TECHNICAL NOTE

Analysis of the Metal Structure of a Greenhouse Intended for Automated Vertical Agriculture

Análisis de la estructura metálica de un invernadero destinado a la agricultura vertical automatizada

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ABSTRACT: The analysis of the metal structure of a greenhouse intended for the production of vegetables, using vertical agriculture technology, is carried out in the present work. The greenhouse will be installed in “San Juan Raboso” Community, belonging to Izúcar de Matamoros Municipality, State of Puebla, Mexico, in response to the community need of food and as part of the strategic project developed by the Center for Interdisciplinary Research and Service in Science, Nature, Society and Culture (CIISCINASyC). The analysis of the metal structure of the greenhouse was carried out applying the Finite Element Method. The objective of the work was to evaluate the resistance capacity and functionality of the greenhouse, by determining the load system that acts on the greenhouse, as well as the distribution of stresses and displacements in the structure.

Keywords: Home-Food-Analysis-Safety.

RESUMEN: En el presente trabajo se realiza el análisis de la estructura metálica que conforma un invernadero destinado a la producción de hortalizas, empleando tecnología de agricultura vertical y que será instalado en la Comunidad San Juan Raboso, perteneciente al Municipio Izúcar de Matamoros, Estado de Puebla, México, en respuesta a las necesidades de alimentación de la comunidad y como parte del proyecto estratégico que desarrolla el Centro de Investigaciones Interdisciplinarias y de Servicio en Ciencia, Naturaleza, Sociedad y Cultura (CIISCINASyC). El análisis de la estructura metálica que conforma el invernadero se realizó aplicando el Método de los Elementos Finitos. El objetivo del trabajo consistió en evaluar la capacidad de resistencia y funcionalidad del invernadero mediante la determinación del sistema de cargas que actúa sobre el invernadero, así como de la distribución de tensiones y desplazamientos en la estructura.

Palabras clave: casa-alimentos-análisis-seguridad.

INTRODUCTION

During the last 30 years in Mexico, the hegemonic economic policy worldwide and its implementation exacerbated the problem of food sovereignty and security, accentuated by the economic recession due to the Covid19 pandemic. An alternative solution to this problem is based on the production of vegetables for urban-peri-urban family self-sufficiency, using automated vertical agriculture modules, which are being applied in “San Juan Raboso” Community, Izúcar Municipality of Matamoros, Puebla.

According to the Food and Agriculture Organization of the United Nations (FAO), approximately one third of the food produced worldwide for human consumption is wasted annually. (Kosai, 2013; FAO, FIDA, OPS, WFP y UNICEF, 2018; Banco Interamericano de Desarrollo, 2020). As a way to reduce the consequences of resource waste, a new form of agricultural cultivation was created, consisting of automated vertical modules, which are placed inside greenhouses and which must be designed to guarantee their functionality. These modules require electric or diode lamps (LED), air conditioners, fans, CO_2 and nutrient supply units (Kosai, 2013), and it is necessary to guarantee the physical integrity of both, these components and the structure and cover of the greenhouse itself, considering the diversity of the loads to which it will be subjected, composed of the self-weight of the structure and its components, the possible blow of high intensity winds and the weight of the crop, among others.

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It is in this sense that the objective of this work is to carry out an analysis of the stresses and deformations that occur on this type of structure, in order to evaluate its resistance to the load system to which it may be subjected.

For the analysis, the Finite Element Method (FEM) is used, which is widely applicable in structural analysis. (Agudelo-Manrique *et al.*, 2015; Toledo-Freire, 2015; Besa-Gonzálvez y Chuliá, 2016; CFE-México, 2017; González *et al.*, 2017; Faires, 2018; Ortiz-Domínguez *et al.*, 2018; Vanegas-Useche, 2018).

MATERIALS AND METHODS

The work process for the analysis of the structure consists of three fundamental steps: preparation of the digitized three-dimensional model of the structure, determination of the loads and application of the Finite Element Method based on the application of the loads on the digitized model.

The loads to be applied are made up of:

- The loads associated with the own weight of the metal structure of the cultivation house.
- The loads produced by the plastic covers and anti-aphid protection elements.
- Loads produced by weather conditions (winds, hail).
- The loads associated with the own weight of the crop, the object of production in the greenhouse.

