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Comparative study on planar model and three-dimensional model for Venlo-type greenhouse structures

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Abstract. Greenhouse structures have been analyzed and designed generally using planar model in Chinese. An essential shortcoming of this type of model is that the spatial effect in the longitudinal direction is not considered. This results in inaccurate design results of the structures. To overcome this shortcoming, a structural design software was proposed based on finite element method with consideration of three-dimensional effect. The software function was introduced and two numerical examples were presented to demonstrate the reasonable results using three-dimensional models. Results using planar and three-dimensional models were compared in respects of strength, stability and lateral displacements.

Keywords. Greenhouse, structural design software, spatial action, finite element method based model.

1. Introduction

Greenhouses are building facilities that provide places for cultivation and growth of plants. The structural design of greenhouses is an important ingredient for the whole construction and generally conducted by means of design software to ensure structural safety, reasonable construction cost and design duration. Up to now, several countries, e.g., the USA, Netherlands, Japan and Israel, have structural design softwares for greenhouses with consideration of specific climatic conditions and industrial characteristics in their countries. One of the famous software is CASTA which is provided by the Netherlands Organization for Applied Scientific Research. However, this software is not sold outside Europe.

Currently, two structural design softwares for greenhouses have been used popularly in China. One is the GSS v1.0 developed by the China Academy of Agricultural Engineering. The other is GSCAD owned by the China Academy of Building Research. The two technical tools have the capability to model, calculate and design typical greenhouses. However, GSS v1.0 can neither model greenhouses in a three-dimensional formulation, nor define a member made up of aluminium alloys. It also can not automatically produce construction drawings. GSCAD can geometrically build spatial model but the mechanical models are actually computed in a planar formulation. From a viewpoint of structural analysis, the computation using planar models generally result in safety side for structures with regular forms. However, for those with irregular forms, both unsafety and overconservativeness can exist.

In this regard, a robust design software for greenhouses, i.e., GreenHouse v1.0, was developed considering spatial action and featured with wide applicability. The software function was first introduced and then two design examples were presented to demonstrate the importance of taking spatial effect into account.

2. Function of structural design software GreenHousev1.0

The software consists of three modules, i.e., the pre-process, structural analysis and post-process modules, as illustrated in Figure 1. The function of the pre-process module is to build the structural model of a greenhouse including geometric system, member system and loads system. The function of the structural analysis module is computation which includes loads computations, mechanical computations based on finite element method (FEM), and checking computations for structural members. The computed results can be shown graphically or in text version in the post-process module. The graphical presentation is achieved using secondary development based on the Autocad Graphic Platform using ObjectARX technique in Visual C++. The Visual Studio2012 was used as programming environment.

A greenhouse is made up of columns, trusses, roof bars, water channels, braces, wall beams and roof. The materials to build roof can be glass, plastics and thin films. In the software only bar elements using a Timoshenko beam formulation are applied to model the structural members. The roof is not modeled in the FEM model. However, its loads including dead loads and wind loads are taken into account. This is because the failure of the glass and plastics are brittle which have negative influence on computational convergence. The checking computations for internal forces, deformations, lateral displacements, and stabilities are conducted in accordance with the Chinese codes [1-3].

The GreenHouse v1.0 has the capacity of three-dimensional modeling and visualization, and is associated with three advantages. The first one is convenient and accurate for computing loads. The second one is implementation of spatial effect. This is important for the greenhouses using brackets which have significant spatial effect relating to structural performance. Finally, the out-of-planar loads can be applied in the model which is essential for appropriate computations.

