

Structural design of a roof steel structure having double curvature.

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Abstract

Having as a starting point the idea of creating a structure with an iconic design, the current article presents all the technical solutions and steps followed in the process of creating this special structure. The structure, having the destination of a showroom for an auto dealer, is presented with an unconventional design of the roof: a roof structure having a double curvature. Starting from a relatively simple structural system, the evolution steps are presented together with the main setbacks, challenges and the final solution: a completely redesigned structural system, with high performance elements, both in strength and material consumption. The article also presents some stages of the structural analysis, with provisional results that shaped and determined the final design of some of the structural elements.

Rezumat

Având ca punct de plecare ideea de a realiza o structură cu un design emblematic, articolul prezintă soluțiile tehnice adoptate și pașii urmați în elaborarea acestei structuri speciale. Structura, cu funcțiune de showroom auto, prezintă o geometrie neconvențională a acoperișului: un acoperiș cu dublă curbură. Pornind de la un sistem structural relativ simplu, sunt prezentati pașii prin care acesta evoluează, obstacolele și provocările intalnite în timpul procesului precum și rezultatul final, un sistem structural complet schimbat față de cel inițial, mult mai performant și mai economic din punct de vedere al consumului de materiale. Sunt prezentate deasemenea elemente din timpul modelării structurale și diverse rezultate provizorii obținute pe parcurs, rezultate care au influențat în mod direct soluțiile adoptate în varianta finală a sistemului structural.

Keywords: steel structure, double curvature, spatial, roof, trusses, unconventional.

1. General design data.

The objective of the project has been to create an “auto showroom” steel structure. The showroom is an industrial structure, divided into three major sections, each of them having a different purpose. The front area (GF only) has the destination of exhibition space. The second area is dedicated to offices. This area is divided into two parts, one having three levels (GF + 3) and the second having only two levels (GF + 2). On the third floor of the first section will be a conference room. The third area of the building is the technical area. This is also divided into two sections, one having the destination of service area (GF only) and the second having the destination of utility space for the staff (GF + 1).

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The shape of the structure in plane has been rectangular. In elevation, the building had an irregular shape, the roof having double curvature, giving the structure a unique signature image.

The building has been located in Cluj Napoca, in the industrial park zone, having a major road passing in front. The area where the building has been placed, has been previously leveled by the municipality and was considered to be plane, with no major irregularities.

According to P100-2006 “Seismic Design Code”, the building was considered to be of importance class III.

For the building location, the following seismic characteristics were given (IMR 100 years): [1]

- ground acceleration: $a_g = 0.08g$;
- control period: $T_{C,S} = 0.7s$.

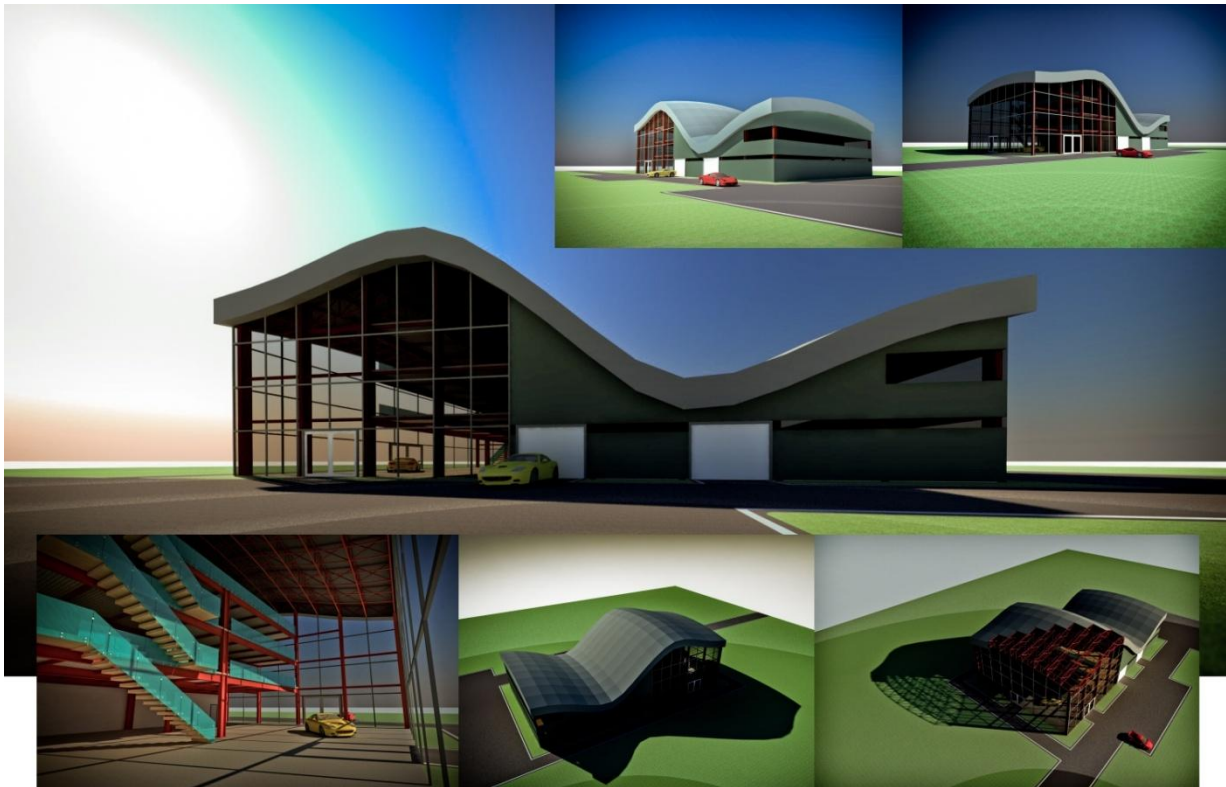


Figure. 1. Architectural design.

The computations for wind actions and wind effects over the structure have been done according to SR EN 1991-1-4-2006 and SR EN 1991-1-4-2006_NA2007 (national annex) design code.

