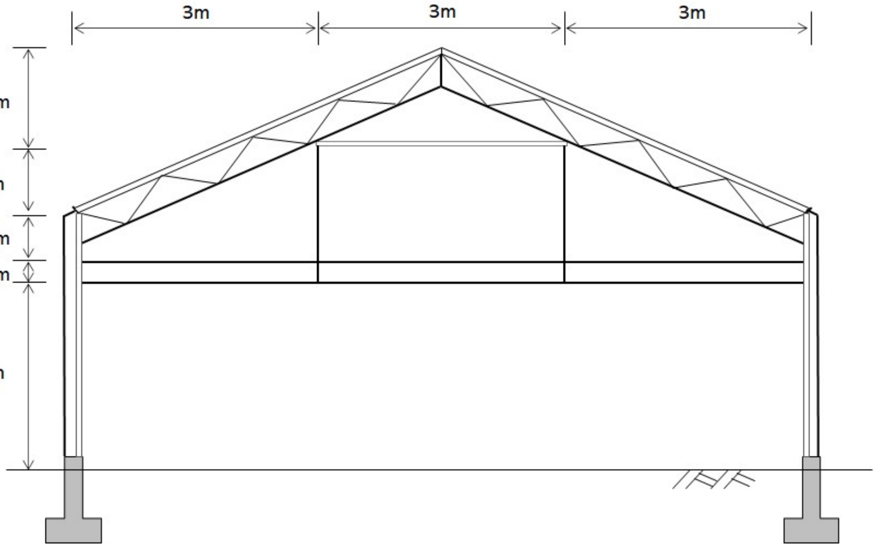
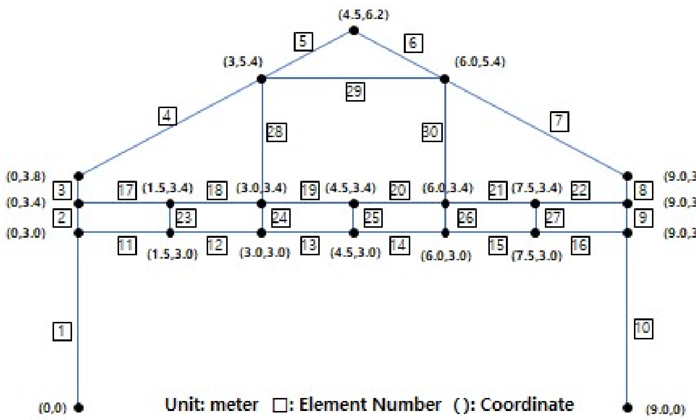


Figure 1. Cross-sectional diagram of wide-single span type of greenhouse.

2.2. Methods

2.2.1. Structural Analysis Modeling

Modeling for structural analysis is divided into geometric modeling and load modeling. Geometric modeling is the process of transforming the shape of a structure so it can be analyzed. Geometric modeling of glass greenhouses converts the skeleton (frame) to nodes and elements. Some elements of the Korean glass greenhouse are manufactured in the form of trusses for structural reinforcement. In this study, in order to set the structure to the worst condition, geometric modeling was performed in a simplified form for the members of the truss. In addition, for the cross-sectional shape of the member, we used the cross-sectional information presented in the standard design. Geometric modeling for analysis in this process was pretreated as shown in Figure 2.



Item	Cross Section	Element
Section 1	□ 100 × 50 × 4.5	1,2,3,8,9,10
Section 2	□ 60 × 30 × 3.2	4,5,6,7
Section 3	□ 60 × 40 × 2.5	11~22
Section 4	¬ 50 × 50 × 4	28,29,30

Figure 2. Geometric modeling of a greenhouse for structural analysis.

Next, we performed load modeling on the greenhouse. The external load acting on the greenhouse can be divided into a constant load acting at all times and an emergency load acting at the moment. Normal loads are classified into fixed loads, facility loads, and crop loads, and emergency loads. Emergency loads including snowfall loads, wind loads, and seismic loads vary greatly depending on the weather conditions, and wind and snow load account for the largest proportion [29–31]. Therefore, we considered emergency loads, especially the wind load and the snow load. It is assumed that the wind load acts in a direction perpendicular to the surface of the greenhouse sidewall. Based on the domestic greenhouse structure design standards and explanations [32], the wind load acting on the greenhouse was calculated by Equation (1), and the design wind pressure and design speed pressure were calculated by Equations (2) and (3), respectively:

$$W_w = pA \tag{1}$$

$$p = q_h G C_f \tag{2}$$

$$q_h = \frac{1}{2}\rho V_h^2 \tag{3}$$

where W_w is the wind load (N), p is the design wind pressure (Nm^2), A is the effective area (m^2), q_h is the design speed pressure (Nm^2), G is the gust factor at the average height of the greenhouse roof, 1.4 [32], and C_f is the wind pressure coefficient for each shape of the structure as shown in Figure 3 [33]; ρ is the density of air, 1.25 kNm^3 and V_h denotes the design wind speed at an average height.