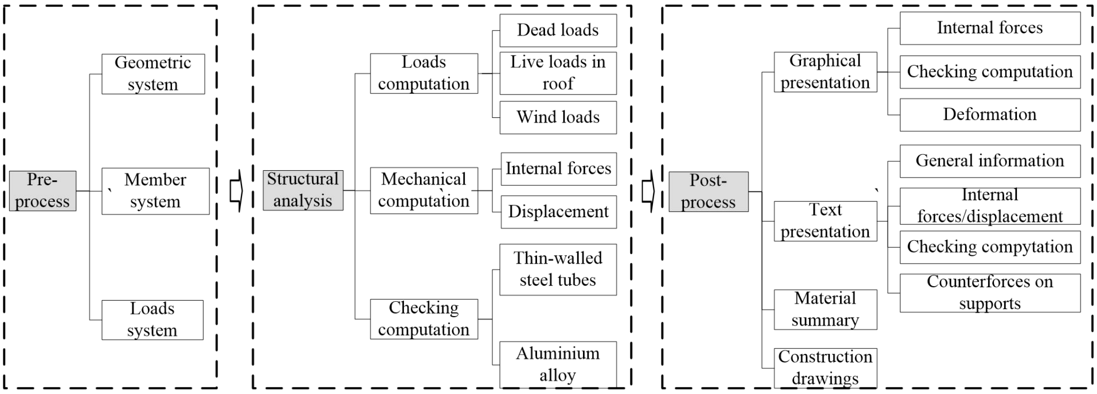


Figure 1. Modular design scheme for GreenHouse v1.0

3. Model verification

Two design examples are presented in this Section for model verification. In the first example a greenhouse was computed using two different softwares and the results were compared with each other. The difference between the results using two- and three-dimensional models was presented in the second example.

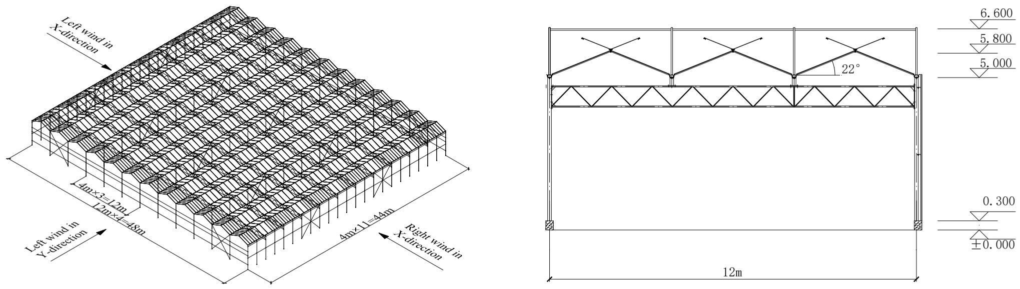
3.1. The first design example

Figure 2 illustrates a glass greenhouse located in Zhejiang province, China. In the transverse direction, the structure has four spans with the span length of 12 m. Each span includes three secondary spans having identical length. In the longitudinal direction, the structure has eleven spans of 4 m span length. The elevations of the tops for roof and for external slabs for sunshade are 5.8 m and 6.6 m, respectively. The roof slope is 22°. Thin-walled rectangular steel tubes 120×60×4.5 were used for the columns. For the trusses in transverse direction, thin-walled rectangular steel tubes 60×40×2.5 were applied for the upper and lower chords. The circular tubes 32×2 were used for webs and the small columns on the trusses were constructed using the thin-walled rectangular steel tubes 120×60×2.5. The braces between columns were built using steel rods of 16 mm diameter and the wall beam were fabricated applying thin-walled channel steel C80×40×2. The water channels, roof ridges and roof bars were built using aluminium alloys. The structure′s service life for design was 20 years. The basic wind pressure w_0 was 0.33 kN/m^2 with the terrain rough category of B type. The wind pressure height coefficient was set to 1.0. The basic snow pressure S_0 was 0.5kN/m^2. The heating coefficient was assumed to 0.6 with consideration of single-glasses. The plant loads were 0.15 kN/ m^2.

Two three-dimensional models, i.e., Models 1 and 2 as illustrated in Figures 3 and 4, were built using softwares GreenHouse v1.0 and SAP2000, respectively. SAP2000 is an analysis software and has no structural design function. As an alternative, the design values of loads were manually obtained based on the computed internal forces using Model 2, together with the partial coefficients for loads and the coefficients for combination of loads conditions[4].

The internal forces and displacements on column tops were obtained using Models 1 and 2. The design values of axial forces in columns and truss members were compared in Table 1 using Models 1 and 2 for the loads conditions of dead loads, snow loads and plant loads. Table 2 presents those design values for the loads conditions of left and right winds in X- and Y-directions. Tables 3 and 4 present the maximum displacement on column tops using Models 1 and 2 for the loads conditions of left wind in X- and Y-directions, respectively. The definition of wind direction is illustrated in Figure 3a. Results found that the data obtained from Models 1 and 2 were close to each other with the maximum error of 7.1%. Similar observations were applicable to other internal forces and displacements which were not presented here. In addition, the checking computations relating to stability were also close to each other using the two models.

