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Deflection of greenhouse truss using finite element

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ABSTRACT: This study analyzes the behavior of a Warren truss for a greenhouse using the finite element method. The truss consists of 50 nodes and 47 identical galvanized steel bars with a span of 5.04 m. It is intended to support an agrivoltaic greenhouse. The objective is twofold: first, to determine the truss' response to external stresses at these nodes—elongations, deformations, stresses, and normal forces in the bars-and second, to understand the modal deformations. This study is part of the development of a calculation tool for designing structures to address our specific challenges. This work is a static analysis of a flat truss beam of hinged bars for a greenhouse, aimed at optimizing agricultural production. It also incorporates the vibration analysis of the truss, including the determination of its natural modes. A calculation program was developed using matrix calculation software, Matlab R2022b. The results are consistent with the RDM 7 structural analysis software. The maximum stress is -3.3305 MPa (compression). This is considerably higher than the material's elastic limit of 220 MPa. These results also confirm the suitability of the structure for agrivoltaic greenhouses. The natural frequencies vary from W1 = 266 rad/s to W47 = 24894 rad/s; W24 = 14232 rad/s is shown in the illustration.

KEYWORDS: study, statics, vibration, beam, Warren, natural mode.

1 INTRODUCTION

Agricultural activity remains predominant in Africa [1]. It is the main pillar of the Ivorian economy [2]. The unpredictable nature of climate change is challenging traditional agricultural production methods. Agricultural greenhouses appear as a palliative solution to optimize production. Although used elsewhere in greenhouse framing [3], Warren truss structures are virtually nonexistent in our tropical regions. They are advantageous from a morphological point of view and are less deformable than Pratt and Howe trusses [4]. Furthermore, many design software programs (Catia, SolidWorks, Ansys, etc.) [5], [6] include structural analysis modules, particularly for trusses, and are generally not widely accessible. Structural analysis is largely carried out using the finite element method [7], [8], [9]. This method is essential for complex structures whose analytical solution would be tedious.

We propose to develop a calculation tool to conduct structural design that best addresses our problems. The core of this work is to conduct a deflection analysis of a 5.04 m span planar truss of hinged members, which could form the frame of a greenhouse. To this end, matrix calculation software, suitable for the finite element method, specifically Matlab R2022b [10], was used. The results were then validated using RDM 7 software [11].

After describing the tools and methodology, we will present the results and discussions arising from this static analysis of the truss's deformation before concluding.

2 TOOLS AND METHODS

2.1 TOOLS

The primary tools for conducting this study are a computer with Matlab R2022b and RDM 7 software installed.

2.2 Methods

The images in Figure 1 illustrate different approaches inherent to the specific conditions of their promoters and clients: availability of materials and production tools, among other things.

a) b) c)

***Fig. 1.** a) Agrivoltaic greenhouse [12] b) Connected greenhouse [1] c) Ivory ventilated greenhouse [13]*

Without referring to the aforementioned specific conditions, which are beyond our control, we are conducting our study on a Warren truss made from the lightest components of the ventilated greenhouse's piping, namely a galvanized steel tube with an outside diameter of 25 mm and a wall thickness of 1.25 mm. We consider a Warren truss beam with a span of 5040 mm comprising 25 nodes and 47 members as follows:

