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Design of a Carport for more Cars

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Debrecen, 10. May 2022

DEBRECENI EGYETEM Műszaki Kar Építőmérnöki Tanszék

Imre KOVACS PhD
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UNIVERSITY of DEBRECEN
FACULTY of ENGINEERING

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I also want to express my gratitude to the department of civil engineering and its administration. The staff is readily willing to help and provide the required information and paperwork in one’s pursuit. All the teachers in the department are phenomenal at their job and it’s no surprise to see more international students coming in to study civil engineering at the University of Debrecen. Lastly, I want to thank my friends, the seniors, the library staff, and the international office for their help and support. The completion of this training course could not have been possible without the contribution of these excellent and professional people. I am truly grateful.

DEDICATION

First and foremost, I dedicate this thesis to Almighty Allah (S.W.T) for providing me with opportunity and strength to undertake this project. Indeed, it's he who laid out this path for me and saw me through in this challenging endeavor.

I dedicate my thesis to my mother Rasheeda Begam and my father Ghulam Mustafa who support and love me unconditionally. My parents have a good soul, and they always have the best interest in their hearts for me. I always turn to them and Almighty Allah during hard times. They believe in me like no other in the world. They have been given nothing but love and support throughout my life. I am truly grateful for everything, and I do not take any of it for granted. Lastly, I want to thank my girlfriend who shows her unrelenting support in any pragmatic thing I undertake. All the people who support me and love me, I want them to know I do not take any of these privileges for granted. I am grateful for everything every single day.

Abstract:

In the discipline of structural engineering, many structurally sound and producible designs can be modeled for a particular structure. On top of that, the implementation and integration of just the right kind of available structural materials to produce the best design before the production stage results in many kinds of design pathways. Through the prevalence of computational and finite element analysis, numerous studies have been made on the optimal design selection. This study focuses on carport structures and aims to conclude on an optimized design. For this purpose, a well-tested four-stage design process will be pursued with the help of CAD and FEM to analyze internal and external effects on the carport structure. Finite element analysis will help produce the model of an optimum material selection and functional efficacy under the examination of multiple load cases. The structure will be inspected against ultimate limit state ULS for critical failures and serviceability limit state for functionality. The carport structure will be designed to host 30 vehicles which means it represents an open parking space for a commercial supermarket or for the occupants of a residential building. For the sake of parameter safety, the vehicle will be assumed to be a cargo van because it's relatively a large vehicle. This ensures that the carport is suitable to host vehicles smaller than cargo vans. This project represents a pragmatic combination of computer-aid design (ArchiCAD) and finite element analysis (AxisVM) software packages to model a structurally sound commercial carport that can withstand multiple load combinations of various types and nature.

Table of Content

1. Preliminary:

In this section, the preliminary overview of carport structures. The design procedure for the project is described and the history of carport structures is explained. We also look at some of the types of carport structure failures under various circumstances with pictures. Furthermore, we establish the type of vehicle we will assume in the designing of the said structure.

1.1. Introduction:

There can be numerous approaches to designing a structure with function, outlook, and economy in mind. Convenience in designing and building a structure is one of the most important aspects for a structural engineer. A poorly executed design can cause several problems such as: shorter lifespan of the structure, increase in the cost due to extra labor and redundant use of materials. When designing a structure, a structural engineer must maintain a balance between safety vs. cost, convenience vs. functionality, labor vs. appearance. Therefore, a structural design of a structure is of the utmost importance.

With theoretical finite element modeling, the main objective is to design a theoretical structure which resembles its real-life counterpart in behavior and is subjected to the same real-life loads. Therefore, it has been proven by business practices that the best approach is to be precise and specific in defining the model and then deal with the optimization problems [1]. However, it cannot absolutely be possible to reach the most efficient design. A structural designer rather seeks to achieve the best feasible design. With the prevalence of finite element modeling and its subsequent optimization tools, a designer can achieve a practical and producible design in a relatively short amount of time while remaining under various constraints. There are many structural analysis software packages suitable to perform finite element analysis FEA.

The design process can be roughly categorized into four stages [2]. The first stage is to determine the essential parameters and functionality requirements of the structure in CAD software; the second stage is to develop a concept model in FEM software; the third stage is to perform optimization on the developed concept model, and the fourth stage is to finalize the most suitable design by producing blueprints of high clarity. In this design project, the carport structure is designed using this four-stage design process. This work contributes to the design of a carport structure analyzed under multiple load cases in that it attempts to reveal the impact of material efficiency and structural rigidity on the best design.

