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Collapse Behavior of Pipe-Framed Greenhouses with and without Reinforcement under Snow Loading: A 3-D Finite Element Analysis

Yasushi Uematsu[1] and Kazuya Takahashi[2]

1. New Industry Creation Hatchery Center, Tohoku University, Sendai 980-8579, Japan

2. Engineering Headquarters, Shimizu Corporation, Chuo-ku, Tokyo 104-8370, Japan

Abstract: The present paper first investigates the collapse behavior of a conventional pipe-framed greenhouse under snow loading based on a 3-D finite element analysis, in which both geometrical and material non-linearities are considered. Three snow load distribution patterns related to the wind-driven snow particle movement are used in the analysis. It is found that snow load distribution affects the deformation and collapse behavior of the pipe-framed greenhouse significantly. The results obtained in this study are consistent with the actual damage observed. Next, discussion is made of the effects of reinforcements by adding members to the basic frame on the strength of the whole structure, in which seven kinds of reinforcement methods are examined. A buckling analysis is also carried out. The results indicate that the most effective reinforcement method depends on the snow load distribution pattern.

Key words: Pipe-framed greenhouse, snow loading, collapse, buckling, finite element analysis.

1. Introduction

Pipe-framed greenhouses are widely used in the agricultural and horticultural industries in Japan, Korea and many other countries. They are generally designed to a lower level of structural safety than conventional buildings, because of the need to minimize capital costs, the demand for a higher level of light transmission and so on. Being light and flexible, they are often damaged by heavy snowfall [1]. Depression of arch pipes is the most popular type of collapse (see Fig. 1).

In Japan, pipe-framed greenhouses are generally designed based on the allowable stress or deformation limit following the structural guidelines of Japan Greenhouse Horticulture Association [2, 3]. In the allowable deformation design, it is assumed that, even if the stresses of some members exceed the elastic limit, the whole structure will not lose the resistance against snow loads because of the restraint effects given by the surrounding members. Whichever method is used for designing the structure, it is not clear what level of safety margin the structure has before it collapses.

The structural system of pipe-framed greenhouses is quite different from those of conventional buildings, particularly in the connections between structural members as well as in the basement; clamp connectors and swivel couplers are generally used to connect beams to columns and arch-pipes to purlins, and the columns are usually driven directly into the ground. Therefore, several researchers have investigated the structural analysis models which reflect realistic conditions of pipe-framed greenhouses [4-6].

The effect of snow load distribution on the response of a large-span pipe-framed greenhouse was investigated by Wang et al. [7]. They indicated that the maximum displacement of the structure under non-uniform snow load was approximately 2.2 times that under uniform snow load. However, the effect of snow load distribution

Corresponding author: Yasushi Uematsu, Dr. Eng., specially appointed professor, research fields: wind engineering, snow engineering, structural engineering and steel structure.

Fig. 1 Collapse of a pipe-framed greenhouse due to heavy snowfall (Akita City, January 2021).

on the collapse behavior was not investigated. Although Briassoulis et al. [8] investigated the collapse of a practical multi-span greenhouse under heavy snow and moderate wind, few studies have been conducted on the collapse behavior under uniform and non-uniform snow loads even for single-span pipe-framed greenhouses.

The snow resistance of pipe-framed greenhouses can be improved by reinforcements, e.g., adding tie beams and/or braces. Wang et al. [9] investigated the effects of discrete lateral braces on the stability of landing assembled Chinese solar greenhouses. In Japan, several reinforcement methods are used without adequate studies on their reinforcement effects. The effectiveness of these methods needs to be verified.

The present paper first investigates the collapse behavior of a conventional pipe-framed greenhouse without reinforcement under uniform and non-uniform snow loads based on a 3-D finite element analysis, in which both geometrical and material non-linearities are considered. Then, the effect of reinforcement on the strength of the structure is discussed, in which seven types of reinforcement methods are examined.

It should be noted that the present paper is an extended version of our previous paper [10], focusing on the 3-D behavior of the structure.