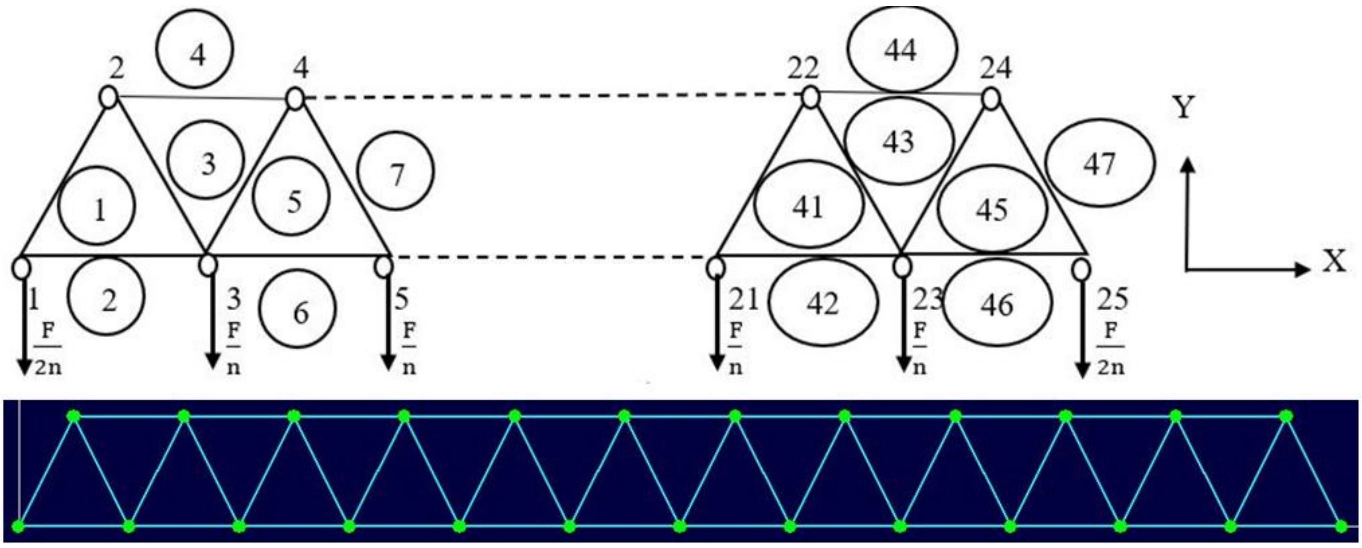


***Fig. 2.** Truss diagrams, a) indicative, b) with RDM 7*

For a coordinate system origin taken at node 1, the node coordinates and member connections are partially given in Tables 1 and 2, respectively:

***Table 1.** Node Coordinates*

No.	1	2	3	4	5	....	21	22	23	24	25
X (mm)	0	210	420	630	840	....	4200	4410	4620	4830	5040
Y (mm)	0	420	0	420	0	....	0	420	0	420	0

Table 2. Bar connections

No.	1	2	3	4	5	6	7	…….	41	42	43	44	45	46	47
1st Node	1	1	2	2	3	3	4	…….	21	21	22	22	23	23	24
2nd Node	2	3	3	4	4	5	5	…….	22	23	23	24	24	25	25

The beam is assumed to support the weight of the PE film with an area of 25 m^2. Table 3 provides some characteristics of the beam under study.

Table 3. Mesh Characteristics

Parameter Designation	Values	Units
Modulus of elasticity of bars, galvanized steel (E)	200	GPa
Yield strength, galvanized steel (R_e)	220	MPa
Density of galvanized steel bars (ρ_{ag})	7850	$kg.m^{-3}$
Height (H)	470	mm
Span (L)	5040	mm
Geometric ratio L/H	10.72	
Number of meshes (n)	12	
Area of bars (A)	93.27	mm^2
Length of horizontal bars (l_h)	420	mm
Length of inclined bars (l_i)	470	mm
Total volume of material V = (23 x l_h + 24 x li) x A	1952990.71	mm^3
Gravity (g)	10	$m.s^{-2}$
Self-weight: P_p = V x ρag x g x 1,05	160.98	$kg.m^{-3}$
Area of PE film (A_f)	25	m^2
Thickness of film (e_f)	200	µm
Film density (ρf)	970	$kg.m^{-3}$
Film weight P_f = Af x ef x ρf x g	49	N
Total external load F' = P_p + P_f	209	N
Total external load retained (F)	210	N
External force at supports Fa = F / (2n)	8.75	N
External force on lower intermediate nodes Fn = F / n	17.5	N
Volume indicator W = Re V / (F L)	405.95	
Second moment of area of a bar (I)	6594.20	mm^4
Shape factor of a bar q = I / A²	0.76	
Slenderness ratio of horizontal bars in compression λ_h = l_i x $(A/I)^{1/2}$	49.95	
Slenderness ratio of inclined bars in compression λ_i = l_i x $(A/I)^{1/2}$	55.90	
Buckling indicator of the structure ψ = Re L / $(q E F)^{1/2}$	196.50	

The volume (W) and displacement (Δ) indicators [14] are:

$W = \frac{n}{2}\frac{H}{L} + \left(\frac{4n^2+3n-4}{24n}\right)\frac{L}{H} = 23{,}2$ et $\Delta = n\frac{H}{L} + \frac{n+1}{4n}\frac{L}{H} = 4{,}02$

Figure 3 shows the local (x, y) and global (X, Y) axis coordinates.