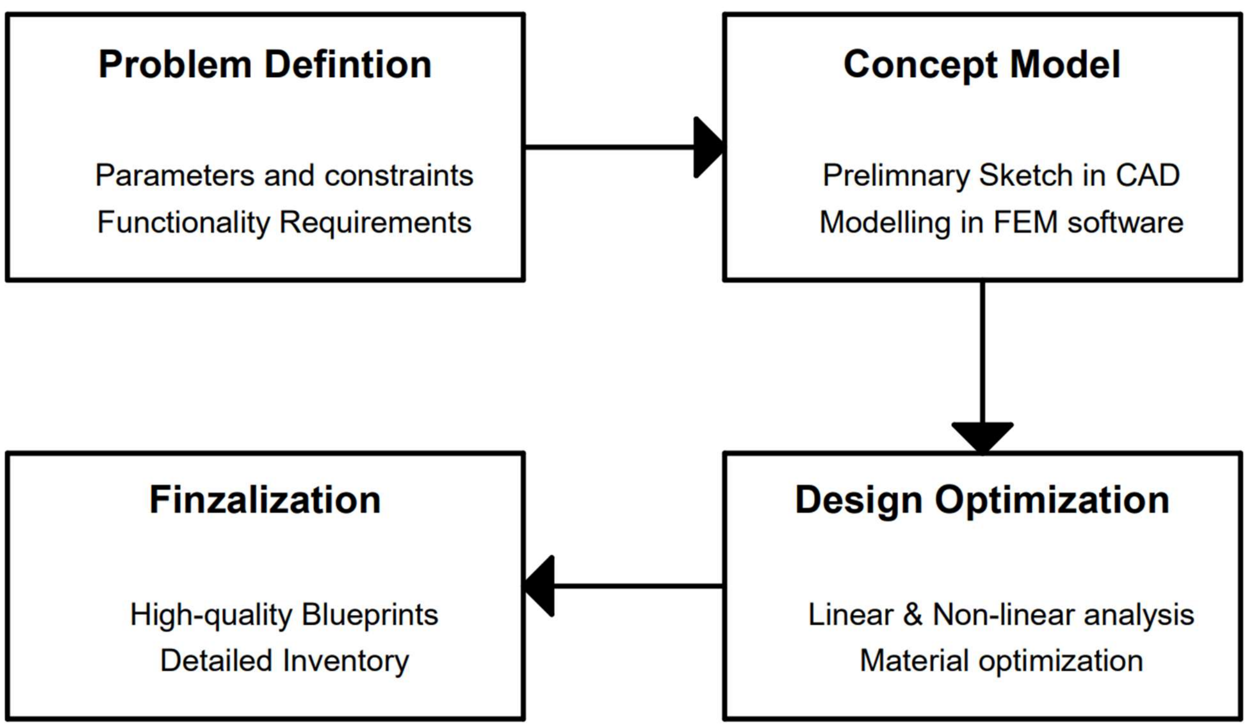


Fig. 1 Flow diagram of the structural design process [9, p. 288]

1.2. History:

The word originates from the French term porte-cochère which means a covered portal [5]. Walter Burley Griffin was the first to design a carport in a house in 1910. The term carport was coined by renowned architect Frank Llyod Wright to describe shelters for automobiles in American/Usonian home designs when he designed a house in 1936 in Madison, Wisconsin. Once he described the idea to a colleague that “A car is not a horse, and it doesn’t need a barn.” He then added, "Cars are built well enough now “o that they do not require elaborate shelter.” [4] He was right because before the manifestation of his idea, the cars were not built completely water-tight or with advanced materials. But by the early twentieth century with the technological advancements in cars, an enclosed structure such as a garage was not necessary. So, in essence, a carport provided an economical and effective shelter because cars could withstand extreme temperatures, sunlight, and wind [6]. Apart from the physical and economical benefits of a carport, Wright emphasized on the fact that carports are cleaner and modern that reduce clutter. Wright believed that the carport was an effective use of materials because it covered the car and served as a protective entryway for the residents [7].

