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DETERMINATION OF MECHANICAL STRENGHT AND STABILITY OF AN EXPO PAVILION MADE FROM METALLIC STRUCTURE

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Abstract: *In the present paper was conducted a study of the resistance and rigidity of a metallic structure placed in the city of Galaţi. The metallic structure studied can be made of unremovable joints or removable systems. It was used as basic elements with trellis girder substructures that provide increased rigidity and reduced weight. Topological optimization of the plate structure highlighted the possibility of using trellis girder elements for basic substructures. Compared from the point of view of the stiffness/mass ratio, several types (3 cases) of trellis girder were considered by choosing the constructive variant with the best ratio. From the resistance study resulted information for the calculation of the foundation on which the structure is located, especially the reactions in the links of the structure, forces and moments corresponding to the most adverse load situations.*
Keywords: *trellis girder, topological optimization, resistance, rigidity, foundation.*

1. INTRODUCTION

Dome-type constructions have always been important in the field of architecture. This is evidenced by the fact that we find numerous historical and religious buildings throughout the world, most of them still standing, after a few centuries, due to the dome shape [4].
With the use of metallic materials in civil constructions, this type of construction has been progressively used due to the advantages offered by the combination of material and particular shape.
Dome-type structures are very efficient because they are lighter in weight compared to other types of construction. Also, this kind of structures can be constructed using less material and offer a longer service life [4].
Generally, dome structures have an area of 30% smaller than the structures designed in any other form. The absence of any corners, angles and flat surfaces makes these structures extremely resistant to very high wind pressures, even hurricanes. This is due to the fact that the wind is able to pass smoothly over their circular shape and at the same time creates minimal turbulence due to excessive air pressure [5][3].
The use of metal for dome-type structures is the main reason why in the last years this type of constructions is used in all fields of activity, from the domestic field and ending with the industrial or zootechnical fields [6]. Metal is a material used due to the degree of safety, as well as mechanical strength related to its own weight [6].
Metal constructions, especially the domed ones, have many advantages compared to the use of structures made of other materials: [7]:

- high value of the allowable stress (σa) compared to traditional structures;
- increased resistance to external natural factors: earthquakes, wind and structural loads (for example snow loading);
- temporary or permanent use.

Considering the advantages of the metallic constructions and the special form of the dome, in the present paper was performed a study of the resistance and rigidity of such a metallic structure with location in the city of Galați. Dome-type structure can accomplish several functions, such as: exhibition space, showroom, botanical garden, etc. [2] The shape and dimensions of the structure analyzed were inspired by a structure from the Grabcad site.[8]

2. TOPOLOGICAL OPTIMIZATION OF THE STRUCTURE

With the intention of maximize the rigidity of the structure and at the same time to reduce its weight, the topological optimization was made from where the definitive form of the structure resulted.
Topological optimization combines the physical aspects of the problem with the finite element method to determine the optimal shape for a particular spatial design and certain boundary conditions. Topological

optimization is important because it realizes an optimum for the rigidity of a structure that could not be directly determined by engineering experience.
In the present paper was realized a topological optimization process of a domed metal structure. The metal (steel) resistance structure of the dome is made of stiffness joined plates.
The first step in the simulation is therefore to use the Static Structural calculation module in Ansys Workbench where the geometry is created, the structure is discretized and the boundary conditions (loads and connections) are imposed.
The second step involves the settings for topological optimization and its realization. To perform the analyze with the topology optimization module (Topology Optimization) must be set: the region to be optimized, the objective function and the mass retention level in the optimized area concerned.
The objective function in the topological optimization process is to maximize the rigidity of the structure at the lowest material consumption and the mass retention level in the optimized area is 30%. The metallic structure has a height of **6.37** meters and an overall span of **14.24** meters.