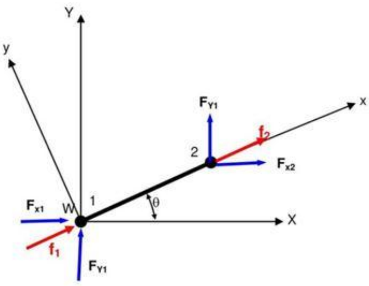


Fig. 3. Coordinate system of an inclined beam

The elementary stiffness and mass matrices in the global coordinate system are respectively deduced:

$$K_e = \frac{E\,A}{L}\begin{pmatrix} \cos^2\theta & cos\theta\ sin\theta & -\cos^2\theta & -cos\theta\ sin\theta \\ cos\theta\ sin\theta & \sin^2\theta & -cos\theta\ sin\theta & -sin^2\theta \\ -\cos^2\theta & -cos\theta\ sin\theta & \cos^2\theta & cos\theta\ sin\theta \\ -cos\theta\ sin\theta & -\sin^2\theta & cos\theta\ sin\theta & sin^2\theta \end{pmatrix}$$

$$K_{em} = \frac{\rho_{ag}\,AL}{6}\begin{pmatrix} 2 & 0 & 1 & 0 \\ 0 & 2 & 0 & 1 \\ 1 & 0 & 2 & 0 \\ 0 & 1 & 0 & 2 \end{pmatrix}$$

The calculation flowchart to obtain our results is as follows (Figure 4):

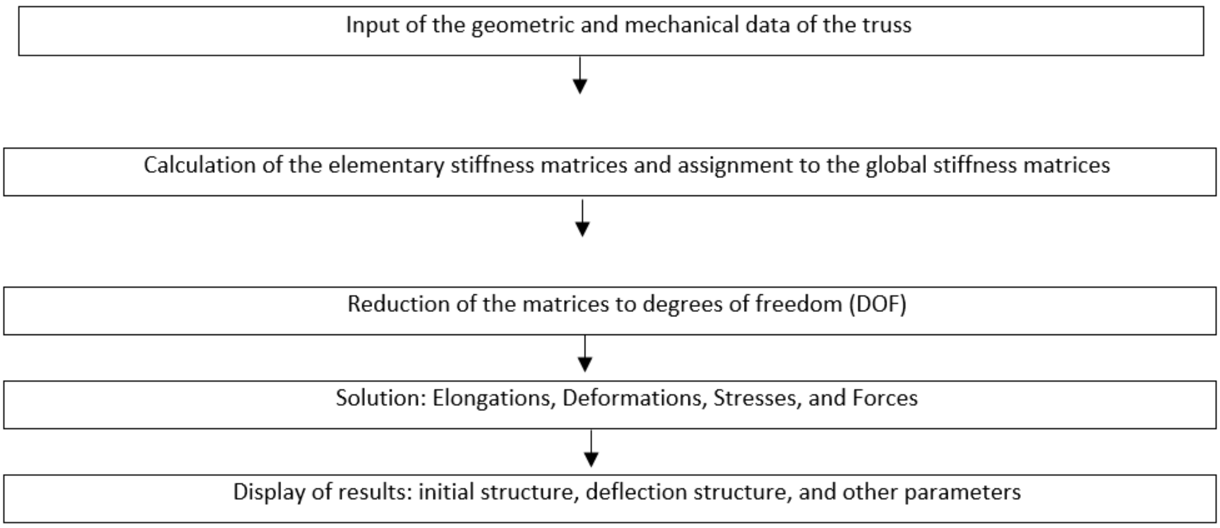


Fig. 4. Calculation Flowchart

3 RESULTS AND DISCUSSION

3.1 ELEMENTARY AND GLOBAL STIFFNESS AND MASS MATRICES

The elementary stiffness matrix in the global axis system of bar 47, for example, is obtained:

$$K_e\ (N.m^{-1}) = 1.0e{+}07 \times \begin{pmatrix} 0.7945 & -1.5889 & -0.7945 & 1.5889 \\ -1.5889 & 3.1779 & 1.5889 & -3.1779 \\ -0.7945 & 1.5889 & 0.7945 & -1.5889 \\ 1.5889 & -3.1779 & -1.5889 & 3.1779 \end{pmatrix}$$