Fig 2. Attached carport [19, p. 5], **Fig 3.** Stand Alone carport [19 p. 6],

Fig 4. Commercial Carport (T frame) [20, p.1]

1.3. Structural Failures:

Just like any other structure, a carport structure is also subjected to many different internal and external effects throughout its lifespan. Therefore, it is imperative to design a model which has been tested to withstand various structural loading scenarios. In essence, defining just the right amount of load combinations is one of the most important and the most difficult tasks of a designer. The loads on carport structures are defined by the different types of forces, such as: dead loads, live loads, and later loads, etc.

Normally, carport structures are highly durable, but some get deteriorated over time, damaged, and collapsed due to different effects. Carport structure is an outdoor structure which means it is susceptible to environmental conditions and natural disasters. If a carport is not well designed, successfully analyzed, and well-constructed; it may drastically decrease its lifespan due to deformation, fracture, fatigue, cracking, and failures in fixtures, etc. Many carports are exposed to destructive vertical loads such as dead load and snow load which can cause serious damages to the structure. This type of vertical damage is very dangerous since it may cause fatal accidents. Therefore, damage risk should be considered, and relevant precautions must be taken to keep the occupants and their vehicles safe.

In addition to vertical loads, lateral loads such as wind loads, and earthquakes may also affect the carport structure. These types of loads cause lateral displacement and irrevocable damage. Wind loads lead to failure of the carport roof and compromise the overall structural stability. Moreover, carport structures may also be subjected to destructive earthquakes which can cause significant damage to the vertical bearings of the carport structure. Recognizing the need to implement these loads in the FEA is crucial.

Fig 5. Carport collapse under load [17]

Fig 6. Collapse of commercial carport [18]

Fig 7. Carport Failure under wind load [9]

1.4. Vehicle:

The vehicle specimen that will be hosted by the carport has been carefully selected. The right candidate is a pickup or cargo truck with dimensions bigger than that of conventional consumer vehicles. This ensures that vehicles of smaller dimensions can comfortably be hosted by the carport. For this project, a van model from Groupe Renault called New Master Z.E. The van has a gross vehicle weight GVW between 3.1 tons to 3.5 tons. The clearance height of the carport is over 3.5 meters.

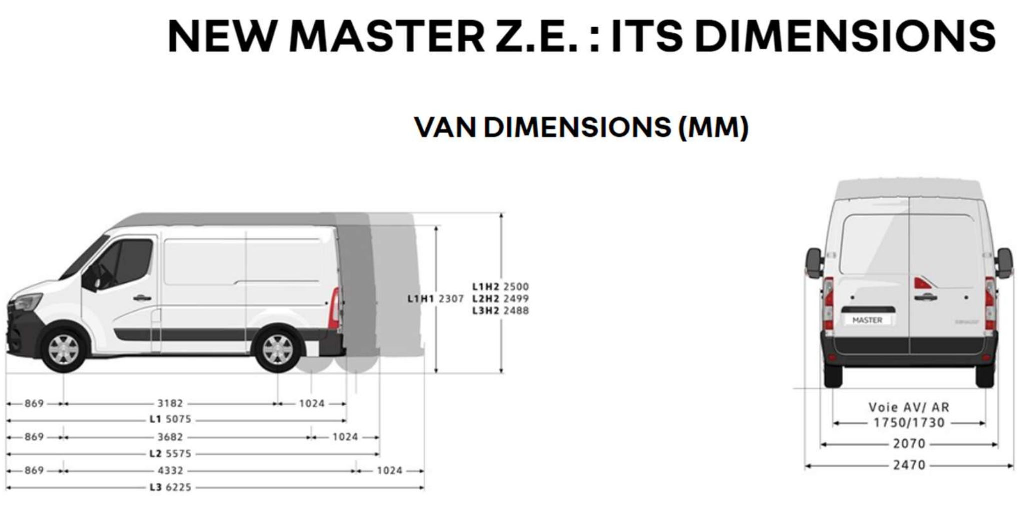


Fig. 8 Van dimension for specific series [1] (p 1.)

1.5. Similar Case Overview:

The purpose of considering and analyzing similar projects is a standard procedure in a design process. It helps the designer with rough estimations regarding the parameters and an idea of what approach has already been proven to work for projects of similar scope. With this method, the designer saves time in the optimization stage in that it eliminates the need to run multiple iterations to reach the desired efficacy of the behavior of a structure. Carport structures of numerous sizes and shapes can be designed. The flexibility and expandability of a carport structure can meet virtually any set of requirements set out by the client.