The computations for snow actions and snow loads effect over the structure have been done according to SR EN 1991-1-3-2005 and SR EN 1991-1-3-2005_NA2006 (national annex) design code.

According to the soil expertise, the good foundation soil, consisting of silty clay, brown, plastic consistent, having $p_{conv} = 408$ [kPa], was located at the depth of 0.5 [m].

2. Design stages.

2.1 Geometrical characteristics.

The shape of the structure in plane was rectangular. In elevation, the building had an irregular shape, the roof having double curvature. In order to obtain the best aspect ratio between all dimensions involved, a scale model was created and different dimension configurations have been studied. The final dimensions of the structure in plane were 25 [m] x 45 [m] with a height ranging from 5.3 [m], in the lowest point of the roof, up to 16.5 [m] at its peak.

The irregular shape of the roof was composed of an arch on the smaller side of the rectangle, which follows a sinus function graph inspired free shape. The result was a unique 3D surface with a great resemblance to the shape of a natural form.

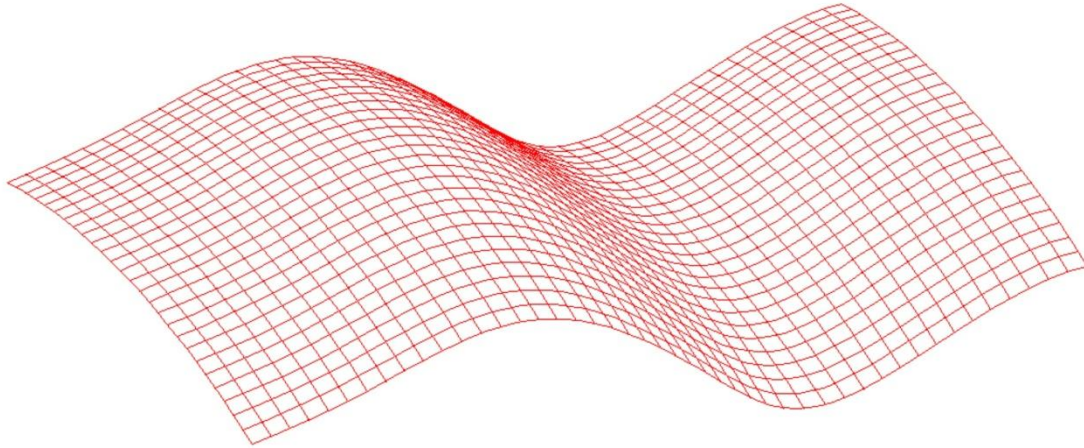


Figure. 2. Roof structure shape.

The roof structure alone, stands out over the plane rectangular shape of the building on the long sides of the rectangle, having the width of 27 [m].

2.2 Structural characteristics.

Before being able to choose a structural system for the building, a complete loads evaluation has been done. Snow loads have been evaluated with respect to SR EN 1991-1-3-2005 and SR EN 1991-1-3-2005_NA2006 (national annex) design code, wind loads have been evaluated with respect to SR EN 1991-1-4-2006 and SR EN 1991-1-4-2006_NA2007 (national annex) design code, live loads have been evaluated with respect to SR EN 1991-1-1-2004 and SR EN 1991-1-1-2004_NA2006 (national annex) design code and seismic loads have been evaluated with respect to P100-2006 “Seismic Design Code”.

Having the loads evaluation complete, one was able to start a new phase of the project: choosing the most suitable structural system in order to obtain best material consumption, ease of manufacture and no compromise to any aspect of the structure shape. Several systems have been analyzed and compared, starting from cold rolled steel sections, derived steel sections, truss members, space truss members and reticulate structures, taking in consideration performance aspects and the available literature for the computational part. The final structural solution for the roof was selected to be a truss structure with plane trusses intersecting from both transversal and longitudinal sides. In order to simplify the technological processes and reduce the costs, the curvature of elements has been designed from several straight steel members (3 [m] length segments for transversal curvature and 2.5 [m] length for longitudinal curvature).

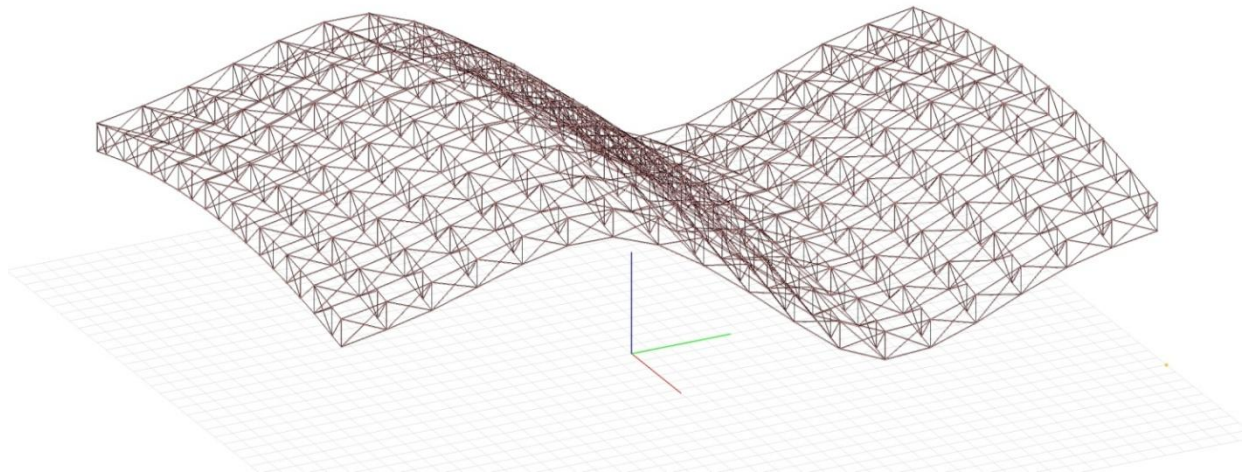


Figure. 3. Initial sizing roof structure.