The global stiffness matrix in part (8 x 8 instead of 47 x 47) after reduction as a function of degrees of freedom is:

$$K\ (N.m^{-1}) = 1.0e+08 \times \begin{pmatrix} 0.5236 & 0.1589 & -0.0794 & -0.1589 & -0.4441 & 0 & 0 & 0 \\ 0.1589 & 0.3178 & -0.1589 & -0.3178 & 0 & 0 & 0 & 0 \\ -0.0794 & -0.1589 & 0.6030 & 0 & -0.0794 & 0.1589 & -0.4441 & 0 \\ -0.1589 & -0.3178 & 0 & 0.6356 & 0.1589 & -0.3178 & 0 & 0 \\ -0.4441 & 0 & -0.0794 & 0.1589 & 1.0471 & 0.0000 & -0.0794 & -0.1589 \\ 0 & 0 & 0.1589 & -0.3178 & 0.0000 & 0.6356 & -0.1589 & -0.3178 \\ 0 & 0 & -0.4441 & 0 & -0.0794 & -0.1589 & 1.0471 & 0.0000 \\ 0 & 0 & 0 & 0 & -0.1589 & -0.3178 & 0.0000 & 0.6356 \end{pmatrix}$$

Below, we also have the results obtained concerning the mass matrix of bar 47 in the global axis system, and the global mass matrix after partial reduction (8 x 8).

$$K_{em}\ (kg) = \begin{pmatrix} 0.1146 & 0 & 0.0573 & 0 \\ 0 & 0.1146 & 0 & 0.0573 \\ 0.0573 & 0 & 0.1146 & 0 \\ 0 & 0.0573 & 0 & 0.1146 \end{pmatrix}$$

$$K_{rm}\ (kg) = \begin{pmatrix} 0.3317 & 0 & 0.0573 & 0 & 0.0512 & 0 & 0 & 0 \\ 0 & 0.3317 & 0 & 0.0573 & 0 & 0.0512 & 0 & 0 \\ 0.0573 & 0 & 0.4342 & 0 & 0.0573 & 0 & 0.0512 & 0 \\ 0 & 0.0573 & 0 & 0.4342 & 0 & 0.0573 & 0 & 0.0512 \\ 0.0512 & 0 & 0.0573 & 0 & 0.4342 & 0 & 0.0573 & 0 \\ 0 & 0.0512 & 0 & 0.0573 & 0 & 0.4342 & 0 & 0.0573 \\ 0 & 0 & 0.0512 & 0 & 0.0573 & 0 & 0.4342 & 0 \\ 0 & 0 & 0 & 0.0512 & 0 & 0.0573 & 0 & 0.4342 \end{pmatrix}$$

Most of these parameters are not generally obtained with the majority of commercial software.

3.2 Static Deflection

Figure 5 shows the deflection of the truss. Given the small displacement values and the shape of the truss, the scale is not respected for better visibility of the deflection shape shown in green (solid line); otherwise, it would be practically indistinguishable from the initial structure shown in red (dashed line).