Weight of the Metal Structure (PEM)

The calculation of the weight of the object of study is determined as:

$$P_{EM} = M_{EM} \cdot g, N \quad (1)$$

Where:

g: acceleration of gravity (g): 9.81 m/s^2

M_{EM}: mass of the metallic structure, which is given by

$$M_{EM} = \gamma_{Ac} \cdot V_{EM}, \text{kg} \quad (2)$$

being:

V_{EM}: volume of the metal structure, m^3

γ_{Ac}: steel density, γ_{Ac}, kg/ m^3

The volume of the structure is obtained automatically from the software used in its digitization (SolidWorks), while the density value is taken from the materials library of the software itself.

Weight of Covers and Meshes (F_{CM})

The weight of the cover and includes: the weight of the plastic that covers the overhead window (P_{PVC}), the weight of the plastic of the upper arch on the left (P_{ASIZQ}), the weight of the plastic of the minor arch on the right (P_{AMDER}), the weight of the plastic of the side curtains (P_{PCL}), the weight of the plastic that covers the front (P_{PFP}) and the weight of the anti-aphid meshs (P_{MAA}).

To determine the weight of the plastic covers, the technical specifications (Table 1) established by the Izucar de Matamoros Community are used.

TABLE 1. Technical specifications

Type	Description
Plastic	milky white
Caliber	720
Density	γ_p=0.19 kg/m^2
Shade percentage	30 %
Protection	UV

The weight of the plastic that covers the overhead window (P_{PVC}) is determined according to the expression:

$$P_{PVC} = M_{(T)} \cdot g, \text{N} \quad (3)$$

being:

$$M_{(T)} = \gamma \cdot \text{A}, \text{kg} \quad (4)$$

where:

$M_{(T)}$: roof window plastic mass l, kg

A: cross-sectional area of zenith window, m^2

γ_π: density per unit area of plastic, kg/m^2

g: acceleration of gravity; g = 9.81 m/s^2

The area of the zenith window is determined by the expression:

$$A = L \cdot B, \text{m}^2 \quad (5)$$

where:

L: roof window length; L = 50 m

B: roof window width; B = 1.43 m

The weight of the plastic of the upper arch on the right (P_{ASder}) is determined according to the expressions:

$$P_{ASder} = M_{(T)} \cdot g, \text{N} \quad (6)$$

$$M_{(T)} = \gamma \cdot A_{ASder}, \text{kg} \quad (7)$$

where:

$A_{AS\,Izq}$: area of the upper arc to the right, given by:

$$A_{ASder} = L_{ASder} \cdot L_{inv}, \text{m}^2 \quad (8)$$

where:

$L_{AS\,Izq}$: length of upper right arc; $L_{ASder} = 4.99m$

L_{inv}: length of the greenhouse; $L_{inv} = 50$m

The weight of the plastic that covers the front (P_{Pcp}) is determined according to equation (9) and depends on the amount of metal structures in the greenhouse.

$$\boldsymbol{P_{Pcp}} = \frac{P_{Pcf} + \boldsymbol{P_{PDA}}}{16}, \text{N} \quad (9)$$

where:

P_{Pcf}: front curtain plastic weight, **N**

P_{PDA}: weight of the plastic below the arches to the tutoring bar, **N**.

The weight of the anti-aphid mesh (P_{MAA}) is determined by equation (10).

$$P_{MAA} = (\gamma_{MAA})(A_{MAA})g, \text{N} \quad (10)$$

where:

γ_{MAA}: density per unit area of the anti-aphid mesh material; $\gamma_{MAA} = 0{,}123\frac{kg}{m^2}$ g: acceleration of gravity; $g = 9{,}81\frac{m}{s^2}$ A_{MAA}: anti-aphid mesh area:

$$A_{MAA} = (L_{MAA})(h_{MAA}), \text{m}^2 \quad (11)$$

where:

L_{MAA}: anti-aphid mesh length; $L_{MAA} = 50\,m$

h_{MAA}: anti-aphid mesh width; $h_{MAA} = 4.20m$

The aerodynamic loads produced by the wind are determined taking into account the standards and specifications for studies, projects, construction and installations: (ASCE, 2005; NIFED-México, 2011; NMX-E-255-CNCP-2013, 2013; INIFED-México, 2017).

The load of wind effects (q_i), on the section of the metallic structure or component thereof, object of analysis, is determined by the general expression:

$$q_i = (q_{10}{*}C_t{*}C_s{*}C_h{*}C_r{*}C_{ra}){*}C_f \quad (12)$$

where:

q_{10} : basic wind pressure, kN/m^2

C_t : recurrence coefficient

C_s: topography or site coefficient

C_h : height coefficient

C_r: blow coefficient

C_{ra}: reduction coefficient per exposed area

C_f: shape or aerodynamic coefficient

The basic wind pressure is determined by:

$$q_{10} = \frac{V_{10}{}^2}{1.6{*}10^3} \quad (13)$$

where:

V_{10}: regional speed, which is defined as the maximum wind speed that occurs at a height of 10 m above the location of the structure, for conditions of flat terrain with isolated obstacles (m/s).