With a structural system established and complete loads evaluation, an initial sizing stage for all elements followed. Using references from the available literature [2],[3] and [4] the following results were obtained:

- columns having a HE 500 A steel profile;
- main beams having an IPE 500 steel profile;
- secondary beams having an IPE 200 steel profile;
- composite floor system having a thickness of minimum 80 [mm];
- transversal truss element (upper and lower chord) having a CHS 114.3x6 steel profile;
- transversal truss element (diagonal brace) having a CHS 88.9x4 steel profile;
- transversal truss element (vertical brace) having a CHS 48.3x4 steel profile;
- longitudinal truss element having a CHS 88.9x4 steel profile.

For all the structural elements, S275 steel class was used.

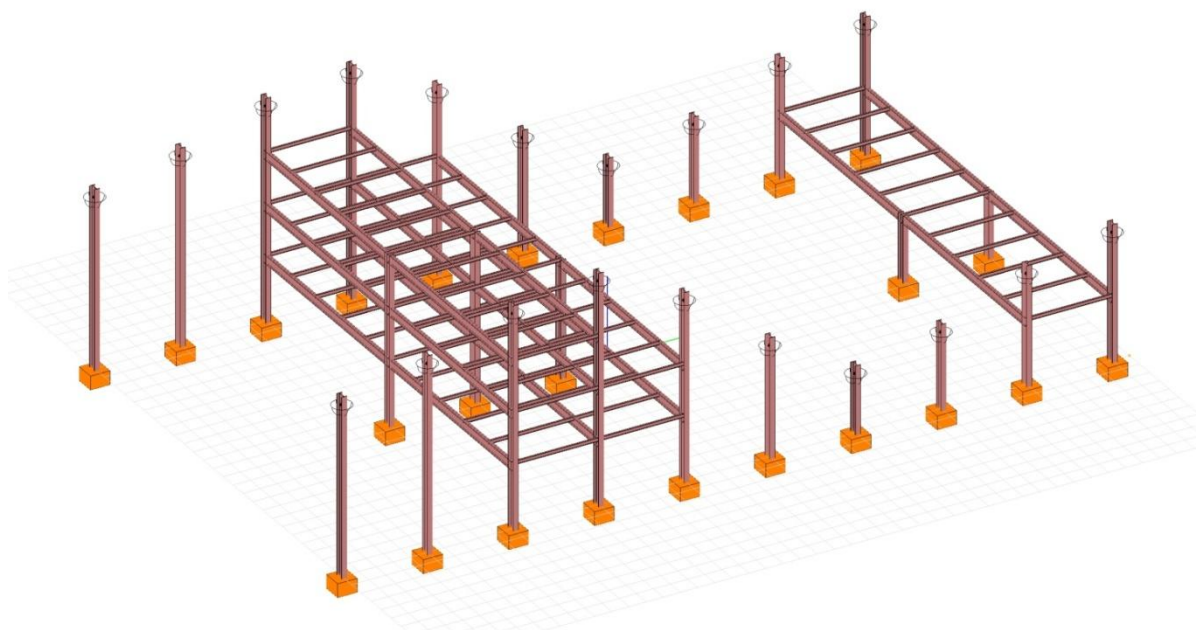


Figure. 4. Initial sizing structural system.

The building envelope elements have also been selected taking in consideration both mechanical and thermal minimal required performance, resulting in:

- high performance curtain wall system;
- FischerTHERM lateral insulating panels;
- TECNORoof insulating panels.

In order to preserve the special shape of the roof and obtain a performance thermal insulation and waterproofing, the roof structure has been covered with flat thermo-insulating panels and above that, a layer of folded sheeting.

2.3 Loads evaluation.

The loads evaluation process presented a challenge itself due to the fact that design codes do not cover this kind of structures. The only reference they provide is that a scale model should be created and all loading scenarios tested.

An accurate scale model to be tested in the wind tunnel could not be provided for the project due to the lack of time. Some trials using ADINA, a finite element simulation program with the ability of modeling fluids, were done but results were inconclusive and unsatisfactory. As a final solution, an approximation of the roof shape was selected to work with.

For the current project the following loading cases were implemented:

- dead load;
- live load;
- wind load acting from direction X +;
- wind load acting from direction X -;
- wind load acting from direction Y +;
- wind load acting from direction Y -;
- snow accidental load 1;
- snow accidental load 2;
- snow accidental load 3;
- seismic load acting from direction X +;
- seismic load acting from direction X -;
- seismic load acting from direction Y +;
- seismic load acting from direction Y -.

The load combinations table was generated according to the prescriptions provided by SR EN 1990-2004 and SR EN 1990-2004_NA2006 (national annex).

2.4 Structural modeling.

For the structural analysis of the project, Consoft's Consteel 5.0 has been used as the main software solution. This software presented the advantage of being completely dedicated to steel structures. It provides the user with a very friendly and intuitive user interface and large steel sections properties library. It was used successfully for the project and the 3D structural analysis results, in the first order analysis and in second order analysis were very pleasing, complex and accurate. It also provided very useful information about the structure itself and was able to generate full analysis documentation on request.

For the smaller tasks, like plotting the diagram for a steel beam or a truss member in initial sizing stage, Autodesk's Robot Structural Analysis Professional 2009 was used. For Robot Structural Analysis Professional 2009, the option of having dedicated modules of computation for different structural elements, enabled obtaining very accurate results.

Modeling the structure in the structural analysis program was the next big step. This process was very time consuming due to the complexity of the project. Each element of the roof structure had to be correctly positioned and then loads applied for each loading case.

The fact that the roof structure was composed of a network of steel trusses resulted in supplementary computational work. Each load applied to the roof structure had to be split into regions and then, for each region, a resultant force computed. These operations enabled the input of concentrated forces in each truss node.

The “dead load” loading case was composed of the total weight of the structural steel elements (automatically computed and added to the computation by the software), weight of the intermediate composite floor slabs and weight of the insulating panels for the roof. In the structural analysis, the loads on the roof structure were modeled as nodal forces.