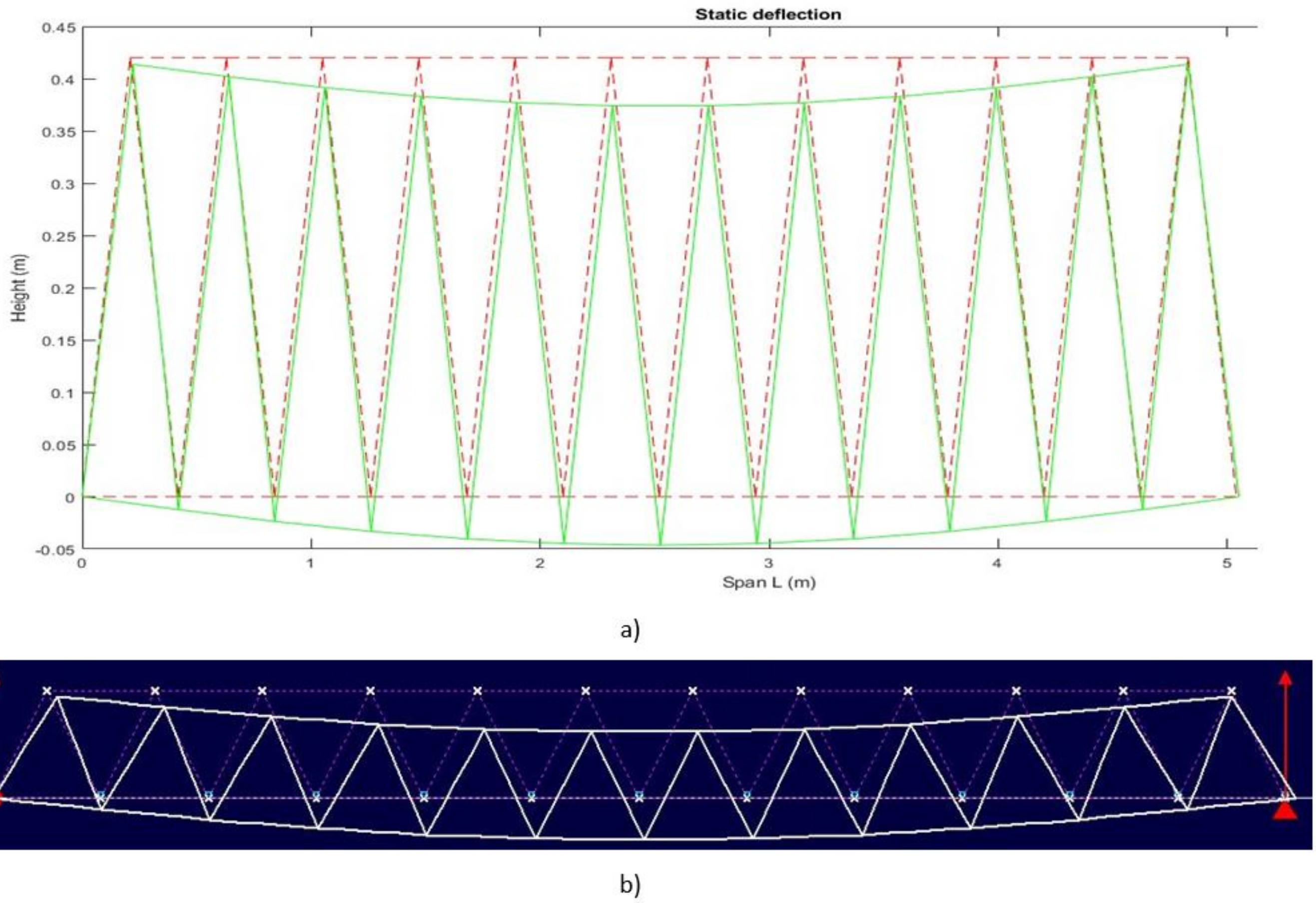


Fig. 5. Deflection of the truss a) with MatLab b) with RDM 7

The reactions at the supports are along the Y-axis: $R_{1Y} = R_{25Y} = \frac{F}{2} = \frac{210}{2} = 105$ N [15].

Considering the number of nodes (25) and members (47) and the centered load distribution, the results will be presented in summary form, focusing on nodes 10 to 16 and members 21 to 27 (Figure 5), where we have extrema

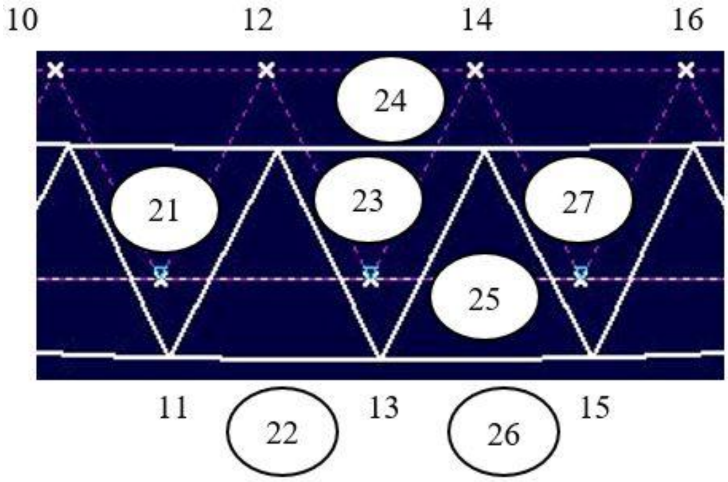


Fig. 6. Central part of the truss

Table 4 shows the displacements obtained at the nodes, with the extreme values in bold.