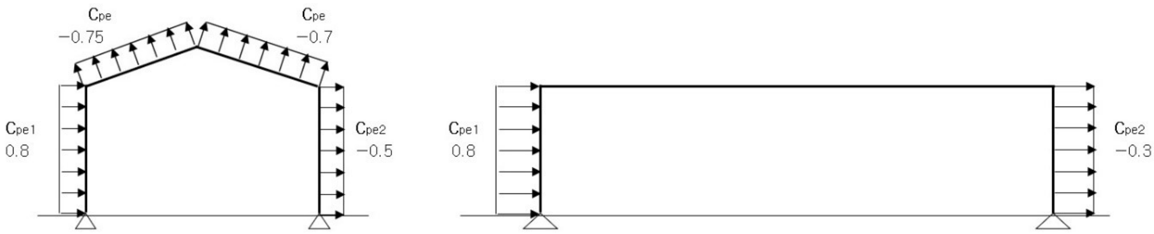


Figure 3. External pressure coefficients of frames by shape of structures.

We used the mean and deviation values of the design wind speed studied previously according to the domestic weather conditions (Figure 4). The design wind speed and snowfall depth for each of the 170 administrative districts in Korea were presented using weather data from 72 points from 2010 to 2021. The average design wind speed was 32.05 m/s, and the deviation was 6.40 m/s [34]. Next, the snowfall load was calculated by multiplying the design snow depth by the unit volume weight and the reduction coefficient (Equation (4)):

$$W_s = \phi W h \tag{4}$$

where W_s (kN/m^2) refers to the snowfall load, and ϕ is a reduction coefficient based on the slope of the greenhouse roof, as shown in Table 1 [32]; W refers to the unit volume weight (kN/cm·m^2) based on the depth of snow (Table 2), and h denotes the design depth based on the return period [32]. The design snow depth was also applied with an average of 38.02 cm and a deviation of 30.24 cm, which are the results of previous studies [35].