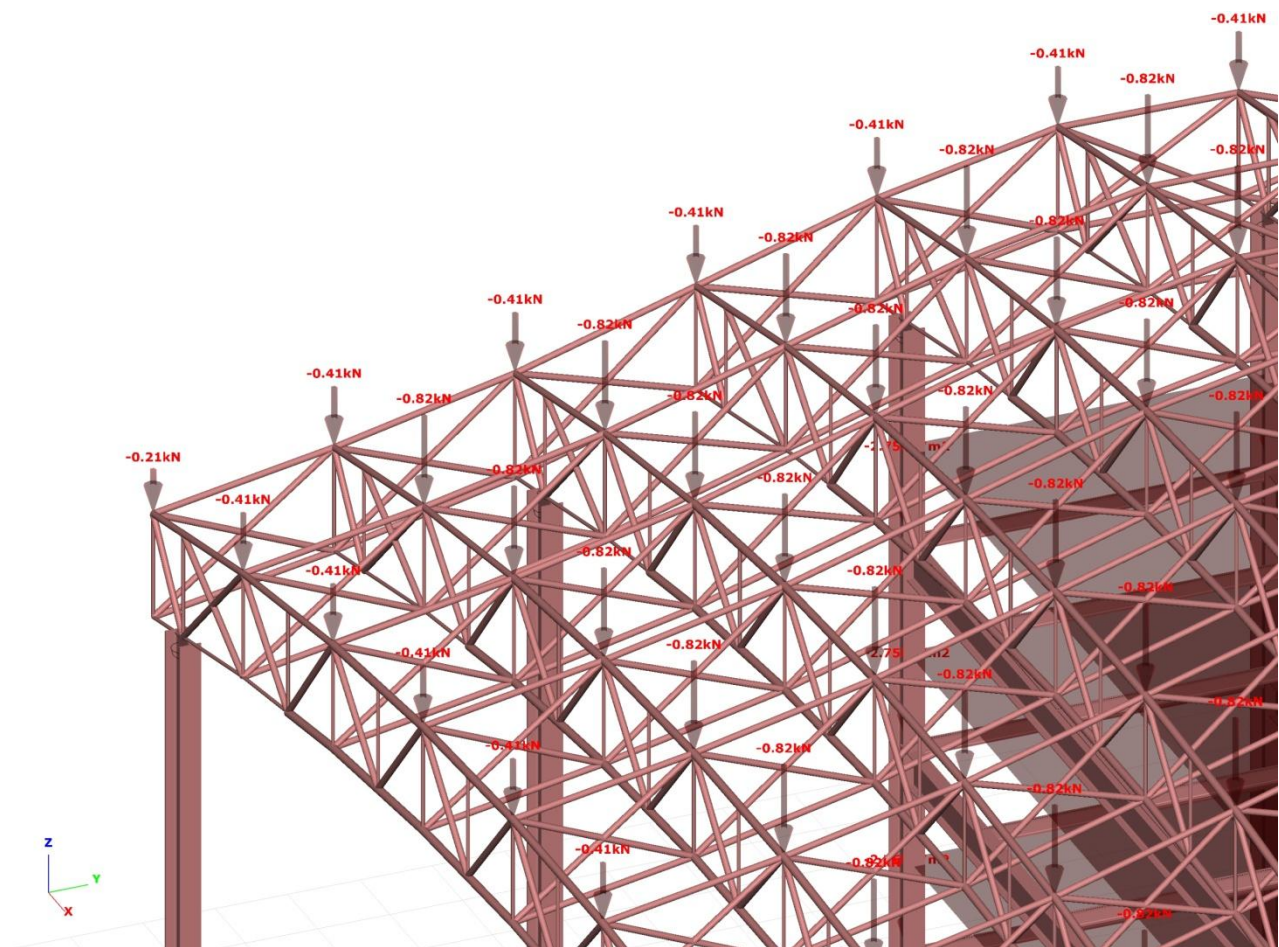


Figure. 5. Dead loads detail.

“Live loads” did not have any influence on the structure of the roof, as they were only present in the interior of the building. “Wind loads” acting on the structure, from different directions, were modeled according to the standards [5],[6] and each wind action region considered, divided and resultant computed. The result were four complex loading schemes, resulted from the wind acting from all four directions, with both suction and compression and different influence areas. “Snow loads” acting on the structure had a very important role in the design stage. As listed above, there were considered three cases of accidental snow loads. No ordinary case of snow load on the structure was considered as it was included and outrun by the first case of accidental loading.

The first snow accidental loading scheme was the one where the snow was considered to be acting on the approximation roof used for the wind loads as well. This loading scheme generated high

snow accumulation in the lower areas of the roof.