Table 4. Nodal Displacements Node Number

No. of nodes	2	10	11	12	13	14	15	16	25
U_X (mm)	**0.0563**	0.0386	0.0212	0.0317	0.0282	0.0246	0.0352	0.0177	**0.0563**
U_Y (mm)	-0.0312	-0.2149	-0.2244	-0.23	**-0.232**	-0.23	-0.2244	-0.2149	0
U	0.0644	0.2183	0.2254	0.2322	**0.2337**	0.2313	0.2271	0.2156	0.0563

The maximum displacement along the X-axis is 0.0563 at nodes 2 and 25, the two non-fixed nodes at the ends of the truss. The maximum displacement along Y and the maximum displacement U are 0.232 mm and 0.2337 mm respectively at node 13, the central node of the truss. We obtain a mid-span deflection of ($\frac{0,232}{5040} \approx \frac{1}{21734}$), which is significantly lower than the practical values of $\frac{1}{500}$ [4].

We observe symmetry around node 13 for the U_Y displacements. This is not the case for U_X displacements, given the fixed support at the left end (node 1) and the sliding support at the right end (node 25). The displacements remain much smaller compared to the bar lengths ($\frac{0,2337}{420}$ x 100 ≈ 0,06 %).

Table 5 presents the parameters of the bars.

Table 5. Bar Parameters

Bar No.	21	22	23	24	25	26	27
1st Node	11	11	12	12	13	13	14
2nd Node	12	13	13	14	14	15	15
Elongations Δl (µm)	-0.246	**6.994**	0.246	**-7.093**	0.246	**6.994**	-0.246
Strains ε	-0.0052	**0.1665**	0.0052	**-0.1689**	0.0052	**0.1665**	-0.0052
Stresses σ (MPa)	-0.1049	**3.3305**	0.1049	**-3.3774**	0.1049	**3.3305**	-0.1049
Forces N (N)	-9.7828	**310.6250**	9.7828	**-315**	9.7828	**310.6250**	-9.7828