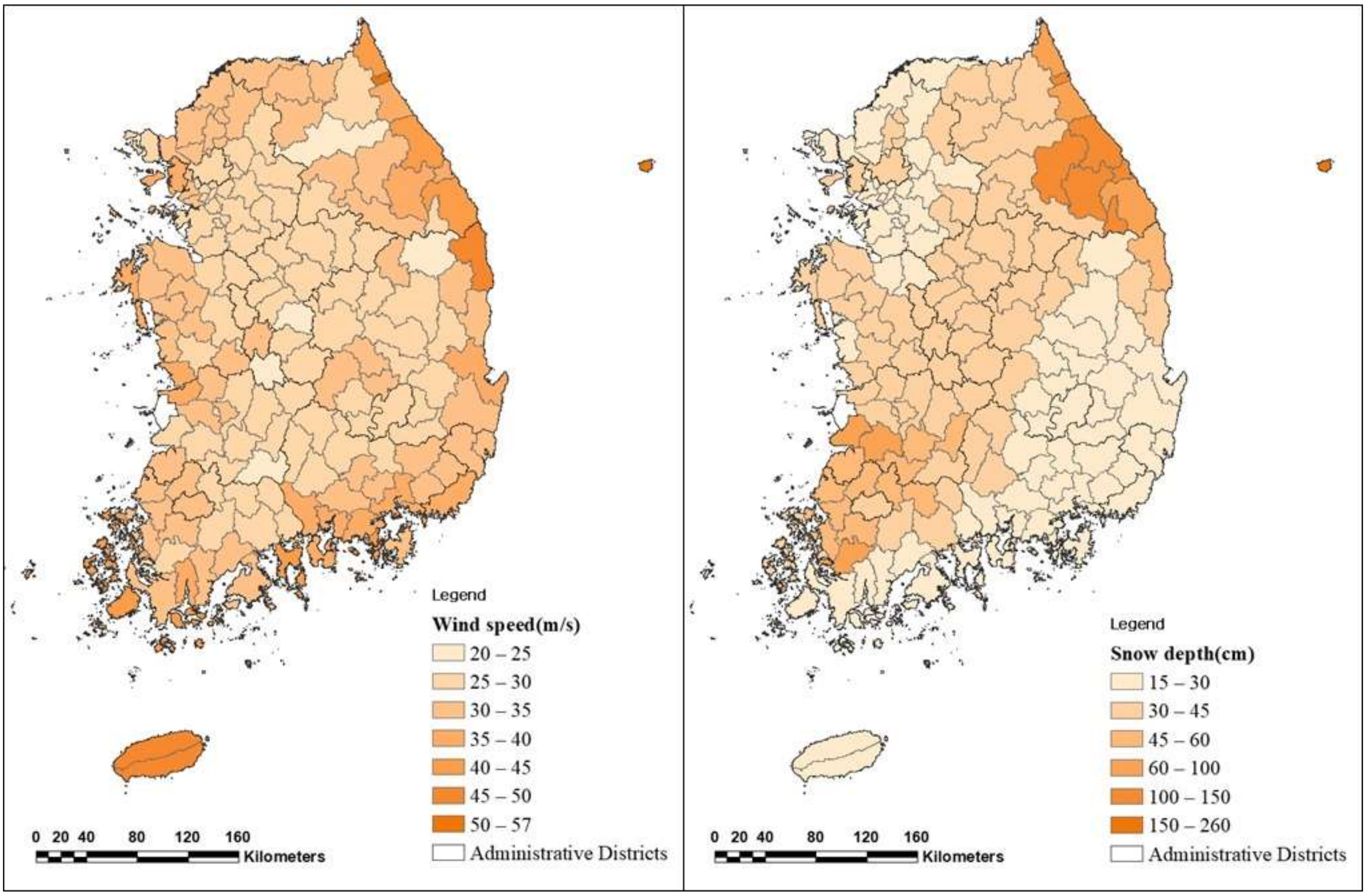


Figure 4. Wind speed and snow depth by administrative districts in South Korea.

Table 1. Reduction coefficient based on the roof slope.

Roof-Slope (°)	10°~20°	20°~30°	30°~40°	40°~60°	60° Over
decrease coefficient	0.90	0.75	0.50	0.25	0.00

Table 2. Unit volume weight based on the snow height.

Snow Height (cm)	50 Less	100	150	200 Over
average unit weight (N/cm·m^2)	9.807	14.710	19.613	29.420

2.2.2. Structural Analysis Method

We construct an optimal cross-sectional setting model using Matlab^{TM} for structural analysis of greenhouses. Using the prepared structural analysis model, we calculated the maximum cross-sectional force generated in the greenhouse member by applying wind load and snow load to the two-dimensional greenhouse structure. In addition, we calculated safety by the average load and reliability using the probability load. In skeletal structures such as greenhouses, the axial force (compression, tensile) and shear force are very small compared to bending stress [36,37]. Therefore, we only considered bending stress as the maximum cross-sectional force to evaluate safety and reliability.

Structural safety is expressed as a factor of safety (SF) and is calculated as the ratio of the maximum stress allowed by the absence of an external average load. Structural reliability is expressed as a probability of failure (PF) and is calculated as the difference between the maximum load [38–40]. This is expressed as a marginal state equation, as shown in Equation (5):

$$G(R, L) = R - L = \sigma_{all} - \sigma_{max} = \sigma_{all} - \frac{M_{max}}{Z} \tag{5}$$

where G refers to the limit state equation, R refers to the resistance, and L is the load. Resistance and load are calculated as σ_{all} and σ_{max}, which refer to allowable and maximum stresses, respectively.

Structural reliability is defined as a multiple integral form for the combined probability density function of probability variables. If the nonlinearity of the marginal state equation is severe, an approximate method is used because it is difficult to accurately grasp the integration path [41]. Monte Carlo simulation (MCS) is the most common technique for approximating the probability of failure, and has the advantage of calculating the probability of failure without any modification to the marginal state equation [42–44]. The MCS extracts random numbers reflecting the distribution characteristics of probability variables to generate a sufficient number of sample groups of probability variables, and then substitutes the values of each generated probability variable into the marginal state equation to determine whether the value is greater than or less than zero, that is, whether the structure is safe or destroyed [45–48]. Through this, when extracting N groups of probability variables, if the marginal state equation is observed n_f times less than 0, the probability of failure P_f can be estimated approximately as shown in Equation (6):

$$P_f = \frac{n_f}{N} \tag{6}$$

After calculating the failure probability of the member based on MCS, the cross-section of the greenhouse was optimized by sequentially applying the sectional data using the maximum value of the failure probability and the ratio of the section, as shown in Equations (7) and (8). Here, α is a coefficient to prevent the divergence of model convergence due to discrete data:

$$A_i^{j+1} = A_i^j + \Delta A_i^j \tag{7}$$

$$\Delta A_i^j = \left(\frac{P_{f\,i}^{\ j}}{P_f{}^i\ max} - 1 \right) A_i^j \alpha \tag{8}$$