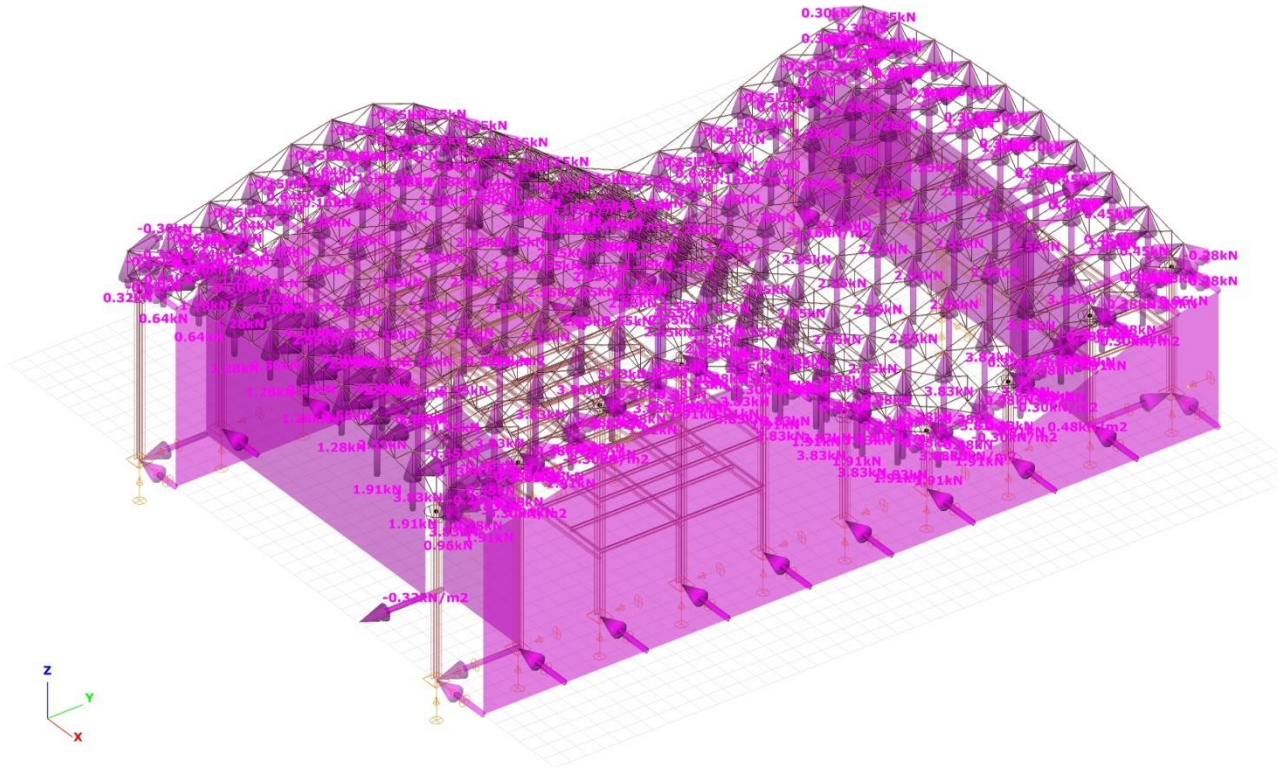


Figure. 6. Complex wind loading scheme.

The second and third snow accidental loading schemes are similar between, having only different direction. They were both considered to be the snow accidental loading scheme provided by the standards [7],[8] for cylindrical roofs.

The “seismic loads” have been computed and introduced manually. Some trials using the software’s capability of computing the seismic loads automatically starting from ground characteristics and location have been done and results were similar.

2.5 Preliminary results.

Having the initial structural system completed, all loading scenarios ready and loads computed and placed on the structure the results from the first run of the structural analysis were created. As it was the first run, it was to be the starting point for the evolution of the structure.

Starting from this point on, each element of the structure was to be analyzed, checked and if required replaced with the most suitable in order to achieve all purposed goals. For the roof structural elements, the element selected to be representative for all transversal trusses was selected the element positioned in the lowest point of the structure.

From the first peeks over the preliminary results of the structural analysis some weak points were spotted. Other would only reveal after thorough analysis of each element. One of the first problems that the initial run of structural analysis created and had to tackled was the displacements issue.

Given the initial design of the structural system and the considered loading scenarios, the structure proved to have a lack of both longitudinal and lateral stiffness for specific elements.

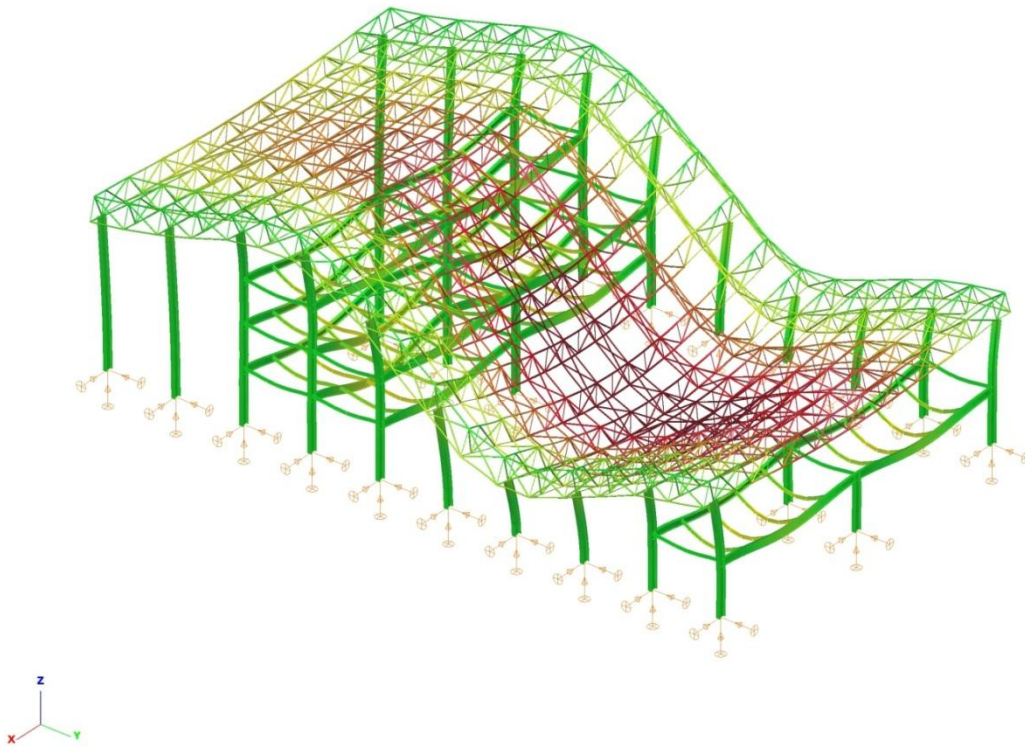


Figure. 7. Deformation according to XYZ produced by a loading scenario with dominant snow action.