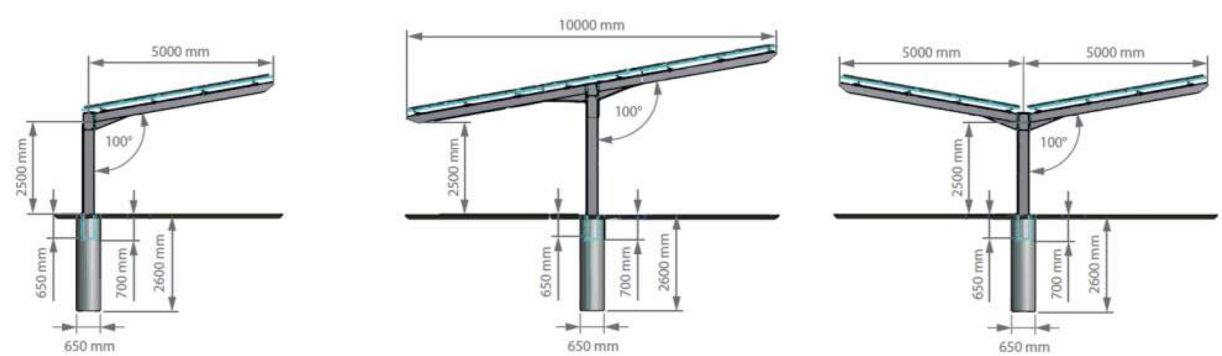


Fig. 9 Car park Mounting System (carport) [3]

1.5.1. Y Frame:

The shape of the roof resembles the letter Y. This type of structure can be used as a single-row version (single pitch roof) or a double-row version (duo pitch roof). Some features of a proven project of different types are outlined below:

1.5.1.1. Double-row version:

1. Clearance height of 2.00 m.
2. Entrance height of 3.10 m.
3. Supporting width of 2.50 m.
4. Tilt angle of 12.5°
5. Overall cross-sectional span of 11.30 m.

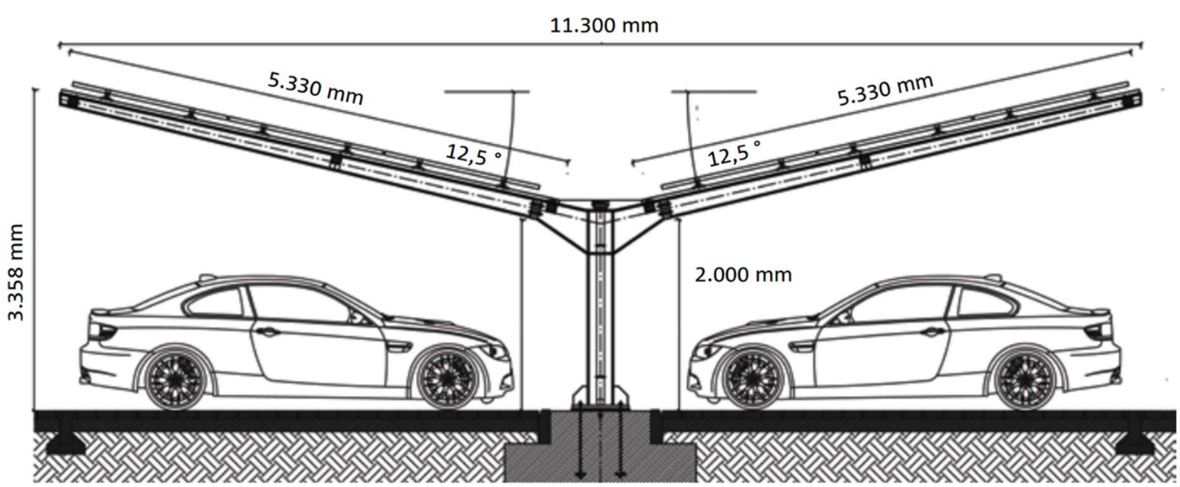


Fig. 10 Double Row [2, p. 5]

1.5.1.2. Single-row version:

1. Clearance height of 2.00 m.
2. Entrance height of 3.4 m.
3. Supporting width of 2.50 m.
4. Tilt angle of 12.5°
5. Overall cross-sectional span of 6.541 m.

