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ASPECTS ABOUT THE INFLUENCE OF THE DIFFERENT FACTORS IN FAMOUS COLLAPSE OF ROOF CONCRETE STRUCTURES

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Abstract. In this paper there are presented the influence of the various parameters which could be involved in the collapse of the roof concrete structures of the Cluj Sports Hall in February 15th 1961 soon after the total solar eclipse. This study takes into consideration the multiple causes for the collapse include the thermal shock due to the solar eclipse, the inappropriate projection of the roof and the cracks in the structure after winter and exactly the rain conditions in previous night of the collapse. This parameters where involved in modeling the structure with SCIA Engineer v16.0. The conclusions of this study reveals as a major factor for collapse the rising the weight of the roof structure due to water accumulation in the cracks of the roof and the secondary cause the superposition of the specific thermal field due to the total solar eclipse. Using the Energonics principles, the superposition of the two main loads (mechanical and thermal), there were performed a lot of iterations in ETABS analysis to determine the load which is responsible for collapse. In these days, the standards for roofs with these dimensions of openings are completely changed. The significance of this study is bonded with superposition of the natural effects above the structures and the partition of their influence. Also this study can be used as a critical analysis of the type of projecting the roof structures in 1960s. This paper presents also a hypothetical analysis with accumulation of snow beside of the other factors involved.

Keywords: collapse, concrete roof structure, thermal loads, cracks, water accumulation

1. Introduction and time testimonies

The design process of any construction defines its life duration. Because of this the designer needs to verify the behaviour of the structure in various load cases

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modeling its state of service. In the past, some shell structures have collapsed due to a lot of factors which initially weren't taken into consideration or all the calculation was realized with many approximations. There are recorded some thin shell concrete collapses like the hypar shell roof of a high school in the USA [1, 2], also near Paris building, in Prague and our Sports Hall from Cluj, Romania. Structural failure is the biggest fear for anyone involved in the design process.

Shells experience includes 'snap-back' behavior, which is characterized by sudden loss in load carrying capacity, leading to immediate failure. Furthermore shells collapse without warning, unlike other structures which show considerable visual deformations before collapse. This warning is unavailable to shell designers adding more significance to checking nonlinear effects in the design process. These days the finite element method and way for modeling structures can be used to include all the parameters and their variation which can be the cause of the collapse. Together with numerous available modeling softwares, they provide the most essential tools for a structural designer. As a designer it is easy to overlook the arising complexities of construction. Usually it has less of significance but these complications caused major problems for shell structures. In fact this was the main reason for the sharp decline in their construction after a promising start in the 1950s [3,4,5]. Lack of advanced methods led to use of conventional form-work being used for shell construction, which is costly and more prone to errors. But this started changing in the last two decades. This rise is mainly owing to the development of new innovative construction techniques coupled with new softwares which enable digital modeling and analysis. [6,7]

In February 15th, 1961, after a major rainfall and solar eclipse, Sports Hall ceiling gave way and crashed shortly after completion of a major meeting. There was just one year or two after its inauguration. Officially, there was no victim, but if it were, this would not have been recognized at that time because of the political frame. Anyway, about the collapse of the Sports Hall of Cluj, has not written any lines in the press. The architects and historians remembered that the collapse came with a loud noise, like the earthquake. They remembered the day of the tragedy was marked by two events that have taken place is that morning: solar eclipse and major meeting with the communist leader John Gheorghe Maurer. This held a speech in front of hundreds of activists. No more than one hour after the end of the event and immediately after the hall was emptied, the ceiling collapsed. There were no casualties, but when disasters do not read anything. This is the testimony of the architect Virgil Pop, Secretary Regional Commission for Historical Monuments. [8]

About the causes that led to the collapse there are all sorts of assumptions, but most likely not very different from things that are still happening today. The reason for the collapse was the rain, the eclipse, the vibrations from applauses of hundreds of people? The general experts' opinion was given by the next idea: the ceiling of the hall gave up because of water ingress into the insulation. The weight to pull the ceiling was too high and the ceiling gave way, possibly because of sizing done wrong [8].

The meteo conditions of that days consists in major rainfall - water quantities far exceeding the normal quotas and positive temperatures.

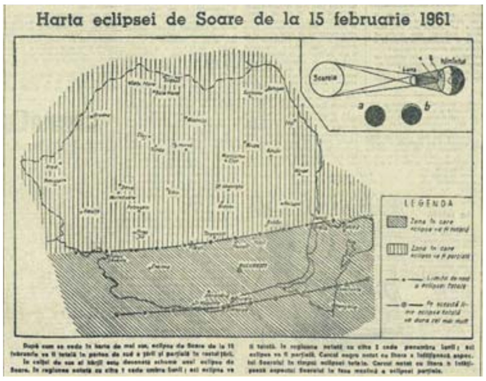
The first draft of the Sports Hall of Cluj was completed between 1956 and 1957 and began immediately thereafter. Hall was inaugurated three years later, in 1960, but Cluj would not enjoy it very long. Ceiling collapse occurred just one year after opening and had taken up the whole process again. They started building almost immediately but were higher divergences among architects and structural engineers, perhaps because of the guilty of initial design process. Reconstruction of the hall began to collapse a few months, by architect Mircea Enescu was completed in 1965 and the second structure keeping it until today.