Figure 2. Greenhouse in the first design example



(a) global views (b) vertical section of one span in transverse direction

Figure 3. Model 1 using GreenHouse v1.0 for the greenhouse in the first design example

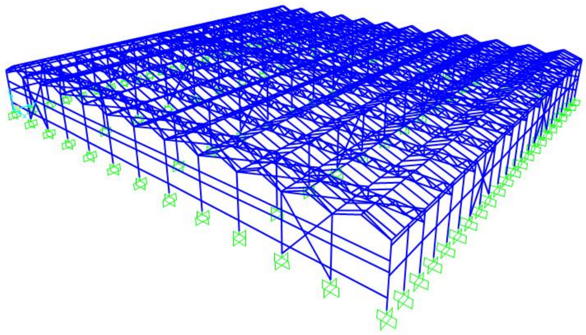


Figure 4. Model 2 using SAP2000 for the greenhouse in the first design example

Table 1. Comparison for axial forces in columns and truss members using different models for the loads conditions of dead loads, snow loads and plant loads

Structural members	Dead loads condition			Snow loads condition			Pant loads condition		
	Model 1 (kN)	Model 2 (kN)	Error (%)	Model 1 (kN)	Model 2 (kN)	Error (%)	Model 1 (kN)	Model 2 (kN)	Error (%)
Side column	-4.70	-4.60	-2.1	-5.12	-5.15	0.6	-2.91	-2.91	0.0
Middle column	-11.49	-11.45	-0.3	-15.77	-15.76	-0.1	-8.07	-8.07	0.0
Upper chord in truss (left roof)	-11.53	-11.50	-0.3	-16.21	-16.19	-0.1	-9.08	-9.07	-0.1
Upper chord in truss (middle roof)	-11.52	-11.49	-0.3	-16.21	-16.19	-0.1	-9.08	-9.07	-0.1
Upper chord in truss (right roof)	15.94	15.93	-0.1	23.21	23.19	-0.1	12.34	12.34	0.0
Lower chord in truss (left roof)	10.69	10.71	0.2	15.55	15.53	-0.1	8.06	8.05	-0.1
Lower chord in truss (middle roof)	12.33	12.32	-0.1	18.08	18.06	-0.1	9.04	9.03	-0.1
Lower chord in truss (right roof)	-10.66	-10.63	-0.3	-14.93	-14.92	-0.1	-8.88	-8.88	0.0
Web in truss (left roof)	3.58	3.56	-0.6	5.17	5.17	0.0	3.43	3.44	0.3
Web in truss (middle roof)	-1.39	-1.34	-3.6	-1.59	-1.59	0.0	-2.05	-2.05	0.0
Web in truss (right roof)	5.73	5.72	-0.2	8.12	8.11	-0.1	5.33	5.33	0.0

Table 2. Comparison for axial forces in columns and truss members using different models for loads conditions of left and right winds in X- and Y-directions

Structural members	Left wind in X-direction			Right wind in X-direction			Left wind in Y-direction		
	Model 1 (kN)	Model 2 (kN)	Error (%)	Model 1 (kN)	Model 2 (kN)	Error (%)	Model 1 (kN)	Model 2 (kN)	Error (%)
Side column	2.81	2.82	0.4	1.68	1.69	0.6	1.15	1.14	-0.9
Middle column	6.83	6.83	0.0	7.20	7.20	0.0	3.44	3.44	0.0
Upper chord in truss (left roof)	-7.73	-7.75	0.3	10.11	10.14	0.3	3.80	3.81	0.3
Upper chord in truss (middle roof)	4.47	4.44	-0.7	10.11	10.14	0.3	3.80	3.81	0.3
Upper chord in truss (right roof)	-8.31	-8.32	0.1	13.18	13.17	-0.1	-4.57	-4.57	0.0
Lower chord in truss (left roof)	-5.73	-5.69	-0.7	-9.61	-9.65	0.4	-2.73	-2.74	0.4
Lower chord in truss (middle roof)	-7.69	-7.66	-0.4	-9.73	-9.76	0.3	-3.34	-3.34	0.0
Lower chord in truss (right roof)	-5.29	-5.27	-0.4	9.71	9.70	-0.1	3.67	3.67	0.0
Web in truss (left roof)	-3.03	-3.04	0.3	-1.65	-1.64	-0.6	-1.18	-1.18	0.0
Web in truss (middle roof)	0.14	0.13	-7.1	1.43	1.43	0.0	0.32	0.32	0.0
Web in truss (right roof)	-3.12	-3.12	0.0	-4.33	-4.33	0.0	-1.75	-1.74	-0.6