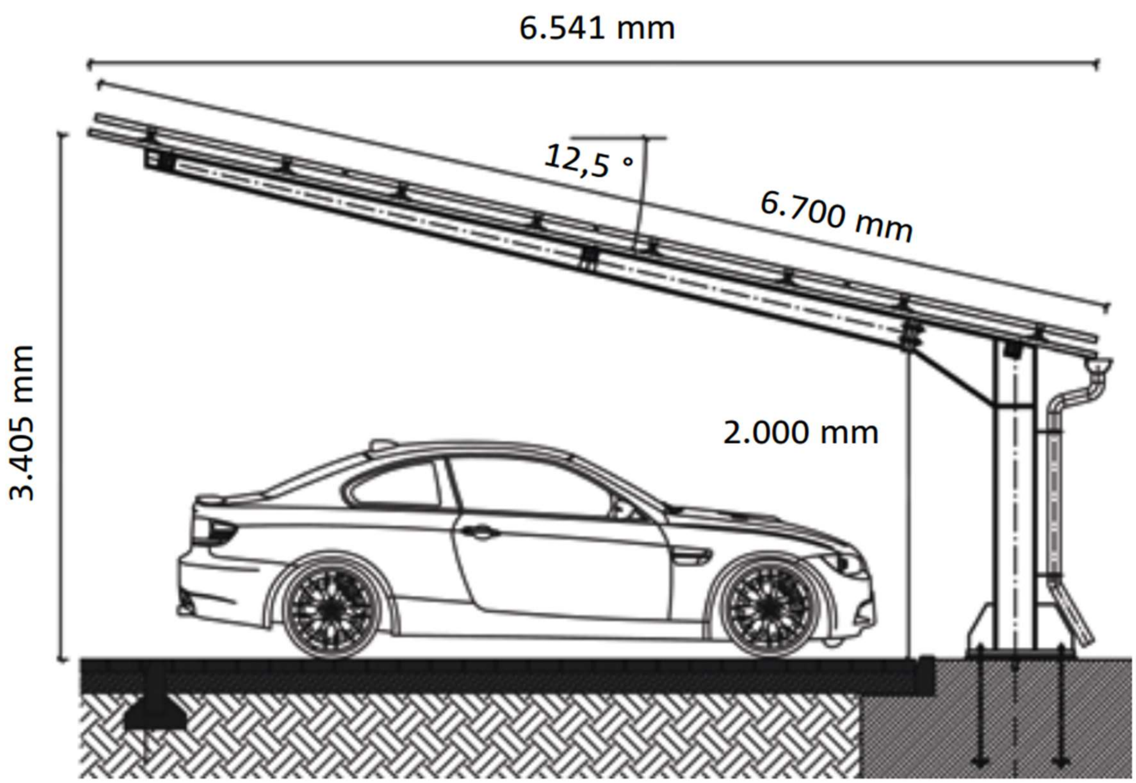


Fig. 11 Double Row [2, p. 5]

1.5.2. T Frame:

The shape of the roof resembles the letter T. This type of structure can be used as a single-row version (single pitch roof) or a double-row version (duo pitch roof). Some features of a proven project of different types are outlined below:

1.5.2.1. Double-row version:

1. Clearance height of 2.2 m
2. Maximum entrance height of 4.3 m.
3. Supporting width of 5.0 m / 5.2 m.
4. Overall cross-sectional span of 10.0 m.
5. Tilt Angle of 12.0°.