Thin shell domes are thin-shelled reinforced concrete structures which became popular after the first was built in the mid 1960's. The domes were well accepted due to their quick construction time, low cost, high strength and reduced carbon footprint when compared to conventional construction. Due to the versatile nature of these structures, they have been used in the construction of schools, housing, sports arenas, shopping malls, storage buildings and silos [9]

2. Problem formulation

2.1. Solar eclipse from February 5th 1961

The figure 1 reveals that Cluj was in the part of Romania with partial solar eclipse [10].



The map of the solar eclipse from February 15th 1961

Zone for total eclipse

Zone for partial eclipse

Fig. 1. The map of solar eclipse from February 15th 1961
with total and partial zonation for Romania [10].

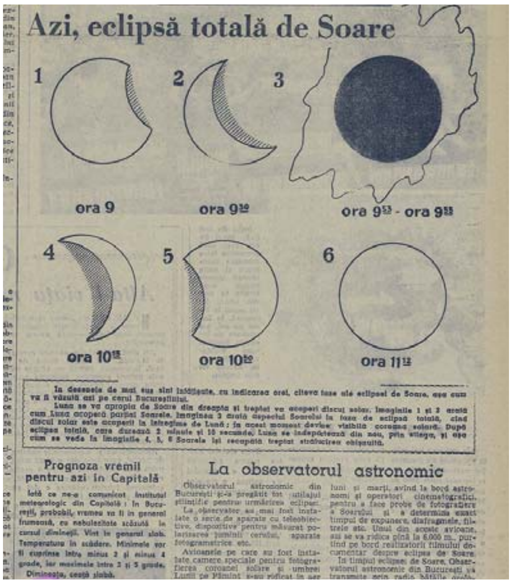
The newspaper of that time show the phases of the eclipse like in the figure 2a and the NASA gives all the details and the diagram of the phenomenon for the entire planet in the figure 2b.

The included data in the newspaper article are presented for Bucharest with the principal time moments of the solar eclipse:

- Beginning time: 8:43 AM;
- Finishing time: 11:00AM;

- Total eclipse – maximum phase 9:54 AM;
- Total eclipse – total duration: 2 minutes and 10 seconds.

The NASA documents about the 15th of February 1961 give all the details related with the phenomenon.



Azi, eclipsă totală de Soare

1 ora 9
2 ora 9⁵⁰
3 ora 9⁵³ - ora 9⁵⁵
4 ora 10¹⁵
5 ora 10⁵⁰
6 ora 11¹⁵

În desenele de mai sus sînt înfăţişate, cu indicarea orei, cîteva faze ale eclipsei de Soare, aşa cum va fi văzută azi pe cerul Bucureştiului.
Luna se va apropia de Soare din dreapta şi treptat va acoperi discul solar. Imaginile 1 şi 2 arată cum Luna acoperă parţial Soarele. Imaginea 3 arată aspectul Soarelui în faza de eclipsă totală, cînd discul solar este acoperit în întregime de Lună; în acest moment devine vizibilă coroana solară. După eclipsa totală, care durează 2 minute şi 10 secunde, Luna se îndepărtează din nou, prin stînga, şi aşa cum se vede în imaginile 4, 5, 6 Soarele îşi recapătă treptat strălucirea obişnuită.

Prognoza vremii pentru azi în Capitală

Iată ce ne-a comunicat Institutul meteorologic din Capitală: În Bucureşti, probabil, vremea va fi în general frumoasă, cu nebulozitate scăzută în cursul dimineţii. Vînt în general slab. Temperatura în scădere. Minimele vor fi cuprinse între minus 2 şi minus 4 grade, iar maximele între 3 şi 5 grade.
Dimineaţa, ceaţă slabă.

La observatorul astronomic

Observatorul astronomic din Bucureşti şi-a pregătit tot utilajul ştiinţific pentru urmărirea eclipsei.
La observator au mai fost instalate o serie de aparate cu teleobiective, dispozitive pentru măsurat polarizarea luminii cerului, aparate fotogrametrice etc.
Avioanele pe care au fost instalate camere speciale pentru fotografierea coroanei solare şi umbrei Lunii pe Pămînt s-au ridicat în aer luni şi marţi, avînd la bord astronomi şi operatori cinematografici, pentru a face probe de fotografiere a Soarelui şi a determina exact timpul de expunere, diafragmele, filtrele etc. Unul din aceste avioane, azi se va ridica pînă la 6.000 m., purtînd pe bord realizatorii filmului documentar despre eclipsa de Soare.
În timpul eclipsei de Soare, Observatorul astronomic din Bucureşti va transmite prin radio ...