2. Finite Element Analysis

2.1 Analytical Model and Condition

Fig. 2 illustrates the analytical model (basic model) investigated in this study, which is one of the most popular pipe-framed greenhouses constructed in Japan. The dimensions are as follows: span B = 5,400 mm; length L = 21,600 mm; ridge height H = 3,000 mm; eaves height h = 1,550 mm; and distance between adjacent arch pipes d = 450 mm. The arch pipes are carbon steel tubes for general structural purpose (JIS G3445 STKM11A) with Young's modulus E = 2.05×10^5 N/mm^2, Poisson's ratio ν = 0.33 and yield stress σ_y = 175 N/mm^2. The outer diameter ϕ and thickness t of arch pipes are 22.2 mm and 1.2 mm, respectively. The whole structure consists of 49 arch pipes, 3 horizontal tie beams connecting the arch pipes together at the location of knees and ridge, and 22 gable columns. The horizontal tie beams are connected to the arch-pipes by means of "cross-over connection". Entrance doors in the gable walls are not modeled, which will not affect the general behavior of the structure significantly. The load bearing width of arch pipe and gable column is 450 mm except for the gable frames; the value for the gable frames is 450/2 mm. The wind resistant performance of this pipe-framed greenhouse was investigated in detail by Uematsu and Takahashi [11].

Fig. 3 shows the methods of reinforcement on the basic frame, which are investigated in this study. "Case 0" represents the basic frame without reinforcement. The reinforcing members are also circular pipes of outer diameter ϕ = 22.2 mm and thickness t = 1.2 mm. They are pin-jointed to the basic frame or to the ground. In Cases 1 to 5, the reinforcing members are attached to the basic frame (in-plane reinforcement) at an

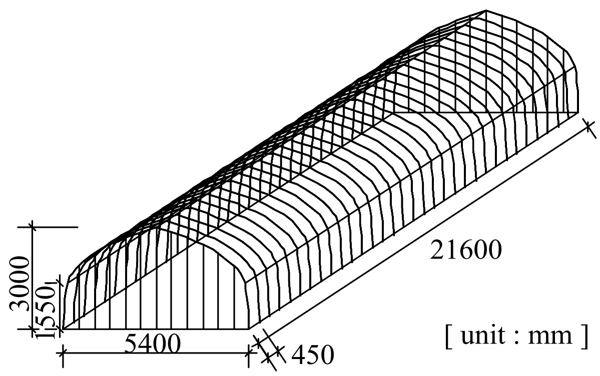

Fig. 2 Analytical model.

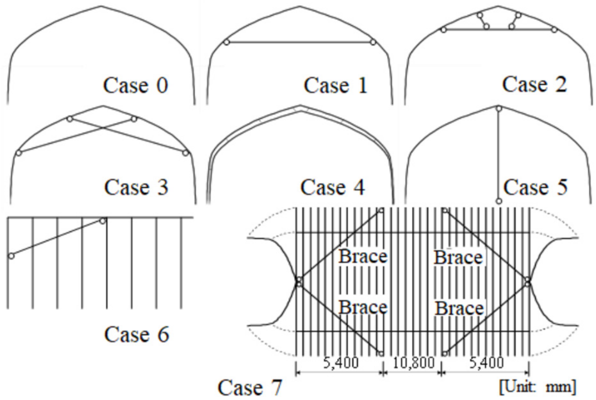

Fig. 3 Reinforcement methods.

interval of 1.8 m in the longitudinal direction. Cases 6 and 7 are out-of-plane reinforcements. Note that the figures of Cases 6 and 7 shows a side view and a development view of the structure, respectively. An angle brace is attached between the central gable column and the top of the fifth arch pipe in Case 6. A pair of diagonal braces are attached between the top of gable wall and the foots of the 13th arch pipe in Case 7. Case 5 is regarded as a temporary reinforcement. The reinforcing members, which may get in the way of work in the greenhouse, are attached to the basic frame only when heavy snowfall is expected.

2.2 Finite Element Structural Analysis

A non-linear finite element analysis of the structure under snow loading is made by using a commercial computer software "ABAQUS 6.13". The arch pipe is divided into 80 beam elements, as shown in Fig. 4. The other members are divided into beam elements of 150 mm length. The length of the elements was determined based on the computation accuracy and load. The arch pipes and gable columns are clamped to the ground. The "multipoint constraint" is applied to the boundary condition of the structural members; that is, at the joint of arch pipe and horizontal tie beam, the displacements of the two members are the same, but the members can rotate independently with each other, which is called "pin connection" in this paper. Such a condition seems practical considering that the arch pipes and the horizontal tie beams are jointed by "cross-over connection". In the structural analyses of pipe-framed greenhouses, for simplicity, it is often assumed that arch pipes and tie beams are rigidly jointed, which is called "rigid connection" in this paper. Therefore, these two kinds of connection methods are used in this study.