The loads q_i (kN/m^2), are determined in the different sections of the greenhouse, such as: the lateral structure on the left (q_{3izq}); the lateral structure on the right (q_{3der}); the portion of the left structure of the lower arch (q_1); the portion of the right structure of the lower arch (q_2) and the portion of the upper arch structure (q_{1sup}).

The strengths F_i (kN) resulting in each section of the greenhouse as a result of the aerodynamic action of the wind, are determined based on the loads q_i , considering the corresponding areas A_i (m^2) of each section.

The force F_{gr} (kN) due to the mass of hail in the gutters, is determined according to the MEXICAN STANDARD NMX-E-255-CNCP-2013 (2013), which establishes as a base 30 kg per linear meter in the gutter.

To calculate the force applied on the structure due to the weight of the crop Pc (kN), the tomato is selected and it is determined according to the Mexican standard NMX-E-255-CNCP-2013 (2013), which allows considering tomato cultivation a heavy load, equivalent to 35 kg/m^2.

The SolidWorks 2018 program is used for the 3D digital modeling of the greenhouse structure, as well as for carrying out the stress and deformation analysis using the finite element method. ASTM A-36 steel with density γ_{Ac} = 7850 kg/m^3 and elastic limit σ_e = 250 MPa.

To carry out the resistance and deformation analysis, the digitized model of the structure under study is subjected to the calculated load system, applying the Finite Element Method (FEM) to determine the distribution of stresses and deformations. The calculation is carried out on a cross section of the tunnel of the metal structure, located in a corner of the greenhouse, considering that this section is subjected to the most severe loading conditions.

RESULTS AND DISCUSSION

Figures 1 and 2 show the three-dimensional model of the metal structure of the greenhouse, as well as the section of the basic module.

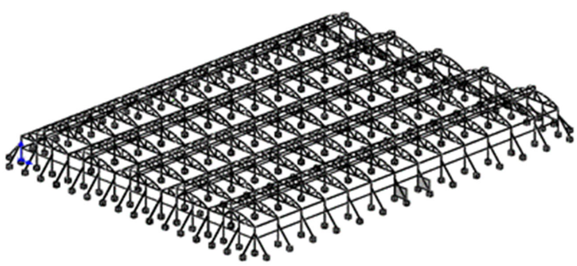

FIGURE 1. Metal structure of the greenhouse**.**

The main geometric characteristics of the greenhouse are provided in Table 2.

Loads Associated With the Own Weight of the Metal Structure of the Cultivation House

The weight of the metal structure (P_{EM}) was determined using equation (1), obtaining the volume of the structure section under analysis, directly as an output from the SolidWorks program and likewise, the density of the material was taken from the materials library of the software itself. As a result, the following values were obtained:

$$V_{EM} = 0.0229 \text{ m}^3$$

$$\gamma_{Ac} = 7850 \text{ kg/m}^3$$

$$P_{EM} = 1{,}76 \text{ kN}$$

Loads Produced by Plastic Covers and Anti-Aphid Protection Elements

The result of the calculation of the different loads due to the weight of the covers and meshes that act on the greenhouse structure is shown in Table 3.

From the table, it can be seen that the weight corresponding to the plastic of the zenith window is the most significant, followed by that of the front curtain, while the rest have much lower values.

Loads Produced by the Meteorological Conditions (Winds, Hail)

To calculate the aerodynamic loads, it was necessary to determine previously the coefficients contained in expression (12). Table 4 shows the result of the determination, according to the standards, of the coefficients required for determining the aerodynamic loads.

The result of the calculation of the aerodynamic loads acting on the greenhouse is shown in Table 5.

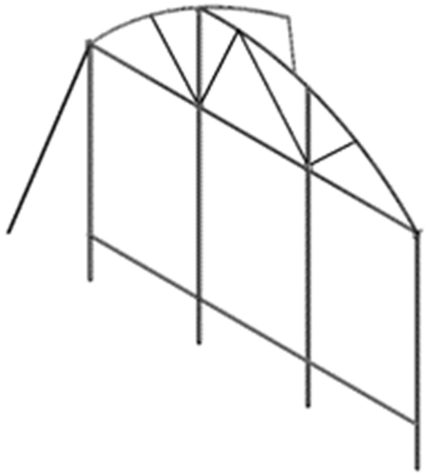

FIGURE 2. Digitized model of the basic module of the structure.