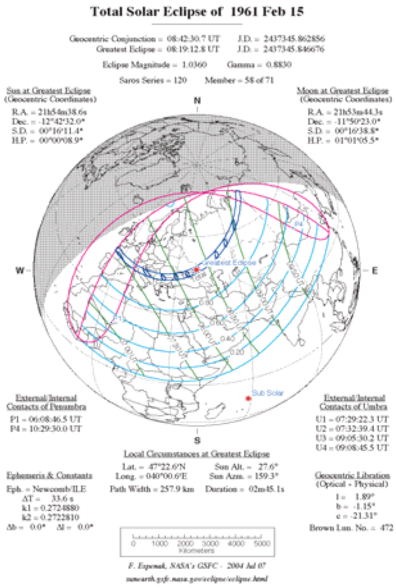


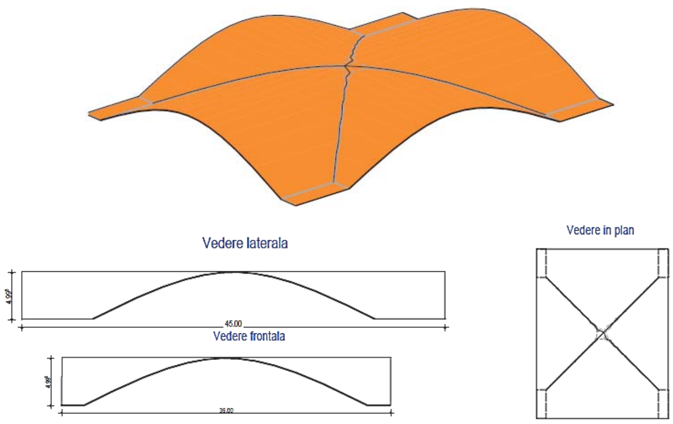
Fig. 2:
a) The principal phases of the solar eclipse for Bucharest [10];
b) The total solar eclipse of 1961 February 15th [11].

2.2. Modelling the Roof Structure of the Sports House

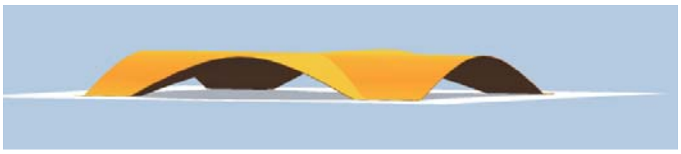
The design of a Thin Concrete Shell Roof is presented in figure 3 and consists in the following elements:

- The structure was **reinforced-concrete monolithic thin shell**;
- The Contour support of the roof were made by **concrete-prestressed beams**;
- The roof (roof covering), thin cloth made of two intersecting horizontal cylinder all-concrete monolith.
- At the intersection, are created on the diagonal, ellipse arches. These arches should have been calculated accordingly. The issue is not so simple, because these arches had the section as "a butterfly with open wings" in order to achieve takeover efforts, resulting in intersection the two cylinders. It seems that here, it would have been the main error of design process, because the calculation had been simplified, reducing the section of the arches at a segments type polyline. [12]

For rebuilding process, it was then decided that the roof will be metal farms structure presented in figure 4.



a) **b)**



c) **d)**

Fig. 3. The design of the thin concrete shell roof for Sports House.

Fig. 4. The top view of the new building - Sports Hall officially opened in 1965 – rear end [8].

2.2.1. Temperature loadings

The temperature of the air during the eclipse can be considered to be modeled with the graphic from the fig. 5. Using the medium temperature for Cluj, in February 1961, and the testimony of some witnesses of that times were combined the parameters involved. Using the observed difference during some phenomenon – the total solar eclipse, inside of the town, in a place not sheltered, as ours, the maximum **thermal shock** can be taken to be likely 4°C.

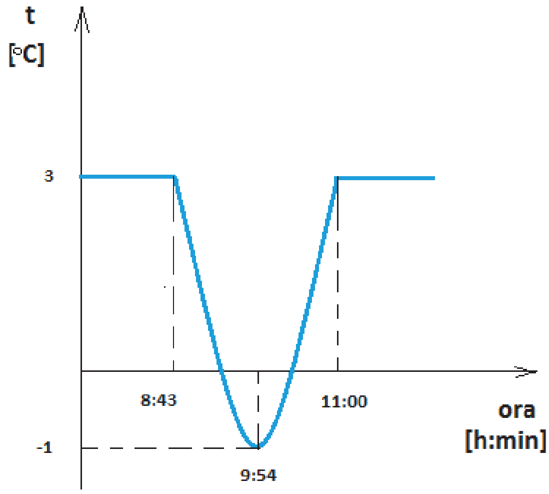


Fig. 5. Temperature function during the eclipse.