In the analysis, both geometrical and material non-linearities are considered. The arc-length method is employed, in which the arc length is controlled so that the equilibrium path up to the collapse of the structure can be traced. Such a condition that a part of the frame reaches the ground is regarded as "collapse". The stress -strain (σ-ε) relationship of the material is represented by a bi-linear model (see Fig. 5), in which the secondary gradient is assumed to be E/420, according to Ogawa et al. [12]. The finite element model and the method of analysis were validated by a comparison of the computed results for the deformation of the frame under vertical loads with the experimental ones provided by Ogawa et al. [12] (regarding the details of validation, see Takahashi and Uematsu [13]).

Buckling may occur before the maximum strength is reached. Therefore, a linear buckling analysis is also carried out by solving an eigenvalue problem. The buckling load and mode are given by the eigenvalue and eigenvector, respectively.

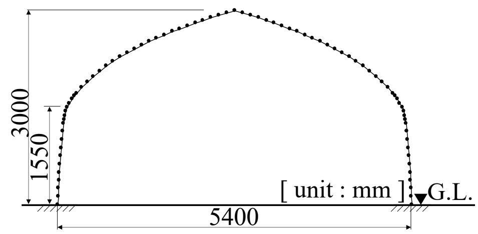

Fig. 4 Finite element model of the arch pipe.

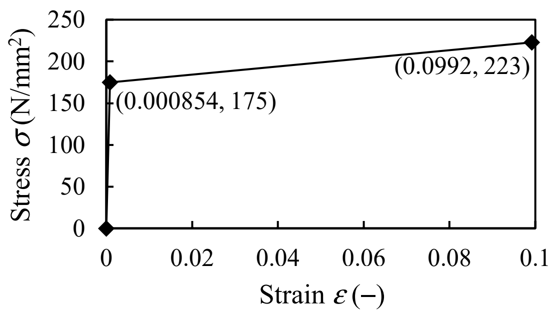

Fig. 5 Stress-strain relationship of the material.

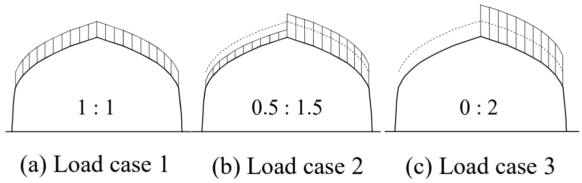

Fig. 6 Snow load distributions.

2.3 Snow Load Distribution

Non-uniform snow load distributions may occur due to the snow particle movement caused by wind. Therefore, not only uniform distribution but also non-uniform distribution of snow load is considered. The snow loads per unit area, S_W and S_L, on the windward and leeward halves of the roof are assumed constant over the areas. The ratio of S_W and S_L is changed on the condition that the total load is kept constant. The snow load per unit area is given by the product of average snow density ρ_s (assumed 9.8 N/m$^2 \cdot$ cm, according to Japan Greenhouse Horticulture Association [2]) and snow depth. The snow depths on the windward and leeward roofs are denoted as d_W (= $\alpha_W d_0$) and d_L (= $\alpha_L d_0$), respectively. Note that "d_0" represents the reference snow depth. Fig. 6 shows three kinds of snow load distributions on the roof, i.e., S_W:S_L = 1:1 (Load case 1), 0.5:1.5 (Load case 2) and 0:2 (Load case 3). The total snow load on the structure is the same for all load cases. The snow loads are applied to the nodes of the finite element model as concentrated loads, which are evaluated by considering the tributary areas of the nodes. For simplicity, the loads are assumed to act in the vertical direction despite the deformation of the frame. Strictly speaking, this assumption is not practical when the deformation becomes rather large, resulting in the redistribution of snow accumulation on the roof due to snow sliding. However, considering the deformation of the frame, which will be shown later, it is thought that all snow remains on the roof even if the frame is deformed.