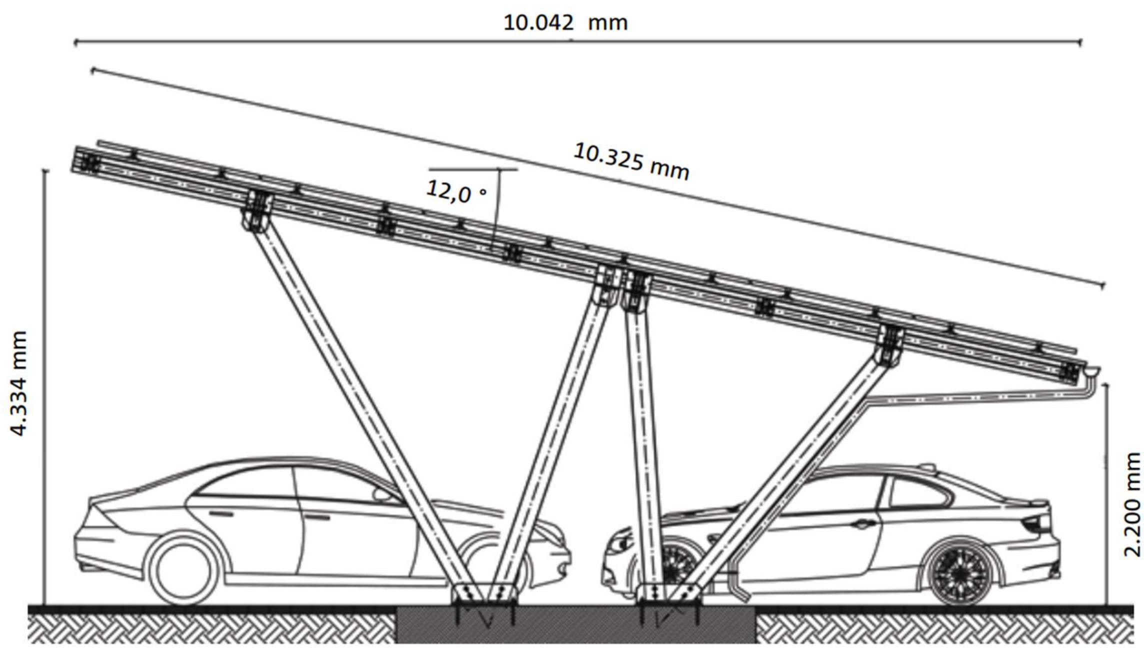


Fig. 12 Double Row [2, p. 7]

1.5.2.2. **Single-row version**:

1. Clearance height of 2.2 m
2. Maximum entrance height of 3.2 m.
3. Supporting width of 5.0 m / 5.2 m.
4. Tilt Angle of 12.0°.
5. Overall cross-sectional span of 5.0 m.