For the calculation of the load caused by hail, the Mexican Standard was taken into account. NMX-E-255-CNCP-2013 (2013), which establishes for calculation purposes, taking as a basis, 30 kg per linear meter in the gutter. Table 6 details the specifications taken into consideration and the results of the calculation.

Loads Associated with the Crops Own Weight

To calculate the own weight of the crop, the object of production in the greenhouse, tomato is selected, which according to the Mexican Standard NMX-E-255-CNCP-2013 (2013), is considered of heavy load, equivalent to 35 kg/m^2. The weight of the crop affects the metal structure of the greenhouse since it is fixed to the staking bar. The available area between

TABLE 2. Geometric characteristics of the greenhouse

Specifications	Magnitudes
Greenhouse width	40 m
Depth	50 m
Height to base of lower arch	5 m
Height to the base of the zenith window	8 m
Angle to the midline of the lower arch	35^0
Angle to the midline of the arch of the zenith window	60^0

TABLE 3. Loads acting on the greenhouse as a result of the weight of the covers and meshes

Denomination	Symbol	Unit	Values	Observations
Weight of the plastic of the overhead window	P_{PVC}	N	9 519,0	Expressions 3, 4 y 5
Weight of the plastic of the minor arch on the right	P_{AMder}	N	37,9	Expressions 6, 7 y 8
Weight of the plastic of the side curtains	P_{PCL}	N	34,6	
Weight of the plastic of the front curtain	P_{Pcf}	N	402,0	
Weight of the plastic below the arches to the tutoring bar	P_{PDA}	N	21,9	
Weight of the plastic that covers the front part	Pcp	N	26,5	Expression 9
Weight of the Anti-aphid mesh	P_{MAA}	N	18,1	

TABLE 4. Values of the coefficients for determining aerodynamic loads

Denomination	Symbol	Value	Observations
Recurrence coefficient	C_t	1,0	Useful life: 10 years Recurrence: 50 years
Topography or site coefficient	C_s	1,10	Severe conditions
Height coefficient	C_h	1,0	Open ground Greenhouse height ≤ 10 m
Blow coefficient	C_r	1,20	Greenhouse height ≤ 10 m
Reduction coefficient per area exposed	C_{ra}	0,90	Exhibition area ≤ 50 m^2
Coeficiente de forma o aerodinámico.	C_f		NMX-E-255-CNCP (2013)
Shape coefficient of the left-lateral structure	C_{f3izq}	0,80	NMX-E-255-CNCP (2013)
Shape coefficient of the right-lateral structure	C_{f3der}	-0,43	NMX-E-255-CNCP (2013)
Shape coefficient of the lower-arch left portion	C_{f1}	-0,325	NMX-E-255-CNCP (2013)
Shape coefficient of the lower-arch right portion	C_{f2}	-0,40	NMX-E-255-CNCP (2013)
Shape coefficient of the upper-arch portion	C_{f1sup}	0,30	NMX-E-255-CNCP (2013)

TABLE 5. Aerodynamic loads acting on the greenhouse

Denomination	Symbol	Unit	Values	Observations
Basic pressure of the wind	q_{10}	kN/m^2	0, 694	Expression 13. It is taken V_{10}=120 km/h (33,3 m/s)
Loading of the lateral structure on the left	q_{3izq}	kN/m^2	0,659	Expression 13; Table 3 coefficients
Loading of the lateral structure on the right	q_{3der}	kN/m^2	- 0,354	"
Load on the left-frame portion of the lower arch	q_1	kN/m^2	- 0,267	"
Load on the right-frame portion of the lower arch	q_2	kN/m^2	- 0,329	"
Load on the structure portion of the upper-arch	q_{1sup}	kN/m^2	0,247	"
Strength on the structure portion of the upper arch	F_{VC}	kN	14,498	
Wind force in the lower arch	F_{V1}	kN	-2,932	
Strength in the right portion of the lower arch	F_{V2}	kN	-35,153	
Lateral strength in the left spine	F_{V2IZQ}	kN	5,794	
Lateral strength in the right spine	F_{V2DER}	kN	2,382	

TABLE 6. Specifications for calculating the load caused by hail

Specifications	Magnitudes
Distance between columns ; D_c	**3.57 m**
Hail mass, between two columns ; M_{GRC}	107.1 kg
Weight of hail in gutter distributed in both gutters ; P_{GRC}	525.32 N
Unit load of hail in the gutter ; C_c	30 kg/m

4 columns of the tunnel is equal to 32 m^2, approximately, so the total load of the crop, including its fruits and the rest of the plant, will be equal to 1120 kg.