For cross-section optimization, it is necessary to determine the final optimal cross-section. The sum of the volumes V_i^j when repeated n times and the sum difference of the volume V_i^{j+1} for $n+1$ times converge in a range of constant tol were set as the optimal cross-section (Equation (9)). Figure 5 summarizes the design process of the numerical model to perform this process:

$$Otp_A = \left| \frac{\sum V_i^{j+1}}{\sum V_i^j} \right| \leq tol \tag{9}$$

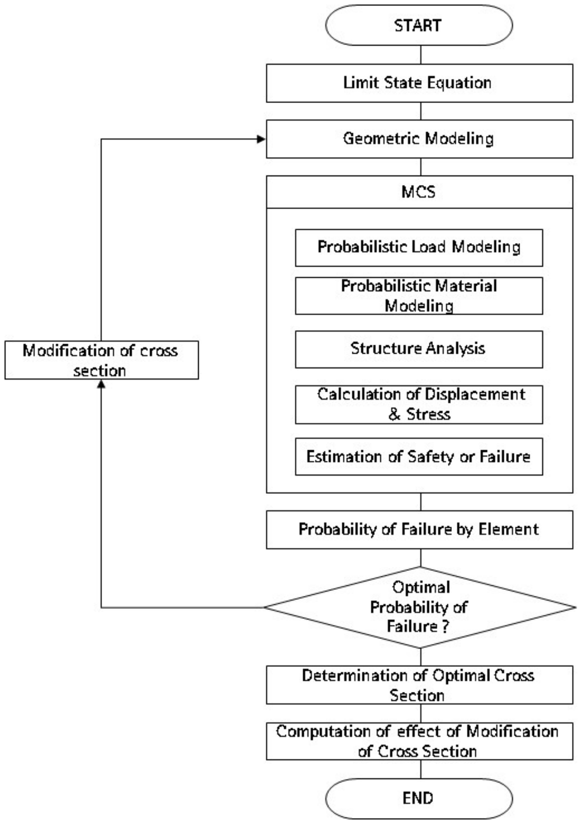


Figure 5. Work flow of the optimal cross-section design process of the numerical model of a greenhouse structure using MCS.

3. Results and Discussion

3.1. Initial Validation of the Model

We validated the optimal cross-sectional setting model using Matlab^{TM} in this study by comparing the results with SAP2000^{TM}, a commercial program. As shown in Figure 6, the stress and displacement of a specific member were compared for a two-span rahmen structure. Table 3 summarizes the cross-sectional shape, load, and material characteristics of the structure used in the verification.

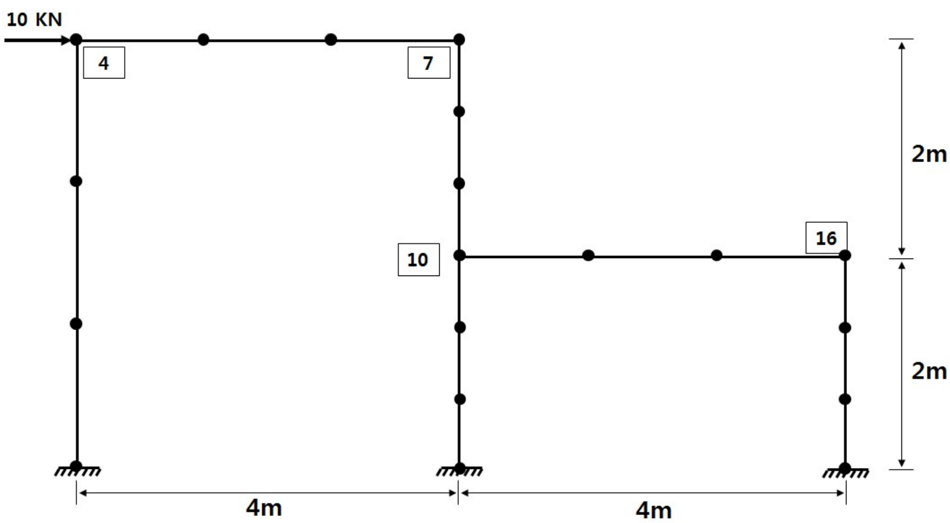


Figure 6. Shape and external load setting of 2-span Rahmen structures for initial verification. The numbers (4, 7, 10, 16) in Rahmen structures mean number of node.