Table 3. Maximum displacement on column tops using different models for the loads conditions of left wind in X-direction

Model	Maximum displacement on column topsin different locations (mm)						
	Axial A	Axial B	Axial C	Axial D	Axial E	Axial F	Axial G
Model 1	6.49	25.72	31.77	32.43	32.46	32.45	32.45
Model 2	6.30	26.00	31.70	32.00	31.90	32.10	32.10
Error (%)	-2.9	1.1	-0.2	-1.3	-1.7	-1.1	-1.1

Table 4. Maximum displacement on column tops using different models for the loads conditions of left wind in Y-direction

Model	Maximum displacement on column tops in different locations (mm)						
	Axial 1	Axial 1/1	Axial 1/2	Axial 2	Axial 2/1	Axial 2/2	Axial 3
Model 1	2.06	4.40	5.77	2.48	5.38	5.99	2.44
Model 2	2.03	4.35	5.76	2.47	5.27	5.88	2.43
Error (%)	-1.5	-1.1	-0.2	-0.4	-2.0	-1.8	-0.4

3.2. The second design example

Figure 5 illustrates a greenhouse located in Tianjin, China. The structure has five spans in transverse direction. The first span has a length of 9.6 m. Each of the other spans has a span length of 19.2 m with 6 secondary spans of 3.2 m. The elevations of the roof top is 7.96 m. Thin-walled square steel tubes 200×5 were used for internal columns and rectangular steel tubes 200×100×5 were used for side columns. For the trusses, the thin-walled rectangular steel tubes 100×80×3 were applied for the upper and lower chords, the square tubes 50×2 were used for webs, and rectangular steel tubes 120×60×3 for the small columns on the trusses. For the brackets in longitudinal direction, the thin-walled rectangular steel tubes 100×80×4 were applied for the upper and lower chord members, the square tubes 50×2 were used for web members. The braces between columns used steel rods of 16 mm diameter and the wall beam applied thin-walled channel steel C80×40×2.5. The water channel, roof ridges, roof bars were built using aluminium alloys. The structure′s service life for design was 20 years. The basic wind pressure w_0 was 0.48 kN/m^2 with the terrain rough category of B type. The basic snow pressure S_0 was 0.26kN/m^2. The plant loads were 0.18 kN/ m^2.

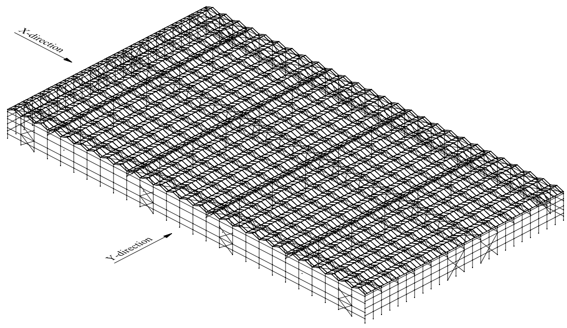


Figure 5. Three-dimensional Model 3 for the greenhouse in the second design example

A spatial model and a planar model were built using GreenHouse v1.0 and denoted as Models 3 and 4, respectively. The loads in Model 3 are designated as the summation of the loads in the two neighbouring half span.

The design values of internal forces and displacements were obtained using Models 3 and 4. Table 5 presents the strength and stability computation results for some typical members using different models. Tables 6 and 7 summary the maximum displacements of column tops in X- and Y-directions for loads condition of left wind using different models, respectively. The definition for X- and Y- directions are indicated in Figure 5. It was shown from Table 5 that:

(1) For the strength and stability, the computation results of the columns from three-dimensional model were small compared to those from two-dimensional model with a maximum error of 32%. This is because the wind-induced moments became small with consideration of spatial action.