Stress and Strain Analysis

Once the load system to which the greenhouse structure will be subjected was determined, an analysis of stresses and deformations was carried out in order to evaluate the resistance capacity of the structure to the system of faces applied. For this purpose, the digitized model of the structure under study was subjected to a static analysis, using the Finite Element Method, using the SolidWorks program.

Once the loads, restrictions, contact options and meshing of the structure were applied, the results were the stress distributions (Fig. 3), safety coefficient (Fig. 4) and displacements (Fig. 4) in the module of the structure under study.

Figure 3 shows that the maximum normal stress amounted to 95.2 MPa, being located at the intersection between the lower end of the zenith window rod and the lower arch of the tunnel, while the minimum normal stress (0.2 MPa) was recorded close to the intersection node between the load bar and the load post on the right of the tunnel.

Likewise, it was verified that this tension is lower than the elastic limit of the material (250 MPa), obtaining a minimum safety coefficient of 2.63, which is verified in Figure 4. This resistance safety coefficient is in the range permissible level established by the user (between 2.5 and 3.0), confirming that the structure is functional and safe.

Regarding the displacements, it can be seen (Figure 5) that the maximum displacement reached 46.11 mm, which, taking into account that the length of the element where it occurs is of the order of 8000 mm, can be considered insignificant. That guarantees that it will not cause physical-structural effects on the structure of the greenhouse, which limit its functionality.

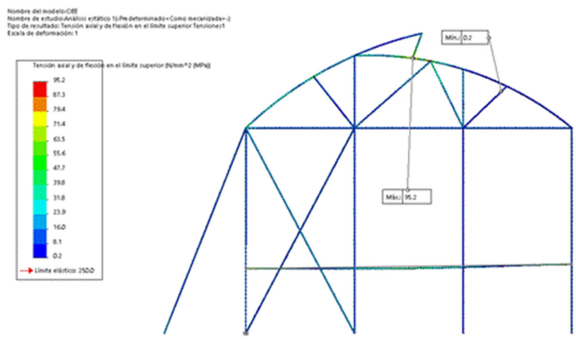

FIGURE 3. Distribution of normal stresses in the structure under study.

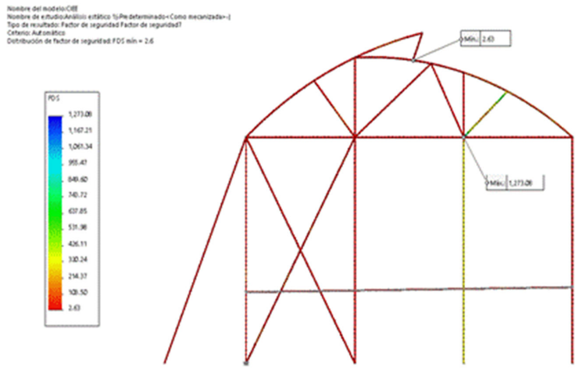

FIGURE 4. Distribution of the safety coefficient.

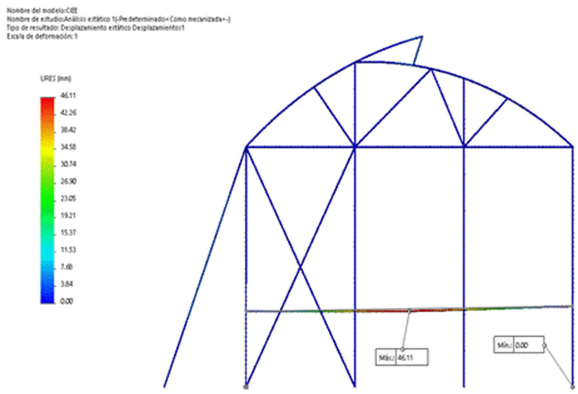

FIGURE 5. Distribution of the displacements.

CONCLUSIONS

As a result of determining the load system that acts on the structure of a greenhouse, considering the loads of the structure's own weight, the covers, the weight of the crop itself and the effects of wind and hail, it is determined, by applying these loads to a digitized model of the greenhouse using the Finite Element Method, that the maximum normal stresses on the structure reach 95.2 MPa, for a minimum safety coefficient of 2.63 in relation to the elastic limit of the material that makes up the metal structure of the greenhouse. Likewise, a maximum level of displacement of 46.11 mm is determined, which is considered, not to limit the functionality of the structure.

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