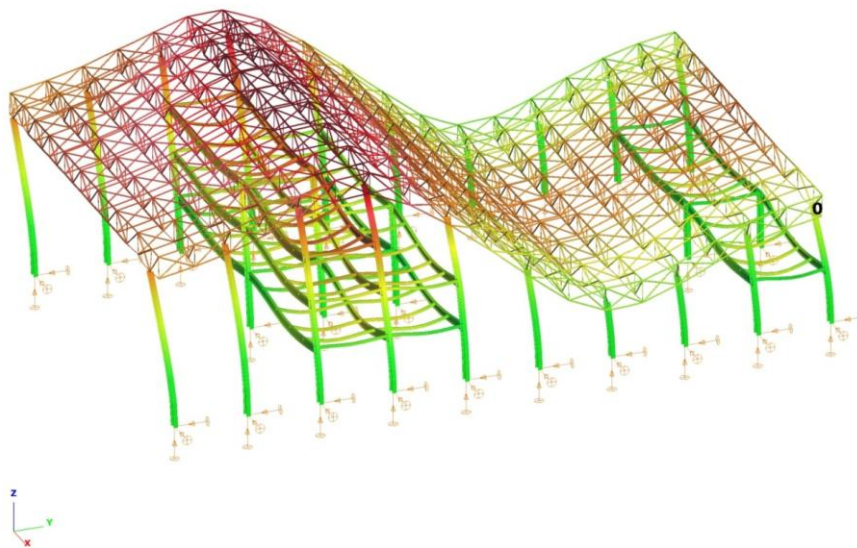


Figure. 8. Deformation according to XYZ produced by a loading scenario with dominant seismic action.

As a concept, the roof structure was intended to behave as a large stiffening element for the whole structure. The first run in the structural analysis revealed that further stiffening was required for

certain members and that some members were oversized.

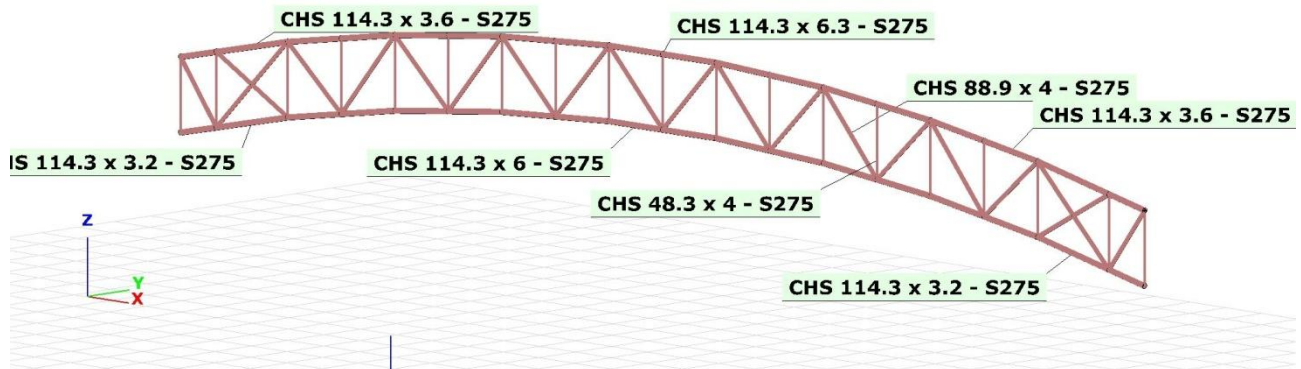


Figure. 9. Transversal truss with variable element thickness.

2.6 Structural optimization.

Having analyzed the initial results of the structural analysis some optimizations for the structural system were to be made. For the lateral columns, a set of stiffening beams at the height of each level were deployed. The selected dimensions were as for the secondary beams and provided good results in reducing the column buckling length and providing longitudinal stiffness for the structure. For the transversal truss of the roof structure, a new structural system was developed. Having the loading diagrams from the structural analysis, the new truss structure was designed to be a truss with variable cross-section. The aim of this redesign process was to create an advantage both in material consumption and element weight. This was an intricate operation because using a variable cross section provided numerous new challenges concerning the shape of the roof.

The solution that fulfilled all demands and provided best structural support was to use truss elements with same diameter along each chord and use variable element thickness. Another aspect of the transversal truss that required close attention was the elements buckling length. As a result for using a truss element, the main stresses in the chords were axial forces. The problem had two major parts: satisfying the buckling length conditions in the plane of the truss and satisfying the buckling length conditions in the plane perpendicular to the plane of the truss. The first section, in the plane of the truss, was easy to deal with by simply adding supplementary vertical braces. On the other hand, avoiding buckling in the plane perpendicular to the plane of the truss required a lot more attention because stiffening the system by simply adding and adding new elements would increase both the costs, through material consumption, and also the mass of the structure.

The natural solution to this problem was to take advantage of the elements that were already present on the building and add as few as possible new ones. The upper chord of the transversal truss was stiffened to reduce the buckling length using the insulating panels composing the roof. The selected panels were mounted in such manner that they provided the required stiffness and reduced the buckling length of the elements in the plane perpendicular to the plane of the truss. The resulting structural ensemble acted as a stressed skin roof. As a result of using a stressed skin roof on the structure, the designed resistance of the roof is not considered to be totally achieved until all roof elements have been placed on the structure. Also, it was very important to note that any further changes or alterations done to the roof structure, must keep in consideration the fact that the roof elements are actually a part of the roof structural system. Maintenance works should also take in account this situation.

For the lower chord elements, a new set of bars was provided as solution for the problem. In order to minimize the relative displacement of each level and of the structure, a bracing system was created. Bracings were applied on the first, third and last bay. They continued as horizontal bracings through the roof structure, in both planes, of the lower and upper chord. The roof structure also had a supplementary longitudinal bracing system, on both sides of the structure.