3. Collapse Process of the Basic Frame

3.1 Deformation

Fig. 7 shows the relationship between the reference snow depth d_0 (snow load ρd_0) and the vertical displacement δ_{top} at the top of the central frame for the three load distribution patterns (Load cases 1 to 3). The connection between arch pipes and horizontal tie beams is assumed to be "pin connection". The vertical dashed line in the figure represents the deformation limit (B/60) specified in Ref. [2]. It is found that the snow load distribution affects the d_0-δ_{top} curve significantly. The value of d_0 providing the allowable stress, denoted as "d_{0s}" hereafter, is 12.8 cm for Load case 1 and 8.9 cm for Load case 3. When d_0 exceeds d_{0s}, the d_0-δ_{top} curve exhibits non-linearity. In Load case 1, the value of d_0 providing the deformation limit, denoted as "d_{0d}" hereafter, is 17.9 cm and that providing the maximum strength, denoted as "d_{0max}" hereafter, is 19.4 cm. The ratio of d_{0max} to d_{0s} is about 1.5 (= 19.4/12.8), while the ratio of d_{0max} to d_{0d} is about 1.1 (=19.4/17.9). This means that the safety margin of the structure is small when the structure is designed based on the allowable deformation limit. In Load case 3, the safety margin is much smaller, as small as almost 1.0. However, the load reduction after the maximum value is small in any load case. The deformation proceeds with almost constant load after d_0 reaches the maximum value d_{0max}.

Fig. 8 illustrates the deformations of the central frame when a part of the frame reaches the ground, which is regarded as "collapse". The figure also shows the result when the frame has initial imperfection in Load case 1 (regarding the initial imperfection, see the next sub-section). The red lines represent the regions where the strain is in the plastic range. As might be

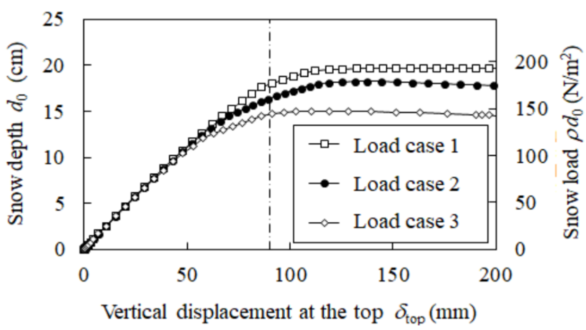

Fig. 7 Relationship between snow depth d_0 (snow load ρd_0) and vertical displacement δ_{top} at the top of central frame.

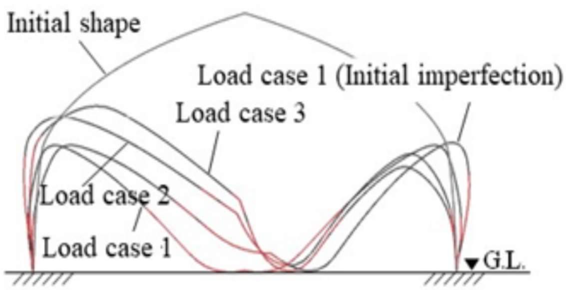

Fig. 8 Collapse modes of the central frame.

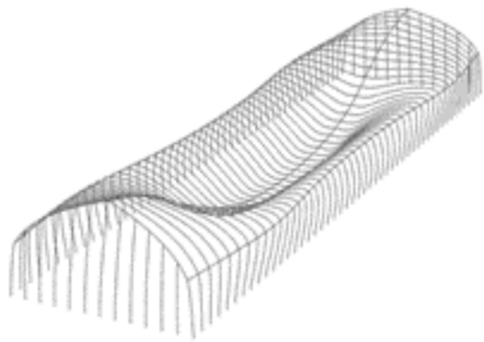

Fig. 9 General view of the collapse mode (Load case 1).

expected, the collapse mode is symmetric with respect to the centerline through the vertex in Load case 1. In practice, however, such a case rarely occurs due to some imperfection in geometry and/or load distribution. In the other cases, the deformation exhibits asymmetry. The point of the maximum displacement shifts to the side subjected to larger loading. Such deformations are consistent with those observed in practical damage investigations (see Fig. 1, for example).