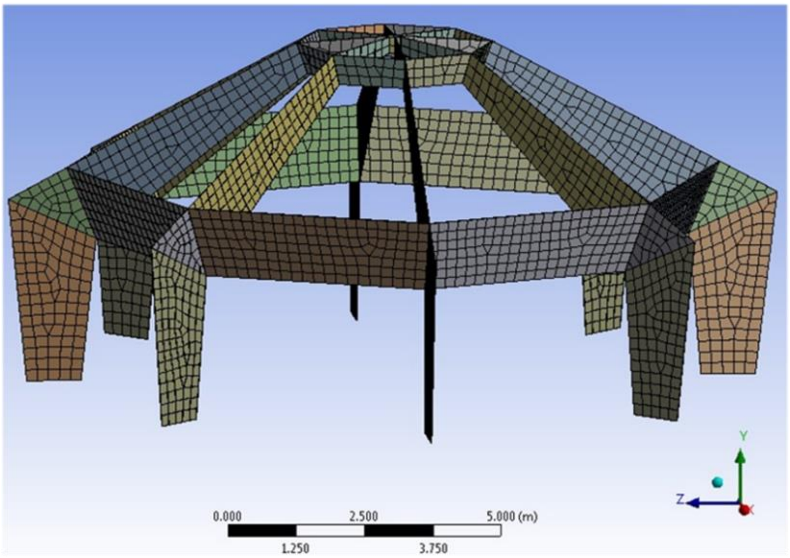


Figure 1a: Structure made from discretized metal plates (element side 0.2 [m]) [17]

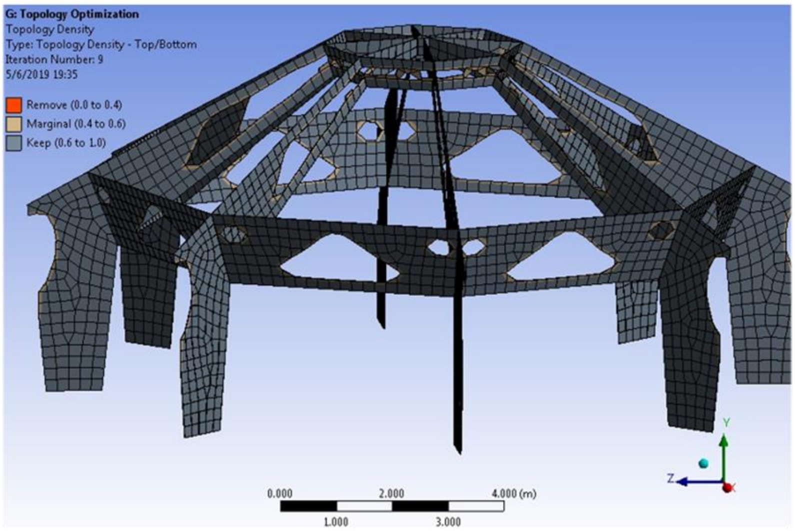


Figure 1b: Topologically optimized structure [17]

From figure 1b you can see cut surfaces in the legs of the structure and in the upper and lower belts that connect the legs.
The shape and size of the cutouts highlight an alternative of modeling the structure using bar systems similar to the beam structures with trellis girder.

3. STUDY OF THE RIGIDITY OF STRUCTURE COMPONENTS

The dome octagonal metal structure made of trellis girder in three of the most common cases in practice (Figure 2) was analyzed in terms of stiffness in the Ansys Workbench program with the Static Structural module.