(2) Significant differences were found for the results of the chords and webs of the trusses in transverse direction between the two models. The main reasons were that the out-of-plane internal forces due to the wind in Y-direction were included in Model 3 but not included in Model 4.

Moreover, Tables 6 and 7 indicated that:

(1) Displacements in Model 3 were smaller than those in Model 4 with a maximum error of 30%. This was because the structure had two secondary spans of 4 m length within one span in longitudinal direction. The columns that connected the secondary spans had the capacity to resist lateral displacements. This resistance was not considered in Model 4, leading to underestimate the resistance capacity of the structure under lateral loads.

(2) The displacements in longitudinal direction were predominant in this study case, which was different from the generally scenarios. In this sense, computation using three-dimensional is indispensable.

Table 5. Strength and stability computation results of some members using different models

Structural members	Ratio of stress to strength			Ratio of in-plane stability-stress to strength			Ratio of out-of-plane stability-stress to strength		
	Model 3	Model 4	Error (%)	Model 3	Model 4	Error (%)	Model 3	Model 4	Error (%)
Side column	0.41	0.54	31.7	0.43	0.55	27.9	0.40	0.32	-25.0
Middle column	0.48	0.61	27.1	0.72	0.82	13.9	0.71	0.48	-32.4
Upper chord in truss (left roof)	0.19	0.17	-10.5	0.17	0.15	-11.8	0.15	0.12	-20.0
Upper chord in truss (middle roof)	0.20	0.11	-45.0	0.19	0.06	-68.4	0.15	0.05	-66.7
Upper chord in truss (right roof)	0.51	0.49	-3.9	0.09	0.20	122.2	0.07	0.18	157.1
Lower chord in truss (left roof)	0.19	0.24	26.3	0.19	0.24	26.3	0.15	0.18	20.0
Lower chord in truss (middle roof)	0.10	0.09	-10.0	0.09	0.09	0.0	0.09	0.08	-11.1
Lower chord in truss (right roof)	0.41	0.40	-2.4	0.44	0.43	-2.3	0.40	0.36	-10.0
Web in truss (left roof)	0.09	0.09	0.0	0.11	0.11	0.0	0.11	0.11	0.0
Web in truss (middle roof)	0.14	0.14	0.0	0.17	0.17	0.0	0.17	0.17	0.0
Web in truss (right roof)	0.31	0.32	3.2	0.37	0.37	0.0	0.37	0.17	-54.1

Table 6. Maximum displacements of column tops in X-direction for the loads conditions of left wind using different models (mm)

Model	Maximum displacement on column tops in different locations (mm)						
	Axial A	Axial 1-A	Axial B	Axial 1-B	Axial C	Axial 1-C	Axial D
Model 1	3.27	4.08	16.74	28.77	34.99	39.23	39.32
Model 2	56.72						

Table 7. Maximum displacements of column tops in Y-direction for the loads conditions of left wind using different models (mm)

Model	Maximum displacement on column tops in different locations (mm)					
	Axial 1	Axial 2	Axial 3	Axial 4	Axial 5	Axial 6
Model 1	11.9	30.76	45.78	50.78	44.46	13.42
Model 2	unavailable					

4. Conclusions

A structural design software for greenhouses was developed featured with three-dimensional modeling. The loads were automatically computed and the spatial action was naturally taken into account. This software is superior to the currently applied softwares which use a planar modeling technique. The function of the software was introduced and two design examples were presented. Following conclusions can be drawn based on the studies:

(1) Generally, the internal forces and lateral displacements are reduced using the model considering spatial effect compared to those using planar model. This positive effect is evident in cases of the presence of brackets in longitudinal direction.

(2) The planar models overestimate the resistant capacity of greenhouses in aspects of strength and stability. This shortcoming is overcome when an appropriate three-dimensional model is used.

(3) The three-dimensional models are applicable for the greenhouses with secondary columns in longitudinal direction because the resistance of these columns in longitudinal direction is appropriately considered. The displacement in longitudinal direction can be computed using a three-dimensional model.

Acknowledgments

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