The general view of the collapse mode in Load case 1 is illustrated in Fig. 9. The collapse mode is symmetric with respect to the vertical planes including the ridge and the central frame. The results for the "rigid connection", not shown here to save space, were found to be almost the same as those shown here. Therefore, it is said that the connection condition between arch pipes and tie beams affects the collapse mode only a little.

3.2 Effect of Initial Imperfection

The geometrical initial imperfection is defined as the deviation of the shape from the complete system. In this study, it is assumed that the imperfection is similar to the buckling mode and the maximum imperfection is 0.01ϕ, with ϕ being the external diameter of arch pipes. Figs. 10a and 10b show the linear buckling modes in Load case 1 for the "pin connection" and "rigid connection", respectively. Note that the buckling mode only for the half structure is illustrated in Fig. 10a, which is dominated by the displacements in the longitudinal direction with almost no in-plane deformations. This is due to the low horizontal stiffness of the structure. It can be seen from Fig. 10 that the buckling mode is affected by the connection condition significantly. The values of d_0 providing the buckling, denoted as "d_{0b}" hereafter, were 25.8 cm and 84.4 cm for "pin connection" and "rigid connection", respectively. These values are larger than d_{0max} (see Fig. 7), particularly in the "rigid connection" case.

The collapse modes for the "pin connection" and the "rigid connection" in Load case 1 are shown in Figs. 11a and 11b, respectively. In the "pin connection" case, large deformation area occurs close to a gable wall. In the "rigid connection" case, on the other hand, the collapse mode is symmetric with respect to the vertical plane including the central frame. However, the collapse mode of each frame is asymmetric with respect to the centerline through the vertex as in the case of perfect system subjected to non-uniform snow loads (see Fig. 8). Despite such a difference in the collapse mode, not only the snow loads providing the allowable stress but also the maximum loads for the two connection conditions were almost the same as those for the perfect systems. This feature implies that the initial imperfection affects the collapse behavior only a little, at least within the limits of the present analysis.

(a) Pin connection (b) Rigid connection

Fig. 10 Linear buckling modes.

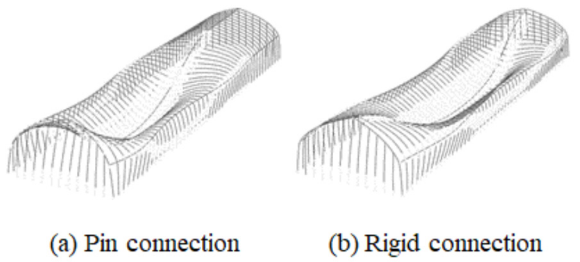

Fig. 11 Collapse modes (Load case 1).

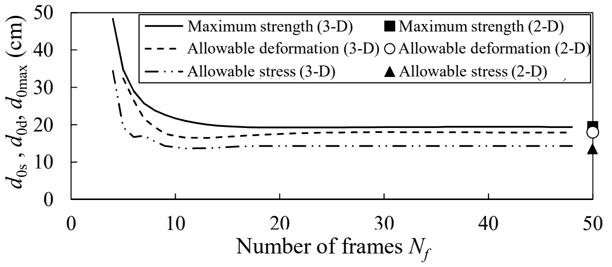

Fig. 12 Variation of d_{0s}, d_{0d} and d_{0max} with N_f in Load case 1.

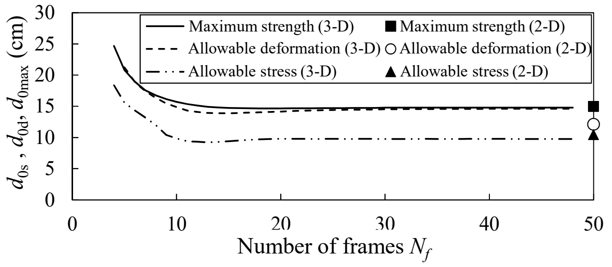

Fig. 13 Variation of d_{0s}, d_{0d} and d_{0max} with N_f in Load case 3.

3.3 Three-Dimensional Effect

To investigate the 3-D effects on the collapse behavior and the strength of pipe-framed greenhouses, the number of frames is changed in this sub-section. The connection between arch pipes and tie beams is assumed to be "pin connection".