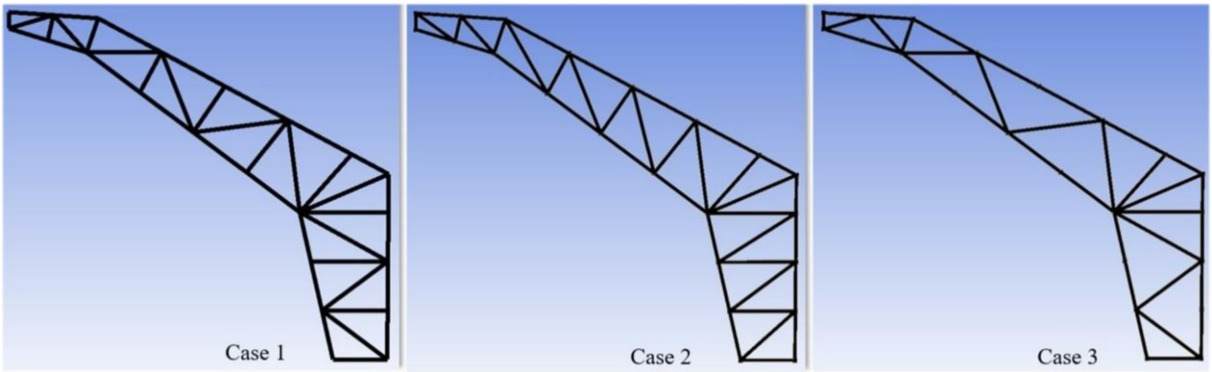


Figure 2: Trellis girder in three of the most common cases in practice [17]

In order to determine the rigidity of the structure, it was considered that the strength structure has the legs embedded in the foundation, and the load is a displacement of 1 [mm]. The results obtained are represented in the table 1:

Table 1: The results of the rigidity analyzes test for the three considered cases [17]

Case	Displacement [mm]	Reaction [N]	Stiffness??? [N/mm]	Total weight [kg]	Maximum Strain [MPa]
Case 1	1	93114	93114	5569.3	43.69
Case 2	1	100350	100350	5568.7	51.71
Case 3	1	96233	96233	5107.5	68.65

As you can see, the results are close but the maximum strain is lowest in Case 1. Therefore, based on this lower level of tensions, the structure of Case 1 will be chosen for checking the resistance. The class of importance can be considered IV.

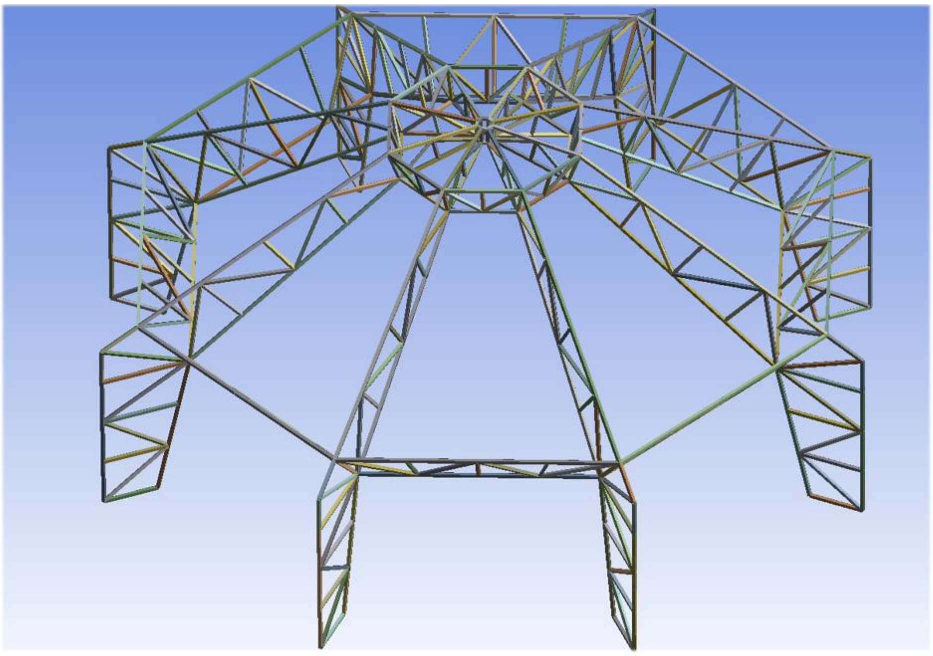


Figure 3: Dome-type metal structure with octagonal shape (Case 1) [17]