2.2.2. Permanent loads, Variable loads

The Structural Software for Building Analysis and Design - ETABS which is a powerful program that can greatly enhance an engineer's analysis and design capabilities for structures. It was realized the model of the entire roof. The analysis began with creating the structural model, define the material properties, defining the structural loads, defining the boundary conditions, defining the load cases. After the model is entirely defined the analysis was performed [13, 14].

On the basis of the hypothesis involved in the analyzed situation from that day the uniform loading of 4 kN / m2 it was considered across the entire structure. For the boundary conditions, the entire roof was considered to lean on the outline of the four horizontal platforms.

For better understanding of the entire analysis next nomenclature were used:

a) For shell element ***internal forces***, the possible components are as follows:

F11 - Direct force per unit length acting at the mid-surface of the element on the positive and negative 1 faces in the 1-axis direction; F12 – Shearing force per unit length acting at the mid-surface of the element on the positive and negative 1 faces in the 2-axis direction, and acting on the positive and negative 2 faces in the 1-axis direction.

FVM: Von Mises principal force per unit length acting at the mid-surface of the element.

b) For shell element internal ***stresses***, the possible components are as follows:

S11: Direct stress (force per unit area) acting on the positive and negative 1 faces in the 1-axis direction; S12: Shearing stress (force per unit area) acting on the positive and negative 1 faces in the 2-axis direction and acting on the positive and negative 2 faces in the 1-axis direction.

V13: Out-of-plane shear per unit length acting at the mid-surface of the element on the positive and negative 1 faces in the 3-axis direction; V23: Out-of-plane shear per unit length acting at the mid-surface of the element on the positive and negative 2 faces in the 3-axis direction.

SVM: Von Mises principal stress (force per unit area). [15]

*2.2.3. Input data based the **PCE** concept*

The principle of critical energy (PCE) and the concept of specific energy participation introduced by this principle, a dimensionless power dependent variable, allows the superposition of effects via algebraic summation, in the case of loads of the same nature but of different types, as well as in the case of loads of different nature (mechanical, thermal) in this specific case of the superposition of the thermal loads and mechanical loads. [16]

For the complete analysis the superposition between the thermal loads and mechanical loads (permanent and exceptional loads – from the big amount of water of the previous rainfall) needs to be taken into consideration and used as input data in the correct and complete analysis. The law of the equivalence of processes and phenomena: "Any two phenomena, at a given time, are equivalent if the total participation of their involved specific energy, compared to the same critical state, are equal. Generally one should write $P_{T,1}(t) = P_{T,2}(t)$, where $P_{T,1}(t)$, $P_{T,2}(t)$ is total specific energy participation dependent on time, t, for process 1 and for process 2. Both or only one of this participations may be time independent.[16]. In our case the thermal process can be time dependent (see the graphic from the fig. 5).

Energonics method, in order to determine the equivalent stress in nonisotropic structures with nonlinear behavior, was developed on the basis of PCE and the law of equivalence of processes and phenomena [17].

The PCE has allowed finding the fatigue life of technical structures with cracks and was analysed from the thermodynamic point of view and was underlined its high degree of generality.

The total participation in releasing the buckling in any kind of shells, under external pressure p_e, axial force F, bending moment Mb, torsion moment Mt, shearing force Q and thermal load T [16],

$$P_T = \left(\frac{p_e}{p_{e,cr}}\right)^{a+1} + \left(\frac{\sigma_1}{\sigma_{1,cr}}\right)^{a+1} \cdot \delta_F + \left(\frac{\sigma_b}{\sigma_{b,cr}}\right)^{a+1} \cdot \delta_b + \left(\frac{\tau_t}{\tau_{t,cr}}\right)^{a_1+1} + \left(\frac{\tau}{\tau_{cr}}\right)^{a_1+1} \cdot \delta_Q + \left(\frac{T}{T_{cr}}\right)^{\beta} \cdot \delta_T, \quad (1)$$

where: W – strength module of shell section, R – the radius and δ – the thickness of the shell wall. The denominators represent the critical values corresponding to the buckling only under the action of that particular load, while δF, δb, δQ and δT are equal to 1 on the surfaces where those loads produce compression and to −1 on the surfaces where those loads produce extension. Exponent β derives from the behavior law of the shell material under the action of thermal loads as compression in our case.

In the **Energonics** method [4; 5], a single concept is used: the specific energy share of the stresses requiring the tree, dimensional dimension, which allows the non-linear behavior of the tree material to be considered; Can be applied beyond the flow limit, both for cracked and cracked structures without the need for other concepts.