Figs. 12 and 13 show the variation of "d_{0s}" (allowable stress), "d_{0d}" (allowable deformation) and "d_{0max}" (maximum load) with the number of frames, N_f, for Load cases 1 and 3, respectively. The results of the 2-D analysis are also plotted in the figure. In the 2-D analysis, the restraint effects of gable wall and tie beams on the deformation of the structure are ignored. The variation of d_{0s}, d_{0d} and d_{0max} with N_f is rather large when $N_f < 10$. However, these values are almost constant when $N_f > 20$. In Load case 1, the values of d_{0a}, d_{0d} and d_{0max} for $N_f > 30$ almost coincide with those obtained from the 2-D analysis. In Load case 3, on the other hand, the behavior of d_{0s} and d_{0max} is almost the same as that in Load case 1. However, there exists a significant difference in d_{0d} between the 2-D and 3-D analyses even when $N_f = 49$. This may be due to a larger restraint effect of the tie beam at the knee of the frame, considering that the horizontal displacement at the knee is larger in Load cases 2 and 3 than in Load case 1 (see Fig. 8). As mentioned above, d_{0d} is close to d_{0max}, particularly in Load case 3. The results of Figs. 12 and 13 indicate that the 2-D analysis can be used in practical cases where $N_f > 10$.

4. Strength of the Reinforced Frames

This section discusses the effects of reinforcement (Fig. 3) on the values of d_{0s}, d_{0max} and d_{0b}. Note that the deformation at the maximum load (snow depth d_{0max}) is smaller than the deformation limit in any case of reinforcement. Therefore, d_{0d} is not considered here.

Tables 1 and 2 summarize the values of d_{0s}, d_{0max} and d_{0b} for the "pin connection" and "rigid connection", respectively. When $d_{0b} < d_{0max}$, buckling may occur before the maximum load is reached, resulting in the collapse of the structure. That is, smaller value of d_{0max} and d_{0b} corresponds to the failure load.

In Cases 1 to 5 (in-plane reinforcement), the reinforcement increases the values of d_{0max} significantly for both "pin-connection" and "rigid connection". In case of "pin-connection", the reinforcement does not contribute to the increase in d_{0b}, because the buckling mode is dominated by the displacements in the longitudinal direction with almost no in-plane deformations (see Fig. 10a). On the other hand, in Cases 6 and 7 (out-of-plane reinforcement), the reinforcement significantly increases the value of d_{0b} for the "pin connection". However, the values of d_{0s} and d_{0max} are not increased by the reinforcement for both "pin connection" and "rigid connection".

There is no reinforcement method that contributes to the increases in both d_{0max} and d_{0b} among those examined in this study. Therefore, a combination of in-plane reinforcement and out-of-plane reinforcement may effectively increase the values of both d_{0max} and d_{0b}. In case of "rigid connection", the reinforcement by using diagonal braces (Case 7) does not contribute to the increases in both d_{0max} and d_{0b}. This feature is not necessarily consistent with the finding in practical damage investigations, where many pipe-framed greenhouses reinforced by diagonal braces were exempted from snow-induced damage. This implies that the connection between arch pipes and tie beams in practical pipe-framed greenhouses is close to the "pin-connection".

Table 1 Effects of reinforcement on d_{0s}, d_{0max} and d_{0b} in case of "pin connection" (unit: cm).

(a) d_{0s} (Allowable stress)

Reinforcement	Load case 1	Load case 2	Load case 3
Case 0	12.8	10.6	8.9
Case 1	17.2	16.3	12.6
Case 2	15.5	12.1	9.1
Case 3	12.5	10.8	9.5
Case 4	14.7	12.6	11.2
Case 5	17.5	17.3	13.5
Case 6	13.4	11.0	9.3
Case 7	13.0	10.7	9.2

(b) d_{0max} (Maximum load)

Reinforcement	Load case 1	Load case 2	Load case 3
Case 0	19.4	17.8	14.8
Case 1	32.0	23.6	16.6
Case 2	24.0	19.1	15.5
Case 3	22.7	20.7	17.9
Case 4	24.4	22.1	17.8
Case 5	42.3	28.9	20.5
Case 6	19.5	17.9	14.8
Case 7	19.4	17.8	14.8

(c) d_{0b} (Buckling)

Reinforcement	Load case 1	Load case 2	Load case 3
Case 0	25.8	25.1	23.5
Case 1	24.3	23.7	22.2
Case 2	24.7	23.9	22.1
Case 3	24.2	22.1	20.0
Case 4	29.4	28.6	26.5
Case 5	23.9	23.9	23.9
Case 6	34.2	32.8	29.7
Case 7	41.1	41.1	41.0

Table 2 Effects of reinforcement on d_{0s}, d_{0max} and d_{0b} in case of "rigid connection" (unit: cm).