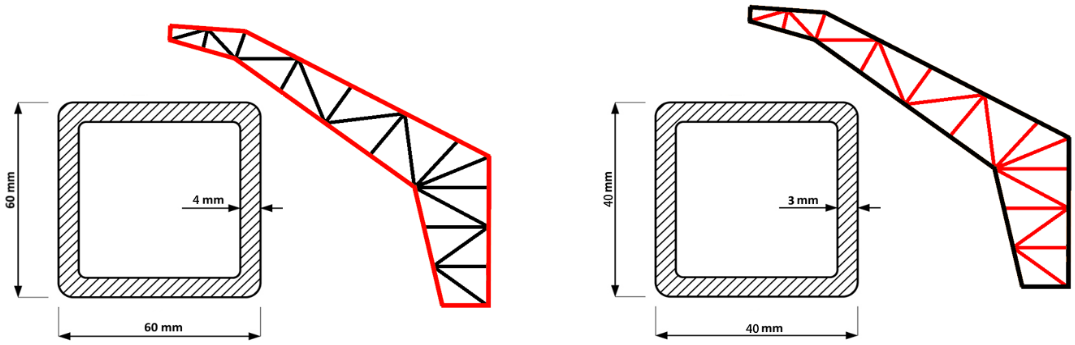


Figure 4: Section and dimensions of the elements of the trellis girder: a): The dimensions of the profiles for the legs contours and sides of the octagon; b) The dimensions of the profiles for the internal trellis girder [1],[9],[17]

4. THE STRUCTURE'S RESPONSE TO THE ACTION OF THE LOADS FROM THE FUNDAMENTAL GROUP [10][11]

4.1. Loading from the weight of the snow

Snow loading acts vertically. The value of the characteristic snow load on the roof is determined by the relation:

$$s = \gamma_{ls} \cdot \mu_i \cdot C_e \cdot C_l \cdot s_k \tag{1}$$

Where:

- γ_{ls} =**1** → the importance factor to the exposition of snow load for construction in class IV;
- μ_i = **0,8** → the shape coefficient of snow on the roof;
- C_e=**0,8** → the complete exposure coefficient of the construction on site;
- $C_l = \mathbf{1}$ → the coefficient of thermal influence;
- $s_k = \mathbf{2.5}$ → the characteristic value of the snow load on the ground [kN/m^2] in the Galați area.

If uneven snow mobbing and local snow load effects on the roof are not taken into account, the pressure applied to the roof by the weight of the snow may be considered:

$$s = 1 \cdot 0.8 \cdot 0.8 \cdot 1 \cdot 2.5 = 1.6 \ \frac{kN}{m^2} \tag{2}$$

4.2 Pressure assessment due to the action of the wind

For the evaluation of the wind action, were considered the formulas from the design code shown in table 2:

Table 2: Factors and coefficients for evaluating wind action [11] [17]

Scopes introduced in calculations	Symbol	Value
The reference height (the height of the metal structure)	Z [m]	6.37
The width of the metal structure	D [m]	14.24
Wind force	$F_w = q_{ref} \cdot c_e(z) \cdot c_f \cdot c_d \cdot A_{ref}$ [N]	
The reference pressure of the wind	q_{ref}[kPa]	0.6
Exposure factor at height Z above the ground	$c_e(z) = c_g(z) \cdot c_r(z)$	
Burst factor	$c_g(z) = 1 + g \cdot 2 \cdot I(z)$	5.095
Peak factor	g	3.5
Length of roughness	z_0	1.00
The turbulence intensity	$I(z) = 2.65/(2.5 \cdot \ln(z/z_0))$	0.585
The roughness factor	$c_r(z) = k_r^2(z_0) \cdot \ln^2(z/z_0)$	0.186
The factor for the land category	$k_r(z_0)$	0.233
Exposure factor	$c_e(z)$	0.94
Coefficient of force that also consider friction	$c_f(z)$	1.16
Approximate dynamic factor	c_d	1
Wind pressure	$p_w = q_{ref} \cdot c_e(z) \cdot c_f \cdot c_d$[kN/m^2]	0.81