In our situation, the multitudes of mini-cracks in the structure of the roof were considered after a long and low temperatures winter.

The condition for admissibility of the load, in **Energonics** method, is given by the mathematical inequation:

$$P_T^* \leq P_{ad} \tag{2}$$

where

$$P_{ad} = 1 - D^*(t) \tag{3}$$

$D^*(t)$ represents the damage (as a function of t - time parameter) reported to the admissible state of the structure during the process, for example, the propagation of the crack.

The Energonic method applied to the roof structure consists in using (1) and (3) relations, in which the damage produced by the presence of the crack is:

$$D^*(t) = \left(\frac{a(t)}{a_{ad}}\right)^{\frac{\alpha+1}{2}} \tag{4}$$

Where a(t) is the characteristically size of the crack, its value may evolve over time t, and a_{ad} - the admissible value of the size of the crack; $a_{ad} = \frac{a_{cr}}{c_f}$, where a_{cr} - critical size of the crack and c_f - safety factor relative to critical fracture size.

From a practical point of view, $a(t) = a(\sigma; t)$, because the action of the σ tensions and τ tensions is more dangerous for crack generation. The condition so that the solicitation state after a solicitation of t duration would be admissible is given by relation(9) in which:

$$P_{ad} = 1 - \left(\frac{a(t)}{a_{cr}}\right)^{\frac{\alpha+1}{2}} \tag{5}$$

Note: The effects of the three known breaking methods (I;II;III) must be cumulated as observed upon the verification of the breaking mechanic of the roof's defective area in the case of their simultanious solicitation. This problem has been solved in a general case of nonlinear behaviour of the roof's material, using the kinetic energy principle. It has been achieved:

$$P_T = \left(\frac{K_I}{K_{I,C}}\right)^{\alpha+1} \cdot \delta_k + \left(\frac{K_{II}}{K_{II,C}}\right)^{\alpha+1} + \left(\frac{K_{III}}{K_{III,C}}\right)^{\alpha+1} \tag{6}$$

in which: K_I, K_{II}, K_{III} – are the tension intensity factors according to the three breaking methods and $K_{I,C}, K_{II,C}, K_{III,c}$ – are the suitable tenacities. $\delta_k - 1$ if normal tensions produce the opening of the fissure, and $\delta_k = 0$ if they close the fissure.

The total participation of the specific energy in relation to the admissible state, P_T^*, is calculated with relation (17), in which the critical values of the denominators are related with the corresponding admissible values. Upon reaching the critical state$P_T = P_{cr}$, and upon reaching the admissible state $P_T^* = P_{ad}$.

In the case of materials with a high capacity of plastic deformation before breaking, the total participation of the specific energy is calculated in relation to the admissible state according to the opening at the top of the crack,δ . In this case though $k \neq$ 1. [16]

Using these concepts the total loads used as input data for the model and using a mediation of the main processes involved the total amount of the loads were 5 kN/ m^2 for **collapse situation**.

2.2.4. Obtained results

Performing the analysis the important conclusions can be done. The most loaded areas are the intersections of the quarter-shells and the intersection between supports area and the roof structure main diagonals.

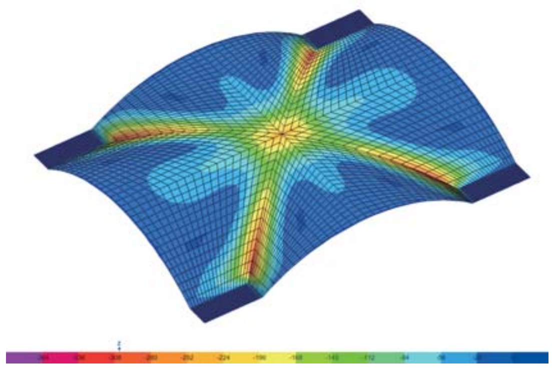


Fig. 6, a) Direct force per unit length acting at the mid-surface of the element on the positive and negative 1 faces in the 1-axis direction.

In the figure 6 a) the direct force per unit length acting at the mid-surface of the element on the positive and negative 1 faces in the 1-axis direction is indicated as a map. Is visible that the maximum recorded values are located on the intersections - 364 kN/m. The figure 6b represents the Fmin – for the elements, the maximum value is 845 kN/m.

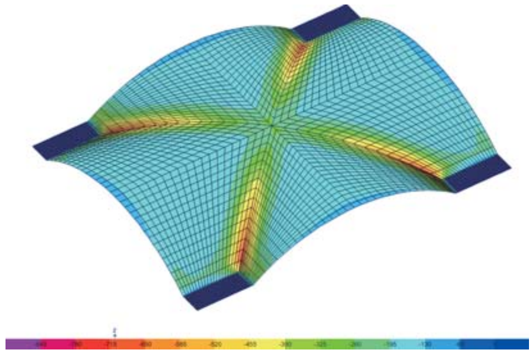


Fig. 6, b) The FMin values map for the structure.