Table 3. Cross-sectional shape and material properties of the model for verification.

Items	Properties
Section	0.2×0.2 m
Poisson's Ratio	0.3
Modulus of elasticity	2.0×10^5 MPa (Steel)
Load	10 kN

For verification, an external load of 10 kN was applied to the upper left of the three-span Rahmen structure, and the stress and displacement of the four nodes were compared. The analysis results showed that the stress had the highest error rate of 2.38% in the 16th member, and the displacement was the highest at 1.17% in the 16th member. The average error rate of stress and displacement was less than 1%, indicating that the accuracy of the calculation based on the external load was high (Table 4).

Table 4. Comparison with existing programs and model.

Node	SAP2000™		Model	
	Displacement (mm)	Stress (MPa)	Displacement (mm)	Stress (MPa)
4	8.062×10^{-4}	5.3486	7.976×10^{-4}	5.3386
7	8.027×10^{-4}	−6.7712	7.941×10^{-4}	−6.7744
10	2.257×10^{-4}	7.2141	2.231×10^{-4}	7.2326
16	2.229×10^{-4}	−4.5699	2.203×10^{-4}	−4.461

3.2. Safety Analysis of Greenhouse Structures

Safety analysis was performed based on the initial cross-sectional conditions considering the average value of the snow load and wind load for a typical Korean glass greenhouse (Table 5). The maximum bending stress for the average snow load was 26.3 MPa (106 N/m^2), and the maximum bending stress for the average wind load was 165.50 MPa. Comparing these stress values with the yield stress that the member can withstand, the SF of all members was safe at 1.0 or more. For the average snow load, the lowest safety factor was 10.4, and the location was an auxiliary column connecting the roof and the auxiliary beam. For the average wind load, the lowest safety coefficient was 1.2, and the location was the columns on the left and right sides.

Table 5. Flexural stress and safety factors by greenhouse member.

Element No.	Stress (N/m^2)		Safety Factor	
	Snow	Wind	Snow	Wind
1	3.29×10^5	2.30×10^8	835.8	1.2
2	1.58×10^7	9.91×10^7	17.4	2.8
3	1.93×10^7	4.16×10^7	14.2	6.6
4	1.02×10^7	8.16×10^6	27.1	33.7
5	1.29×10^7	3.92×10^7	21.3	7.0
6	1.29×10^7	3.27×10^7	21.3	8.4
7	1.02×10^7	3.31×10^7	27.1	8.3

Table 5. *Cont.*

Element No.	Stress (N/m^2)		Safety Factor	
	Snow	Wind	Snow	Wind
8	1.93×10^7	9.72×10^7	14.2	2.8
9	1.58×10^5	1.02×10^8	17.4	2.7
10	3.29×10^5	2.10×10^8	835.8	1.3
11	4.73×10^6	4.90×10^7	58.1	5.6
12	1.23×10^7	1.72×10^7	22.3	16.0
13	5.18×10^5	5.02×10^7	531.3	5.5
14	5.18×10^5	4.61×10^7	531.3	6.0
15	7.87×10^6	6.82×10^7	35.0	4.0
16	4.73×10^6	8.57×10^7	58.1	3.2
17	1.18×10^7	6.10×10^6	23.3	45.1
18	6.47×10^6	2.32×10^7	42.5	11.9
19	8.15×10^5	4.58×10^7	337.6	6.0
20	8.15×10^5	4.96×10^7	337.6	5.5
21	6.47×10^6	7.11×10^7	42.5	3.9
22	1.18×10^7	7.46×10^7	23.3	3.7
23	1.38×10^7	4.34×10^7	19.9	6.3
24	1.04×10^7	7.54×10^7	26.5	3.6
25	3.31×10^6	9.39×10^7	>10,000.0	2.9
26	1.04×10^7	1.12×10^8	26.5	2.5
27	1.38×10^7	1.28×10^8	19.9	2.1
28	2.63×10^7	4.99×10^7	10.4	5.5
29	8.91×10^6	3.14×10^7	30.9	8.8
30	2.63×10^7	9.05×10^7	10.4	3.0

3.3. Reliability Analysis of Greenhouse

The reliability analysis for each member was performed by applying MCS based on the limiting state equation for the greenhouse structure. The variability of probability variables was as follows: for snow load and wind load, the average and deviation values suggested in the analysis modeling were used. The elastic modulus of the member was set to 200 GPa, the yield stress was set to 270 MPa according to the domestic steel standard (KSD 3503), and the variation coefficient was set to 1%. In addition, the probability of failure was calculated by setting the number of repetitions using MCS to 100,000 times.