4.3 Determination of the aerodynamic coefficients for the action of pressure / suction of the wind on surfaces and of the matching pressures [12]

The wind speed is obtained from the dynamic pressure relation:

$$p_w = \frac{1}{2} \cdot \rho_{aer} \cdot v_w^2 \tag{3}$$

Where:

- p_w → is the pressure exerted by the wind (last line of table 2)
- ρ_{aer} → is the density of air 1,25 [kg/m^3]
- v_w → is the wind speed

Under the conditions of the structure, the wind speed at the ground surface is **36 m/s**.
In the published literature and even in standards, the approach of the influence of the wind on the octagonal structure is realized approximately by means of coefficients sometimes difficult to estimate. For this reason, it was necessary to use the Fluid Flow module (CFX) to properly determine the pressures of the wind action. The wind pressure and wind speed determined using the Fluid Flow module are shown in figure 5:

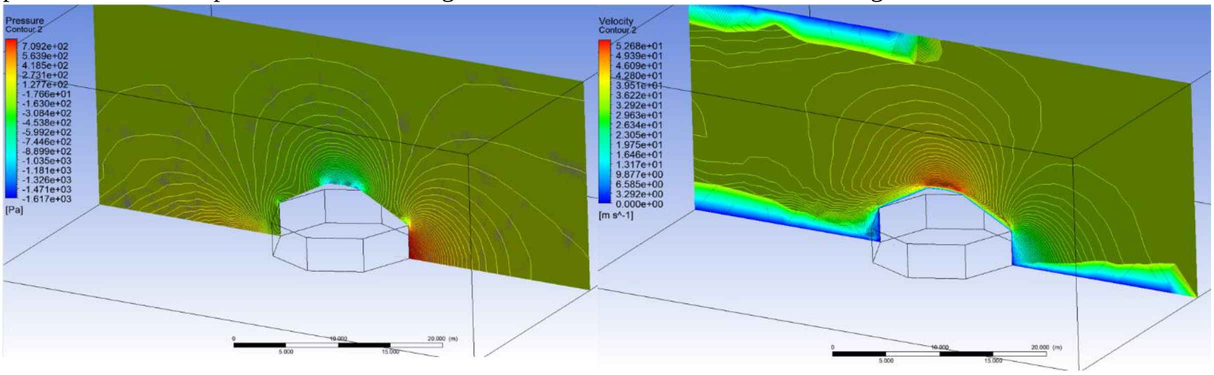


Figure 5: Pressure distribution (left) and speed (right) along a section plane [17]

The pressure value is subsequently imported into the Static Structural module of the Ansys program to complete static analysis of the structure at the wind demand. The obtained results are presented in the table 4:

Table 4: The results obtained for the resistance structure [17]

Deformation [mm]	11,056
Maximum Combined Stress [MPa]	8,48
Minimum Combined Stress [MPa]	8,45

4.4 The loads from the fundamental group [11]

In accordance with STAS 10101/0A-77, the following groups of actions are constituted, the succeeding notations are used:

- G_{kP} → Permanent loads;
- Z_k → loading with uniform snow;
- V_{kL} → wind loading according to the longitudinal direction of the structure;
- V_{kT} → wind loading resulting the transverse direction of the structure;

All the above notations refer to the normative value of the respective load determined.
For the ultimate limit state, the following groups of loads are defined in the fundamental grouping:

- $1,1 \cdot (G_{kP}) + 2,13 \cdot Z_k$
- $1,1 \cdot (G_{kP}) + 1,2 \cdot V_{kT}$
- $1,1 \cdot (G_{kP}) + 0,9 \cdot (2,13 \cdot Z_k + 1,2 \cdot V_{kT})$
- $1,1 \cdot (G_{kP}) + 0,9 \cdot (2,13 \cdot Z_k + 1,2 \cdot V_{kL})$

Table 5: The results obtained in the 3 cases of loads [17]

	Types of loads	Load combinations	Total Deformation [m]	Maximum Combined Stress [MPa]	Minimum Combined Stress [MPa]
Case1	Dead load + snow	$1,1\cdot(G_{kP})+2,13\cdot Z_k$	0,005133	73,9	85,4
Case2	Dead load + wind	$1,1\cdot(G_{kP})+ 1,2\cdot V_{kT}$	0,001772	20,8	20,94
Case 3	Dead load + wind + snow	$1,1\cdot(G_{kP})+0,9\cdot(2,13\cdot Z_k+1,2\cdot V_{kT})$	0,005624	82,91	85,42

5. DETERMINATION AND VERIFICATION OF THE STRUCTURE OF THE BUCKLING STRENGTH PHENOMENON [13]

After determining the sections of the profiles (based on the loadings in the most unfavorable case) and standardizing them, the obtained results are introduced in the program for performing the determiation and verification of the buckling phenomenon. To determine if the analyzed structure resists to the buckling phenomenon, were determined the first 10 buckling modes.

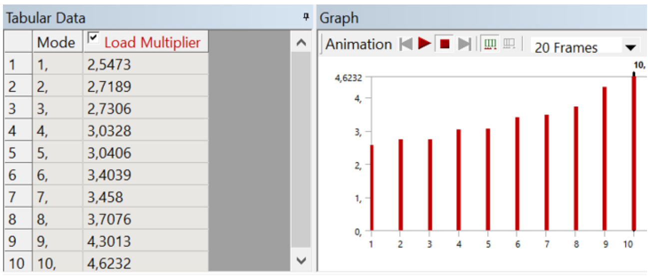


Figure 6: Buckling modes with respective load multiplication factors [17]

In the first mode of losing stability, the Load Multiplier has a minimum value of 2.5473 greater than 1. This mode corresponds to a global buckling of the contour beams that support the roof. The value of the multiplier is associated with a safety coefficient in relation to the most unfavorable load combination and since the value of this coefficient is greater than 1, the structure can be considered stable in terms of stability.

6. ESTABLISHING THE DYNAMIC RESPONSE OF THE STRUCTURE TO THE EXCITATION PROVIDED BY THE EARTHQUAKE

The essence of the dynamic behavior of a structure is given by its own forms of vibration, its own frequencies and the associated modes, depending on the rigidity and distributed masses, but also on the damping properties of the material.
The determination of the characteristic frequencies and of the own modes of vibration of a structure is realized by means of the modal analysis. The matrix system of equations of the structure modeled with finite elements can be written in form [14]:

$$[M]\{\ddot{u}\}+[C]\{\dot{u}\}+[K]\{u\}=\{F(t)\} \tag{4}$$

Where:

- [M] is the matrix of masses;
- [C] the depreciation matrix;
- [K] the stiffness matrix;
- $\{\ddot{u}\}$ is the vector of nodal accelerations;
- $\{\dot{u}\}$ is the vector of nodal speeds;
- $\{u\}$ is the vector of nodal displacements;
- $\{F(t)\}$ is the vector of excitatory (external) nodal forces and moments.

Stand on the matrix form (4), the dynamic response of the structure to the excitation caused by the earthquake was determined using the Modal calculation module from Ansys Workbench.