Fig. 7 represents Faxial diagram with the maximum values from the leaning surface is 1814 KN/m and the figure 8 represents the shear - direct stress (force per unit area) acting on the positive and negative 2 faces in the 2-axis direction. The maximum value is 1814.48kN/m^2 and it is located on the inside corners of the leaning surfaces.

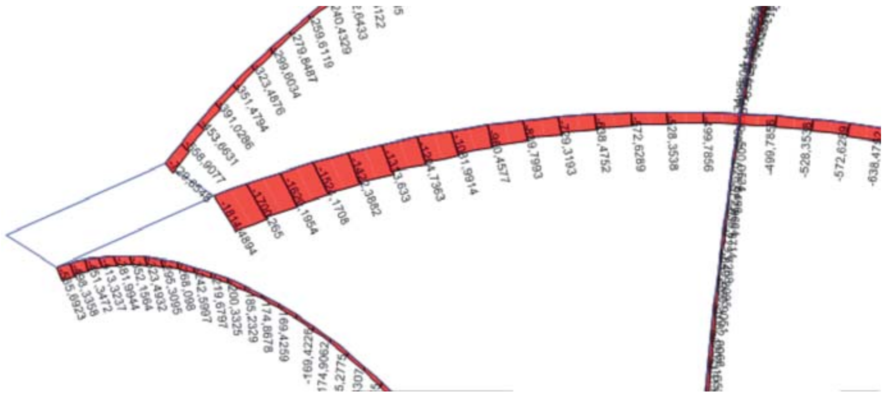


Fig. 7. The F axial diagram for the entire roof structure.

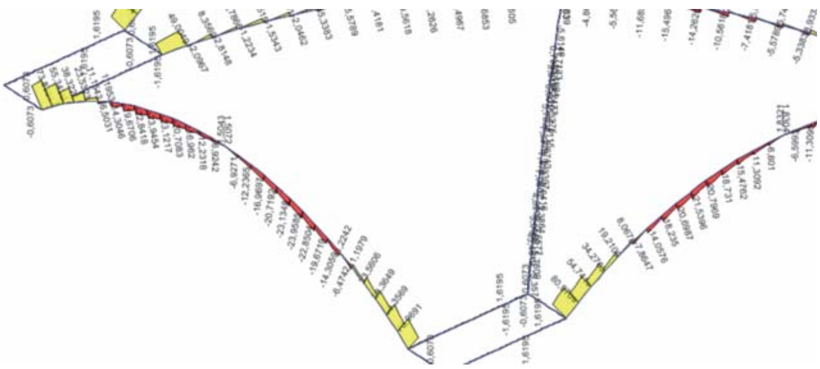


Fig. 8. The Shear 22 diagram for the entire roof structure.

The figure 9 a) shows the maximum principal shear per unit length acting at the mid-surface of the element, with the maximum value of 42.0kN/m and the figure 9 b) shows Von Mises principal stress (force per unit area) for the entire structure. The maximum value is 12.6 kN/m^2 located on the supports area.

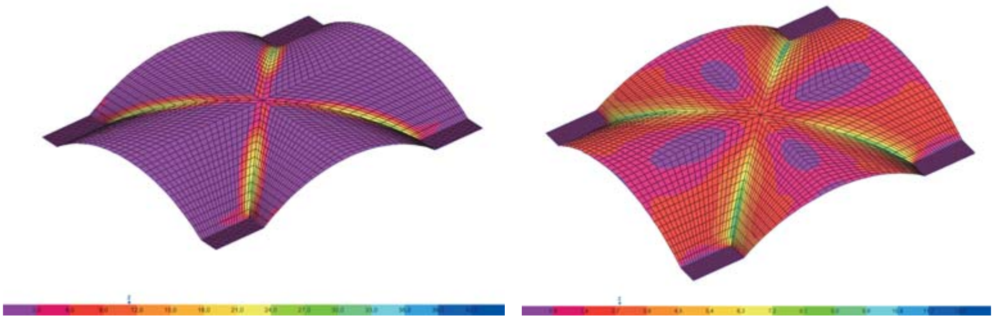


Fig. 9 a) Vmax - Maximum principal shear per unit length acting at the mid-surface of the element; b) SVM - Von Mises principal stress (force per unit area).

The fig. 10 a) represents M11 diagram of moments - direct moment per unit length acting at the mid-surface of the element on the positive and negative 1 faces about the 2-axis. The maximum value is 8.50kNm and it is located on the intersection of the quarters of the model.

The M33 maximum vaue (fig. 10 b) is 125.878 kNm and it is located on the four supports.