(a) d_{0s} (Allowable stress)

Reinforcement	Load case 1	Load case 2	Load case 3
Case 0	13.4	11.1	9.5
Case 1	19.4	19.0	14.6
Case 2	16.0	10.4	7.7
Case 3	13.2	11.2	9.7
Case 4	15.7	13.5	11.7
Case 5	21.5	21.2	14.8
Case 6	13.4	11.1	9.5
Case 7	13.4	11.2	9.6

(b) d_{0max} (Maximum load)

Reinforcement	Load case 1	Load case 2	Load case 3
Case 0	19.7	18.2	15.0
Case 1	34.9	26.1	18.9
Case 2	25.2	20.3	16.5
Case 3	24.1	22.6	20.2
Case 4	24.7	22.6	18.4
Case 5	46.3	30.3	20.9
Case 6	19.7	18.3	15.0
Case 7	19.8	18.5	15.2

(c) d_{0b} (Buckling)

Reinforcement	Load case 1	Load case 2	Load case 3
Case 0	84.4	83.7	81.7
Case 1	72.8	72.6	71.9
Case 2	98.2	96.7	93.1
Case 3	64.9	63.3	59.3
Case 4	110.1	98.0	85.0
Case 5	25.3	25.3	25.3
Case 6	84.4	83.7	81.8
Case 7	57.0	56.9	56.8

The effect of reinforcement depends on the snow load distribution significantly. Cases 1 and 5 are effective for uniform load (Load case 1), but not so effective for non-uniform loads (Load cases 2 and 3). For example, the value of d_{0max} in Load case 3 is about one half of that in Load case 1. Cases 2 to 4 are not so effective for uniform load compared with the other reinforcement methods, but effective for non-uniform loads. Case 3 provides larger values of d_{0max} for Load case 3, because it has a greater restraint effect on the displacement of the frame at the knee. Our previous study [11] indicated that this reinforcement method was also effective in improving the wind resistance performance of the structure.

Case 5 seems effective. However, considering the workability in the greenhouse, it is difficult to install the vertical reinforcing members at all times. The members are temporarily installed when heavy snowfall is expected. The increase in initial cost for the reinforcement can be suppressed. However, if the reinforcing members have not been installed securely before heavy snowfall, the risk of the frame collapsing increases. The values of d_{0b} are small. This is due to the buckling of the reinforcing members. For increasing the buckling strength, it is necessary to use members with larger moment of inertia or to take some measures to prevent buckling of the reinforcing members.

5. Concluding Remarks

Three-dimensional finite element analysis was conducted on a pipe-framed greenhouse commonly used in Japan to clarify the collapse behavior under snow loading and to obtain basic knowledge for establishing a more rational snow-resistant design method for pipe-framed greenhouses.

First, the analysis was performed for the basic frame considering both geometric and material nonlinearities to reproduce the process leading up to the collapse. The results qualitatively well reproduced the actual collapse behavior of pipe-framed greenhouses due to heavy snowfall. It is found that the design based on the allowable deformation limit employed in the current structural guidelines has a small safety margin until the ultimate bearing capacity is reached beyond the allowable capacity, and that the non-uniformity in load distribution reduces the load bearing capacity of the structure significantly. The buckling behavior is significantly affected by the condition of connection between arch pipes and horizontal tie beams. The “pin connection” provides more realistic failure modes than the “clamped connection”. The effects of initial geometric imperfection and the number of frames N_f (provided that $N_f > 10$) on the strength and collapse behavior are small.

Next, the effects of various reinforcement methods on the strength of the frame were investigated, in which seven kinds of reinforcement methods were used. The results indicate that in-plane and out-of-plane reinforcements are effective against different collapse modes. Therefore, a combination of these two reinforcement methods seems effective in improving the snow resistance of the structures. The results also show that reinforcements using diagonal members are effective against non-uniform loads too.

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