The structure is considered embedded in the contact points with the ground and represents the basis of the modal analysis in which the first 100 vibration modes were determined. The number of modes is resolved in such a way that the mass participation factor is greater than 0.9 in order to be able to correctly evaluate the contribution of the excitation to the dynamic response of the structure.
The longitudinal and transverse excitation directions X and Z are identical (symmetrical structure) and for this reason the analysis was made for a single direction, X. To this analysis was added the excitation by means of acceleration at 45°, with components on the X and Z axes.
The analysis shows that the structure is in line with the rigidity / mass ratio in the requirements of the domed metal constructions for which the first proper frequency must be higher than 3 [Hz] (the first own frequency is 3.6 [Hz]).
For the determination was used the spectral analysis with the acceleration spectrum from the seismic design code corresponding to the Galati area. Was considered a single excitation curve (Single Point) for acceleration, and the modes are combined according to the SRSS method. In Ansys Workbench the spectrum of accelerations is introduced as accelerations according to frequency.
The results obtained from the simulation are presented in the table 6:

Table 6: The spectral response of the structure to the basement excitation [17]

	Excitation in X direction	Excitation among X and Z (45°)
Deformation [mm]	2,4	3
Maximum Combined Stress [MPa]	14,3	18,74
Minimum Combined Stress [MPa]	14,3	17,9

From table 6 it results that if we consider the allowable stress of 150 [MPa], taking aside the maximum normal stress of about 20 [MPa], the permissible stress to consider for static groups is 130 [MPa].

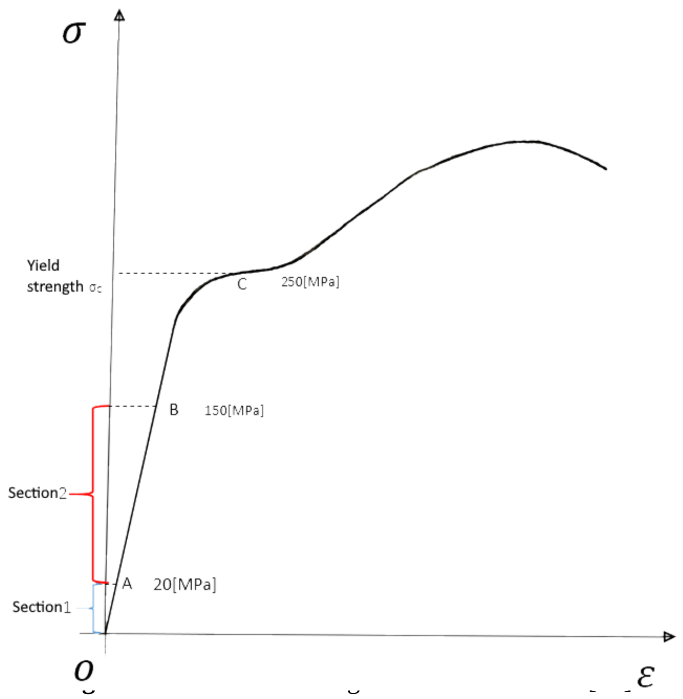
7. CONCLUSION

The present paper proposed the determination of resistance of a metal structure with reinforcements of beam elements with trellis girder.
The definitive shape of the structure resulted from a topological optimization followed by the choice of the best constructive variant in terms of rigidity for the beam type elements with trellis girder.
All types of analysis were performed in the Ansys Workbench finite element analysis program. The modules used were the following: Static Structural, Topology Optimization, Modal, Response Surface Optimization, Response Spectrum, Eigenvalue Buckling, Fluid Flow (CFX).
The material was considered steel with linear-elastic behavior with the characteristics of the table 7: "Structural Steel S235 JR" [15].