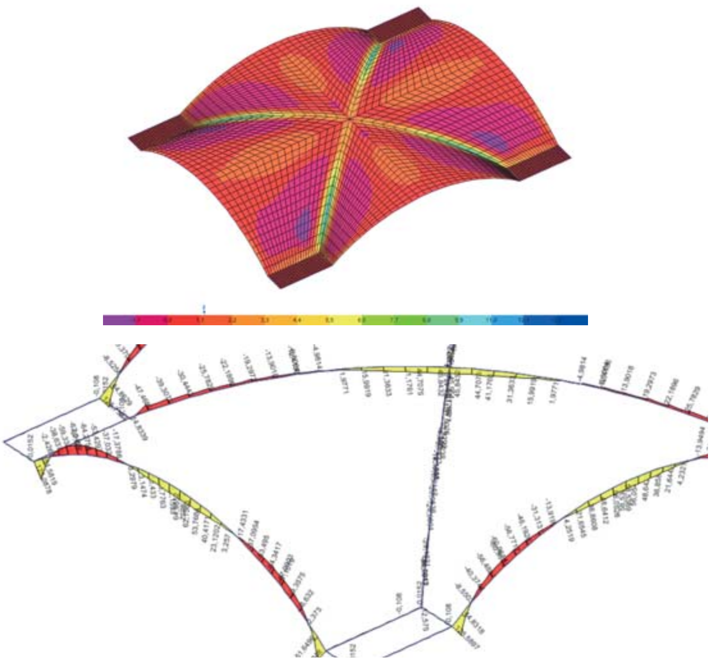


Fig. 10a) M11 - Direct moment per unit length acting at the mid-surface of the element on the positive and negative 1 faces *about the 2-axis*; b) M 33 –Load case combining maximum value of V22 and M33.

3. Discussions

After the complex analyzes were performed, the structure also had good stability at loads of 5kN / m^2 additional to its own weight, and the tensions are relatively small.

The problem is the four supports of the two diagonal beams. In those supports we have great efforts. If the bearings resist, it also resists the structure, but if one of the supports yields, it will obviously yield the structure of the slab. The yielding of a support due to external conditions is highly probable because they are exactly where the water, ice and snow are leaking from the cylindrical areas. Cracks and frost can weaken the support area.

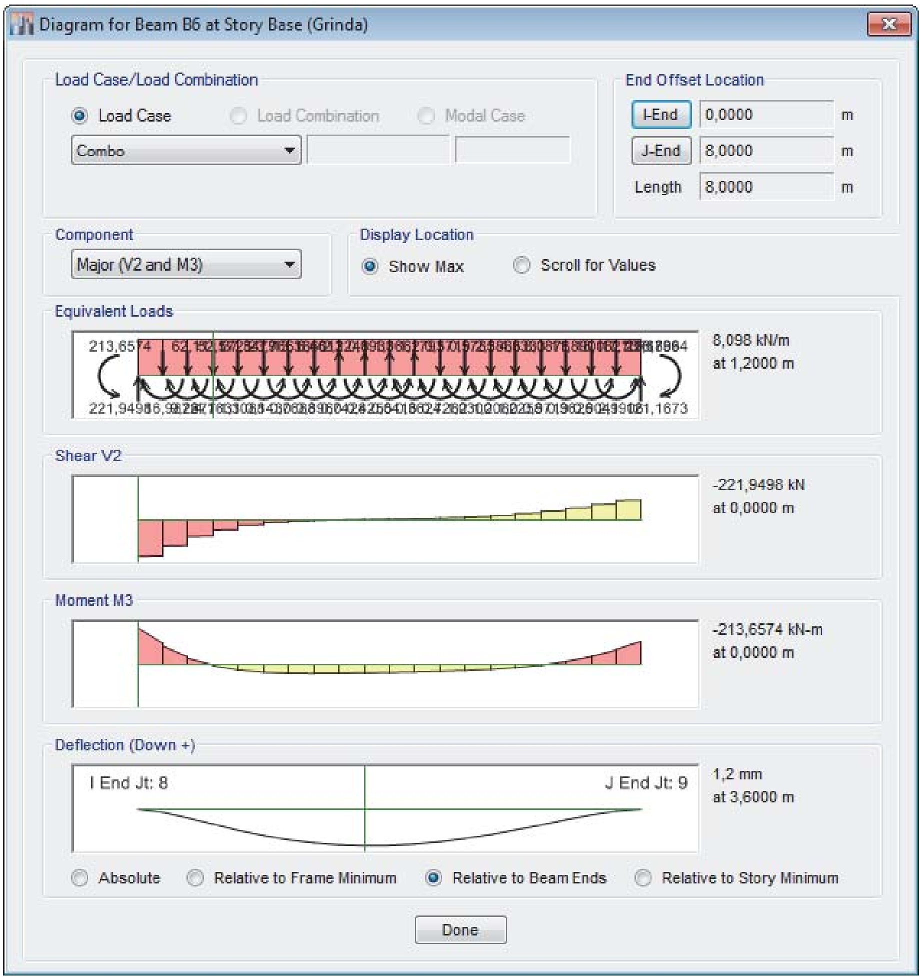


Fig. 11. The diagram and details for M33-2 – Load case combining maximum value of V22 and M33, 8.098kN/m as equivalent loads.