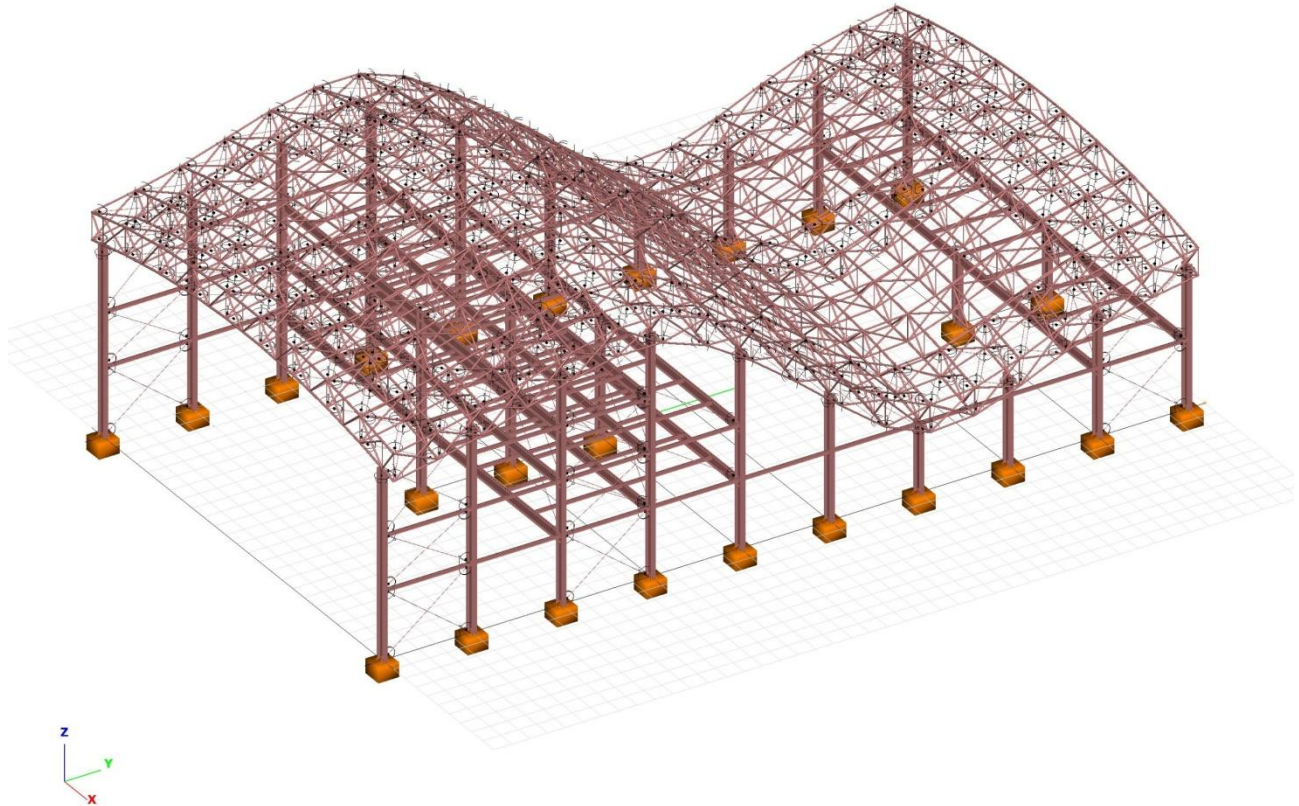


Figure.10. Final structural system of the project.

2.7 Final structural analysis.

Having changed the design of some elements and replaced others, together with the addition of several new elements into the structural system, a new structural analysis was done. This was to be the final structural analysis and results provided by it would be used for the design and checking stage of each element.

From this point on, every component element of the structure was subjected to a thorough analysis taking in consideration its position on the structure and loads applied.

Displacements issue was the first to be tackled with. After a close inspection of relative level displacements both in Ultimate Limit State and Serviceability Limit State the results were satisfying and all conditions imposed by current standards [1] met.

Soon followed specific control procedures for each structural element, starting from marginal columns, to central columns, main beams, secondary beams, composite floor slabs, truss element and finishing with the bracing system. For the roof structure, the representative transversal beam used up until now in the initial sizing process, first step of structural analysis, redesign process and final structural analysis, was set for a detailed checking. This started by checking the relative

displacements of the upper level in comparison with the allowable limits. Having these conditions satisfied, a thorough analysis of each composing element started: both upper and lower chord, with variable cross-section, were checked in axial tension, centric compression, buckling in the truss plane and buckling in the plane perpendicular to the truss plane. Diagonal and vertical braces were checked for axial tension, centric compression and buckling in the truss plane.

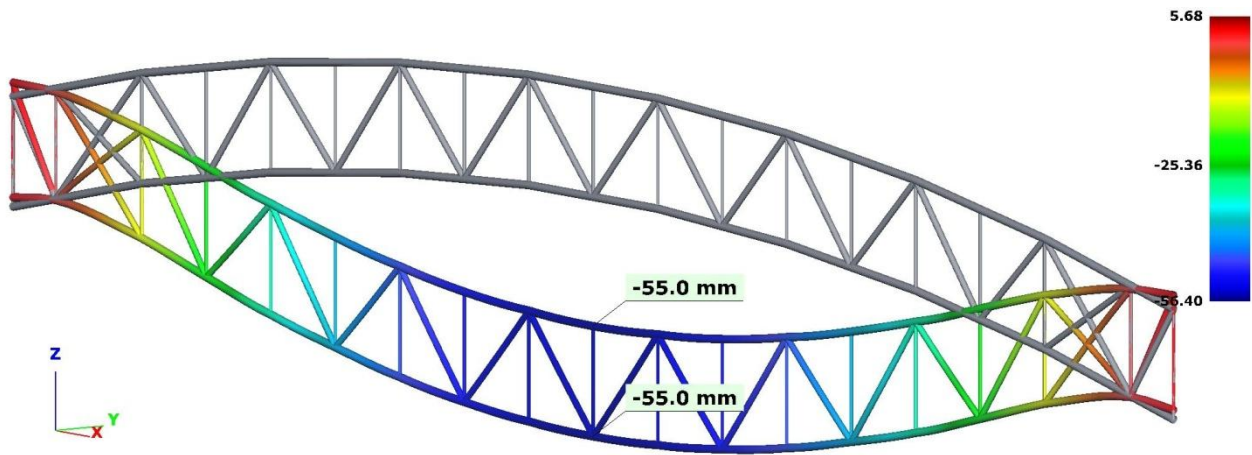


Figure.11. Deflection check for Serviceability Limit State.

The final check for the transversal truss was the deflection check. Standards [9],[10],[11] provided the maximal allowable values for deflection. In the case of the transversal beam, as shown in Fig.10, the peak value of deflection computed in the serviceability limit state was considerably smaller than the limit imposed. For the current structure, the limit deflection was of 100 [mm], while the final result obtained using the final form of the truss was of only 55 [mm].