Table 7: Properties of the material used [17]

Structural Steel S235 JR	
Density	7850 [kg/m^3]
Poisson's Ratio	0,3
Young's Modulus	$2 \cdot 10^{11}$ [Pa]
Tensile Yield Strength	$2{,}5 \cdot 10^{8}$ [Pa]

The loss of the stability of the structure represents the worst phenomenon of its failure and therefore for the metallic structure, the proportionality tension of the material was chosen as a state of limit, which for a steel (S235 JR - a variant of the old steel OL 37) is around 190 [MPa].
Because in the resistance determination, the elements of the roof were not taken into account, nor the stress scenarios that include important temperature variations, corrosion rate, possible material defects, the safety coefficient with respect to the limit state was considered 1.2, and the permissible stress becomes 150 [MPa], corresponding to the current permissible stress for metal structures. Choosing this value as a limit state we had the possibility to apply the principle of superposition of effects for exceptional loads and combinations of loads including linearized buckling which is realized only in the linear-elastic domain below the proportionality limit of the material.
The intervals corresponding to the permissible stress for exceptional loads and for static load combinations are shown in the figure 7 below:



Where:

- Section 1 – Stress section 0 ÷ 20 [MPa] corresponding to the exceptional load (earthquake);
- Section 2 – Stress section 0 ÷ 130 [MPa] corresponding to the limit states of the static load (the most unfavorable load combination);
- Point B – Represents the current allowable stress for metal structures: 150 [MPa];
- Point C – Represents the yielding point of the material used: 250 [MPa].

Strength and stability requirements imposed on the structure were also added to meet the rigidity condition that the trellis girder structure must fulfil [16] (the maximum displacement must not exceed the value of the opening length ratio / 250, namely, it must not exceed 57 [mm] , the opening being of 14,238 [m]). For the metal structure, the maximum displacement is about 48 [mm] falling within the allowable limit.

REFERENCES

[1] http://www.adimet.ro/acasa/portofoliu-de-produse/tevi-patrate/#prettyPhoto[gallery1]/0/
[2] https://inhabitat.com/tag/geodesic-dome/
[3] Course: Mechanics of Construction and Structural Design – MCPS (in Romanian language)
[4] http://www.alcox.in/blog/important-facts-about-dome-structures-that-make-them-so-popular/
[5] https://www.constructii-neamt.ro/materiale-constructii/dom-geodezic-avantaje-dezavantaje/
[6] https://ucpet.org/care-sunt-avantajele-si-dezavantajele-constructiilor-metalice/
[7] https://www.arenaconstruct.ro
[8] https://grabcad.com/library/octagon-metal-structure-1
[9] Square tubular profiles: DIN EN 10210-2, ed. November 1997 (in Romanian language)
[10] Example of calculation of a single-storey hall, having the main strength structure made of elements composed of welded boards with sections of class III or IV: according to the norms NP 042/2000, P100 / 92 and STAS 10108/0 -78. (in Romanian language)
[11] Design code. Evaluation of actions on constructions: Indicative CR 1-1-4 / 2012 (in Romanian language)
[12] Xiaolin Chen, Yijun Liu: Finite element modeling and simultaion with Ansys Workbench, http://www.mediafire.com/file/3d2kyc121yji7yj/Finite_Element_Modeling_and_Simulation_with_%2ANSYS_Workbench.pdf/file
[13] Doina Boazu: Strength of materials, Simple and composite bar loads, Euro Plus Publishing, Galati, 2006. (in Romanian language)
[14] Book of Dynamic: Ioan Pascariu, Finite elements: Concepts. Applications of the military publishing house, Bucharest 1985 (in Romanian language)

[15] Cranes – Design principles for loads and load combinations, Indian Standard IS/ISO 8686-1 1986 (Reaffirmed 2006)
[16] Standardized stiffnesses for metal hall beams STAS 10108 / 0-78 (in Romanian language)
[17] Lucrare de licență: Calculation of mechanical strenght and stability of an expo pavilion made from metallic structure, Gheorghe Dron & Doina Boazu, „Dunărea de Jos University" of Galați, 2019
[18] Ansys Help Viewer, Ansys Workbench 19.2, 2018
[19] Silviu Butnariu, Gheorghe Mogan, Finite element analysis in mechanical engineering. Practical applications in Ansys, Ed. Transylvania University, 2014. (in Romanian language)