The probability of failure due to snow load was found to be zero for all members (Table 6). The absence of a greenhouse structure was set to a cross-section that can sufficiently withstand the domestic snow load. The probability of failure due to wind load was up to 0.45992, and the location of the member was a pillar located on the left. This pillar had the highest probability of failure of a member as the wind load acts as the largest load on the pillar on the left. This shows that, in Korea, the possibility of failure due to wind loads is higher than that of snow loads and is the most vulnerable for columns.

Table 6. Probability of failure by greenhouse member column.

Member	Element No.	Probability of Failure	Member	Element No.	Probability of Failure
Column (L)	1	0.45992	Column (R)	9	0.00005
	2	0.00005		10	0.20629
Sub Column	26	0.00014	Etc.		0
	27	0.00132			

Next, the member with a high probability of failure was a pillar located on the right, indicating that both cranes are the most vulnerable due to wind loads. Thus, structures are more likely to be destroyed by wind loads in Korea than by snow loads and wind loads make the pillar most vulnerable. The analysis indicated that the pillars at both ends began to be destroyed at a wind speed of about 45 m/s. When the wind speed was 45 m/s, the left pillar was destroyed 1340 times, and at 46 m/s, it was destroyed 95,753 times (Figure 7). Therefore, considering the safety margin such as the weight of the greenhouse and crop load, the wind speed that the greenhouse can withstand is about 40 m/s. This amount of wind speed can be generated by typhoons, which corresponds to the intensity of typhoons at "Grade 3 (max. Grade 5)" in Korea [49]. Therefore, considering that the frequency and intensity of typhoons have increased due to climate change, the possibility of failure has also increased.

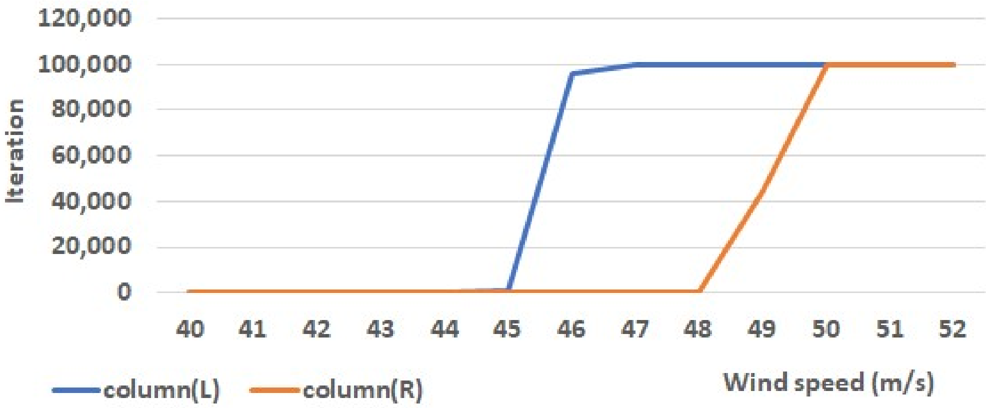


Figure 7. Number of failures according to MCS of columns at both ends based on the wind speed.

3.4. Optimal Section Setting by Failure Probability

The probability of failure by snow load was analyzed as zero for all members. Cross-section optimization was performed based on the probability of failure by wind load. In addition, the failure probability was reviewed by applying the snow load to the set optimal cross-section. Based on the initial cross-section, members with a high possibility of failure by wind load were analyzed as left pillars, and 10 cycles were required for the optimal cross-section. Finally, the probability of converging failure was analyzed as 0.37728, which occurred in the left column as in the initial condition (Figures 8 and 9). As a result, the total amount of materials was reduced by 18.31%. The final optimal cross-section is shown in Table 7. Comparing the optimal cross-section with the existing cross-section, the cross-section of the pillars at both ends decreased. In addition, the cross-section decreased even in the roof connected to the pillar.