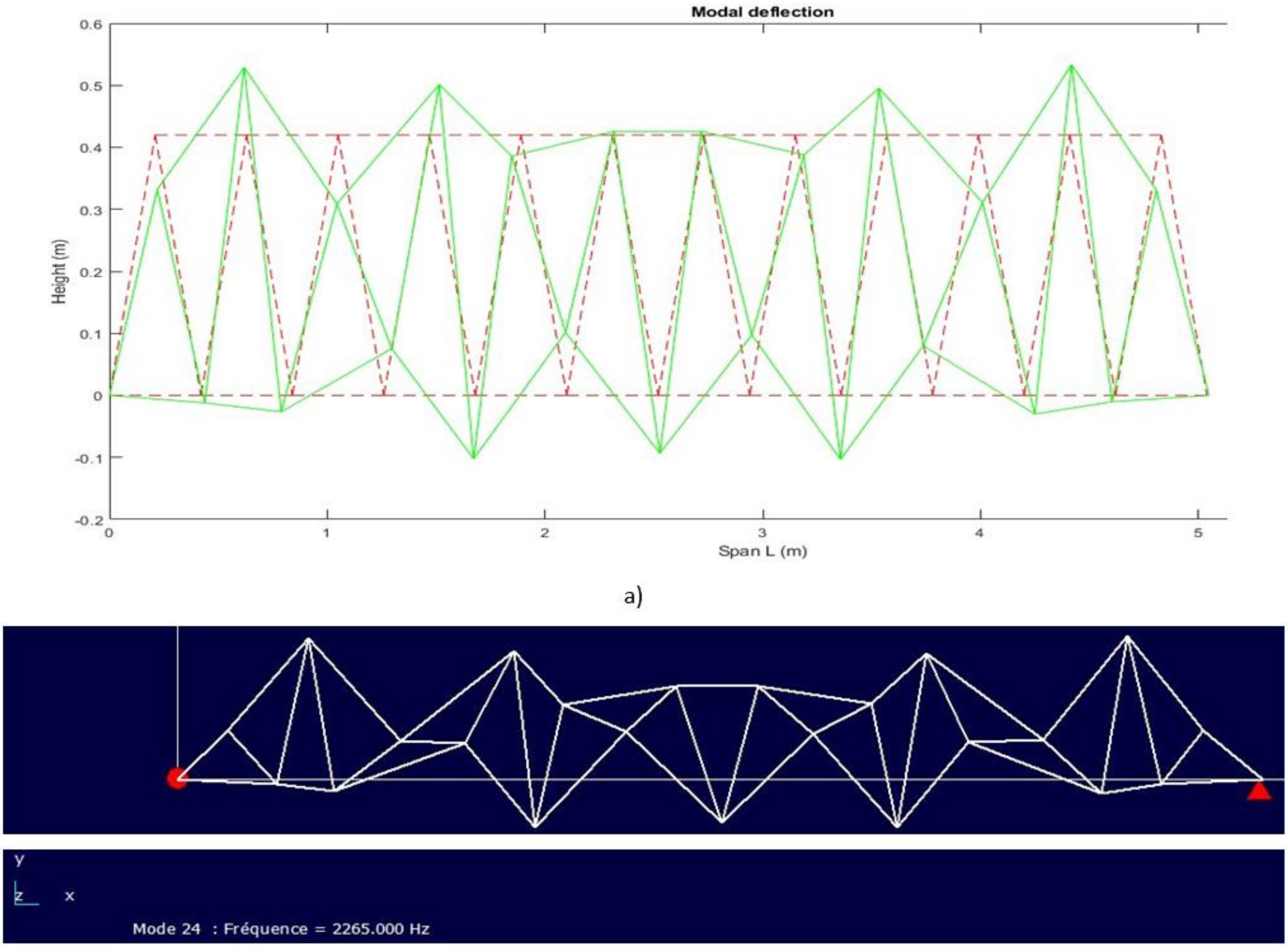
The maximum shrinkage is 7.093 µm with a minimum strain of -0.1689 and a normal stress of -3.3305 MPa for a normal force of -315 N. These values are observed on bar 24 (in compression), followed by bars 22 and 26 (in tension). However, they are considerably far from the elastic limit Re = 220 MPa [8].

We therefore observe very good performance of the trellis. This reinforces its use for agrivoltaic greenhouses with a number of photovoltaic panels. Solar radiation is abundant in our tropics, despite the effect of wind, which can be taken into account in terms of loads depending on the region.

3.3 MODAL DEFLECTION

Furthermore, we can determine the deflection modes of our truss with this calculation code, with a few variations.

This allows us to determine natural frequencies that conform to those of RDM 7, for example: W_1 = 266 rd.s$^{-1,}$ W_{12} = 7796 rd.s$^{-1,}$ W_{24} = 14232 rd.s$^{-1,}$ W_{36} = 18255 rd.s^{-1} et W_{47} = 24894 rd.s^{-1}. Figure 6 shows, for example, the modal shape of the angular frequency $W_{24,}$ whose natural frequency is: f_{24} = 2265 Hz.



a)

b)

Fig. 7. Modal deflection W24 a) with MatLab b) with RDM 7

Other modal deflections can also be determined.

4 Conclusion

We proposed developing a structural design calculation tool by conducting a study of a greenhouse truss.

The use of agrivoltaic greenhouses is practically nonexistent in our tropical regions despite abundant sunshine. Furthermore, the structures are apparently oversized, which is almost commonplace, albeit in varying proportions. This does not invalidate the local approach, which certainly takes into account contingent factors:

- availability of materials
- flexibility of production tools,
- limits in load estimation,
- etc.

Our study highlights a potential optimization of greenhouse truss reinforcement using small cross-section bars (93.27 mm^2) and contributes to the development of tools tailored to our specific needs. It also provides an application of the finite element method for students, focusing on the analysis of deflections in trusses made of hinged bars.

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