Figure10 b) with M33 diagram shows the high values of the moment and the cutting force in the support. Most of the failures that occur in a roof system are not major collapses, but simply performance failures.

Although each roof system has its own specific failure modes, there are a variety of common performance failures that can result in necessary repairs. [14,15,16]. Some of these failures that require repair include the following: Blistering, Splitting, Punctures/ Penetrations, Wrinkles, Flashing Installation, Surfacing, Fasteners, Shrinkage, Ponding, Leaks or moisture intrusion, Abuse, neglect, and lack of maintenance.

Although most roof-related failures that occur are simply performance issues to the roofing system, there are several failure types that can be more serious. These types of failures are strength-related failures and can create large openings in the roofing system, damage interior systems and spaces, or even lead to partial or full collapse of the building. [17, 18, 19]. The ultimate cause of these failure types is an overloading of the roof. Whether it be positive or negative pressure, if roofs are pushed past their limit, failure will occur.

The most common types of strength related failures are wind uplift and overloading caused by excessive snow, sitting water, or live load.

As discussed in an earlier section, ponding water can be very problematic on roof assemblies, and excessive amounts can cause overloading failure to occur. Poor drainage and heavy rainfall is often to blame for dangerous ponding situations. [20, 21, 22]. At 312 kg/m^2, water loads can increase quickly. If a roof structure has a bay size of 9 m in each direction, and an 2.5 cm of rain is ponded on that bay due to a clogged drain, the water weight for that bay would be almost 2.265 t alone. When heavy rainfall puts multiple cms of rain onto a roof, this weight can increase dramatically.

4. **CONCLUSION**

Recent history contains many cases of accidents with the partial or total collapse of buildings of great importance. Elucidating the causes of these collapses allowed the development of calculation rules and construction techniques.

As water build up occurs, structural framing can start to fail under the load or due to **unbalanced loading conditions** with adjacent bays. Additionally, as water accumulates at low points, the deck can deform further allowing for further **drainage problems** and ponding to occur, and parapet walls can create a "pool" effect trapping large amounts of water. The final result of this is often progressive or sudden roof collapse.

The total solar eclipse (Cluj was partial, not total) lasted about 2 minutes at the maximum, and a total of two hours since the beginning until the end. Not much is thermal shock - everything is progressive. More material was bitumen from the roof. Furthermore, temperatures were positive - rain. The temperature difference on the ground during an eclipse of the sun is max 3-4 degrees in cities. That small difference in temperature cannot provide the thermal shock material Sports Hall terrace. But if the temperature decrease below 0°C, all the water from the mini-cracks could be frozen.

So the variant of frost as the cause of the failure of the structure is plausible for 4 reasons:

- all the four supports- surfaces are the areas that **accumulate the largest amount of water due to leakage**;

- the water in these four areas does not leak due to the horizontal platform;

- **freezing water in the cracks** in these four areas causes the support to be weakened;

- the four supports are the most requested areas within the structure, the disposal of one having serious effects;

- the conclusion of the performed analysis conducted to the idea that the big rain in that morning, was led to a **large amount of infiltrated water in roof terrace** (made absolutely classic) and due to the excess weight of water the collpase occured.

The collapse demonstrates the consequences of improper design and construction procedures from that times – 1960's. Using the **Energonics** principles, the superposition of the two main loads (mechanical and thermal), there were performed a lot of iterations in ETABS analysis to determine the load which is responsible for collapse.

Although the roof had been standing under its own strength for almost one year, additions of the total loads were being made during the storm from a day before of the collapse day. Since construction was still taking place, no insulation or weather proofing had been installed on the exterior of the roof. The insulation is vital to the roof because it prevents possible thermal gradients to occur through the shell of the roof. All the **mini-cracks which occured during the winter from the freeze-thaw** cycles were full of water and if the gradient of the temperature had been under freeze point, the tensions inside the roof structure increased and lead to the final collapse.

The performance failures to roofing systems can eventually lead to greater (and more expensive) problems, and should, therefore, not be ignored. Preventing deferred maintenance by repairing the problem early can save a building owner and other parties involved a lot of money and possibly even court time. Finally, it is important that we, as an industry, learn from our mistakes. By understanding past roof failures, we should be able to improve both the design and integrity of the systems we create, and prevent catastrophic failure from occurring again.

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