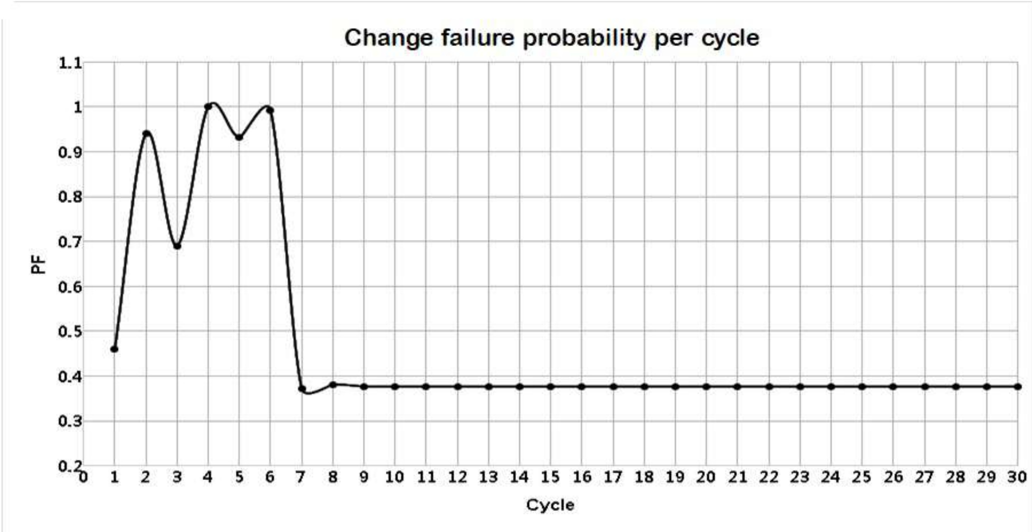


Figure 8. Change failure probability per cycle.

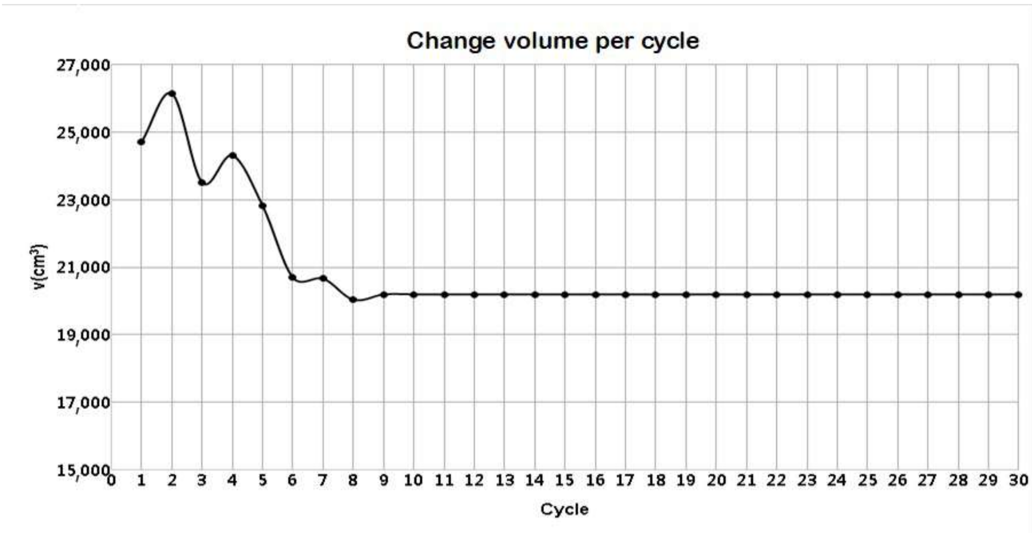


Figure 9. Change volume per cycle.

Table 7. Comparison of the initial section and optimal section.

Items	Cycle #1(Initial)			Cycle #10(Opt section)		
	Pf	A (cm^2)	Section Form	Pf	A (cm^2)	Section Form
Column (L)	0.45992	12.690	□-100 × 50 × 4.5	0.37728	12.160	□-100 × 60 × 4.0
Roof (L)	0.00000	5.350	□-60 × 30 × 3.2	0.01107	4.710	□-50 × 30 × 3.2
Roof (R)	0.00000	5.350	□-60 × 30 × 3.2	0.00000	2.458	□-50 × 30 × 1.6
Column (R)	0.20629	12.690	□-100 × 50 × 4.5	0.13256	12.160	□-100 × 60 × 4.0
Cross Beam	0.00000	4.750	□-60 × 40 × 2.5	0.00004	3.468	□-50 × 30 × 2.3
Roof Support	0.00000	3.840	ㄱ-50 × 50 × 4.0	0.00000	2.247	ㄱ-50 × 50 × 2.3

For the columns at both ends, the size of the cross-section decreased, but the cross-sectional coefficient increased due to the change in shape. As a result, bending stress caused by the bending moment was reduced, resulting in an effect of reducing the probability of failure. For both roofs, the cross-sectional coefficient decreased due to a decrease in the cross-section, which increased the probability of failure. The application of the tongue load based on the optimal cross-section showed that, despite the difference in cross-sections, the possibility of failure in all members was low. Therefore, the optimal cross-section was a cross-section set based on the wind load.