In the process of evaluating and creating the final design of the structure, one took in consideration the advantage provided by the software solution to create a map of the most stressed elements of the structure. For each of the elements analyzed and checked, a such map was plotted and the maximal percentage of section use computed. It proved to be a very useful tool all along the design stage as, together with the stress and strain diagrams, marked out the most unfavorable beam sections and even predict area where loss of structural stability could occur.

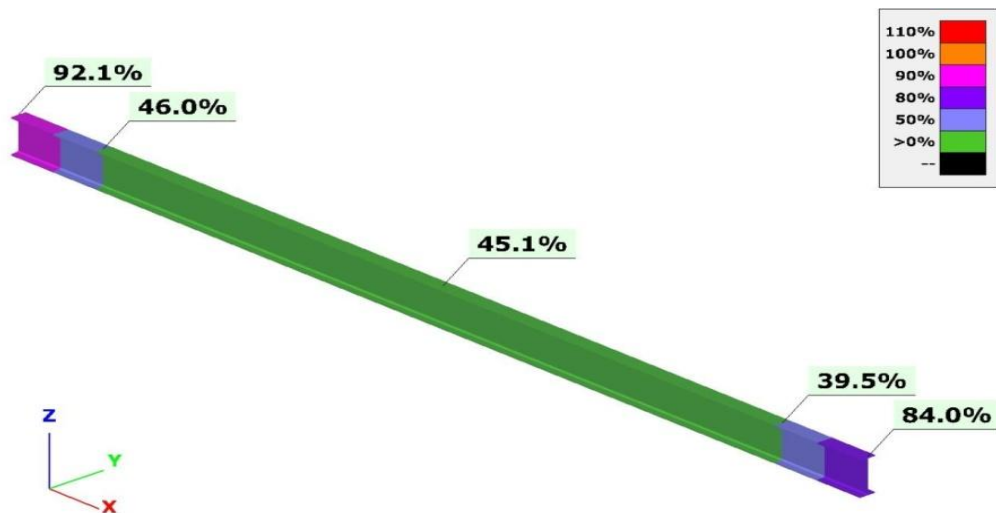


Figure.12. Local element stress map.

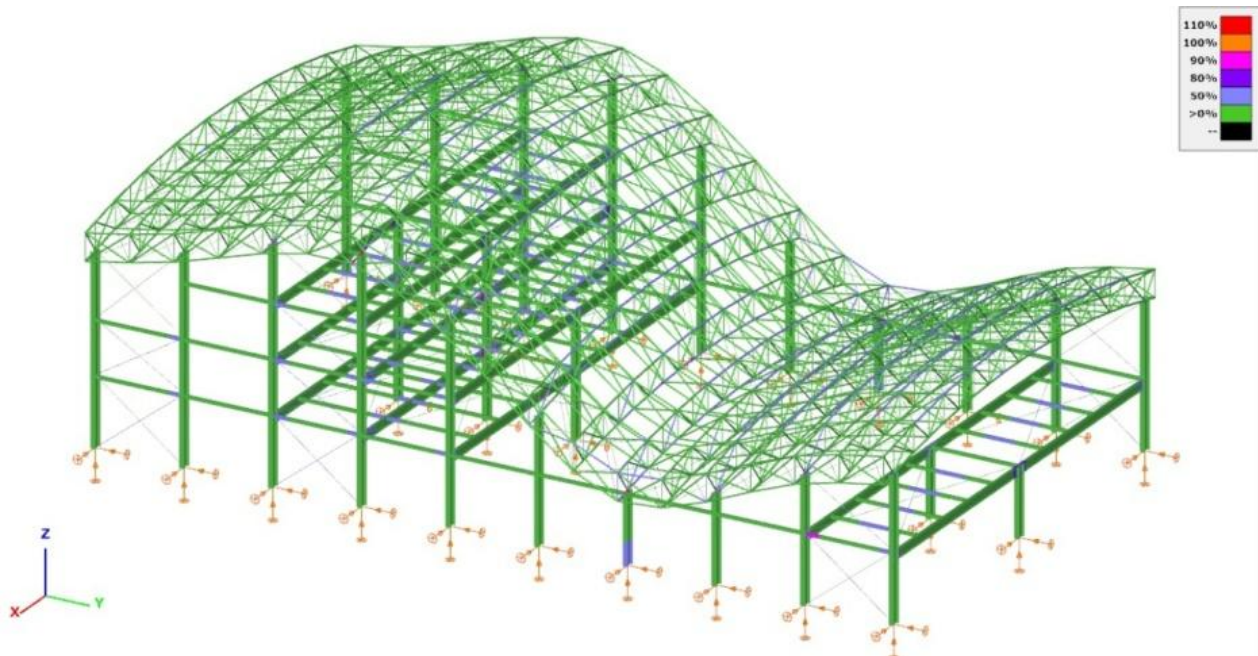


Figure.13. General building stress map.

3. Comments and conclusions.

From start to finish, dealing with an unconventional project presented several challenges. Having to build a scale model in order to obtain best aspect ratio, then search for the most effective structural system in terms of ease of manufacture and reduced production costs and finishing with the selection of the structural program were just the “tip of the iceberg”. Even the most simple tasks, like loads evaluation required a lot of work, mainly because modeling these type of structures is not covered by the design codes. A lot of decisions had to be made in order to be able to compute the loads acting on the structural elements.

Modeling the structure in the structural analysis program was very time consuming due to the complicate nature of the project. This stage also included modeling the loads acting on the building, some in very complex schemes.

Refining the structural system and providing the best solutions (to be used as final solutions) was the most interesting stage. This stage was special through the fact that for each structural element, several design proposals were made, each with pros and cons. All of them were then analyzed and compared and the most suitable picked. For some of the designed elements, up to six different solutions were analyzed and based upon them a new one created.

All in one, having a special project presents numerous special problems which can be solved by finding new and creative engineering solutions.

4. References

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