4. Discussion

Due to climate change, this study developed a model to reevaluate the safety of glass greenhouses and the agricultural production infrastructure and to select the optimal cross-section that reduces the possibility of failure. The analysis using the model indicated that structures can be seen as safe based on the degree of safety (F.S). However, from a reliability (PF) perspective, there could be some destruction. For greenhouse members, there is no significant variation in material properties based on national standards (KSD). However, for snow load and wind load corresponding to external load, the deviation is large. In recent years, the frequency of occurrence of localized gusts and snowfall has increased due to climate change. Therefore, it is necessary to provide the wind load and snow load as specific values in the existing greenhouse design as probabilistic values. Currently, Korea's greenhouse design method is based on the ultimate strength design method (USD). However, in 2014, the limited state design method (LSD) was applied to bridges based on probability theory and reliability theory, but it has not been applied to steel structures such as greenhouses. Therefore, the LSD design method should be introduced in the standard design of greenhouses. This requires verification based on the external load and characteristics of each member. Reliability analysis shows reliable simulation results with already widely validated numerical analysis models [50–53]. However, since the probabilistic values for external loads are not clearly established, a quantitative basis for determining them is needed by continuing to conduct structural experiments to review them.

We also performed structural analysis on the frame of the greenhouse. However, the glass in the greenhouse is an important cladding for maintaining an environment for internal growth. Therefore, an evaluation of safety and reliability for glass corresponding to the covering material of the greenhouse should be conducted at the same time. In particular, for wind loads, rapid gusts not only affect the structural safety of the greenhouse, but also the usability of the greenhouse when the glass is destroyed. In particular, typhoons in Korea are concentrated in July and August along with the rainy season, so greenhouses are the most vulnerable due to wind loads. Many more greenhouses are being installed to grow paprika, which is recognized as a high-income crop. Paprika is harvested from June to October for spring cultivation, and from November to March for summer cultivation. Therefore, if a typhoon causes a problem in the covering material of the greenhouse (i.e., glass), it affects the internal growth environment and leads to damaged crops. In other words, wind load not only causes a potential external collapse of the structure, but also has the possibility of causing internal problems for crop cultivation. Therefore, future studies should be conducted on the covering of greenhouses, and should include an evaluation of the safety and reliability of glass due to displacement of greenhouse structures or local gusts.

5. Conclusions

We programmed a model to calculate the probability of failure for greenhouses and developed a sectional setting model for the optimal failure probability applying the concepts of the Monte Carlo simulation technique and simplex method.

The initial cross-section, the safety rate by the average snow load and wind load in Korea, was 1.0. The results identified no problem with safety. However, the possibility of failure was quite high when the concept of probability is introduced. This can be seen as a lack of safety margin for external loads in the current cross-section of greenhouse designs. In Korea, well-known materials are used under relatively constant conditions, and the range of the safety coefficient is set to 1.5 to 2.0 when the size of the load and stress can be easily determined. The lowest safety rate in this study was 1.7, which is included in the safety range. The material used in this study used the cross-section provided by KSD 3503, which is the domestic standard, and is a standardized material with domestic public confidence. In addition, since the snow load and wind load can be set within the range of climate statistics, the safety of the analyzed results has deteriorated. Climate statistics for external loads have changed rapidly due to climate change and abnormal weather. For old greenhouses, materials are aging over time, so it would be unreasonable to simply guarantee safety based on the current safety coefficients.

For this reason, a reliability analysis was performed, and the highest probability of failure of a member was analyzed to be 0.4 or more. Thus, the possibility of failure is quite high. Therefore, it is necessary to change the cross-section to reduce the possibility of failure with the setting of the optimal cross-section of this study. Using the optimal cross-section, it was possible to reduce the probability of failure by about 80%, and the amount of materials could be reduced by about 18%. Therefore, the cross-section we propose makes it is possible to build an economical greenhouse while ensuring that the greenhouse is safe from destruction.

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