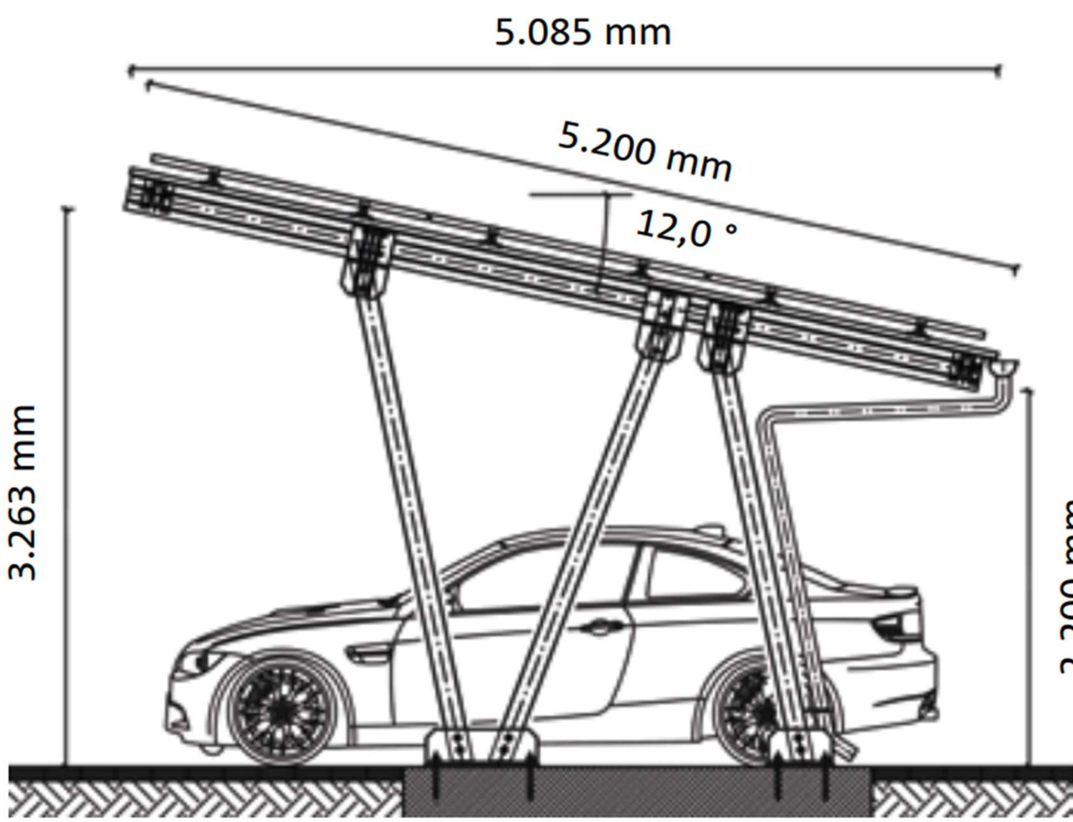


Fig. 13 Double Row [2, p. 5]

2. Design:

In this section, the design of the carport will be carried out in a FEM software. The process starts with defining the geometry and various other parameters as discussed with the designated supervisor. After, the supports and elements are defined to depict the real-life situation as much as possible. Once that has been established, load cases and load combinations are defined to carry out linear and non-linear analysis (where applicable). The critical utilizations and relevant results will be checked, and iterations will be made to optimize the design.

2.1. Geometry:

2.1.1. Front View:

Following is the front-view of the carport. It is a Y-Shaped commercial carport. It is different than some of the structures we have looked at in that it transfers load to the ground via a reinforced wall instead of steel columns, as is the case with most carports. It is a symmetrical structure in z-x plane.

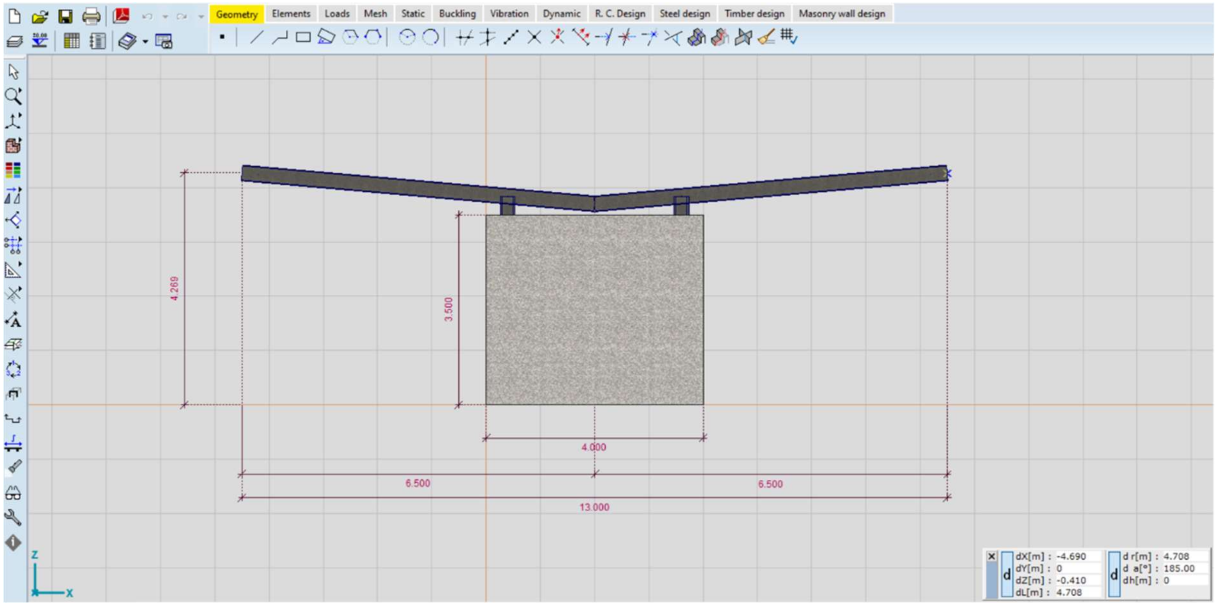


Fig. 14 Front View of the structure

2.1.2. Side View:

This is the side view of the structure as seen from the z-y plane. In total, its length is about 75 meters. Each carport module is about 5 meters wide. Each module is capable to host 2 cars. There are 15 modules in total which means, this commercial carport can host a maximum of 30 vehicles (New Master ZE). The structure is symmetrical in this plane as well. The biggest version of the model comes 6.225 meters in length and 2.470 meters in width. The vehicles can comfortably park in the carports with plenty spare space.

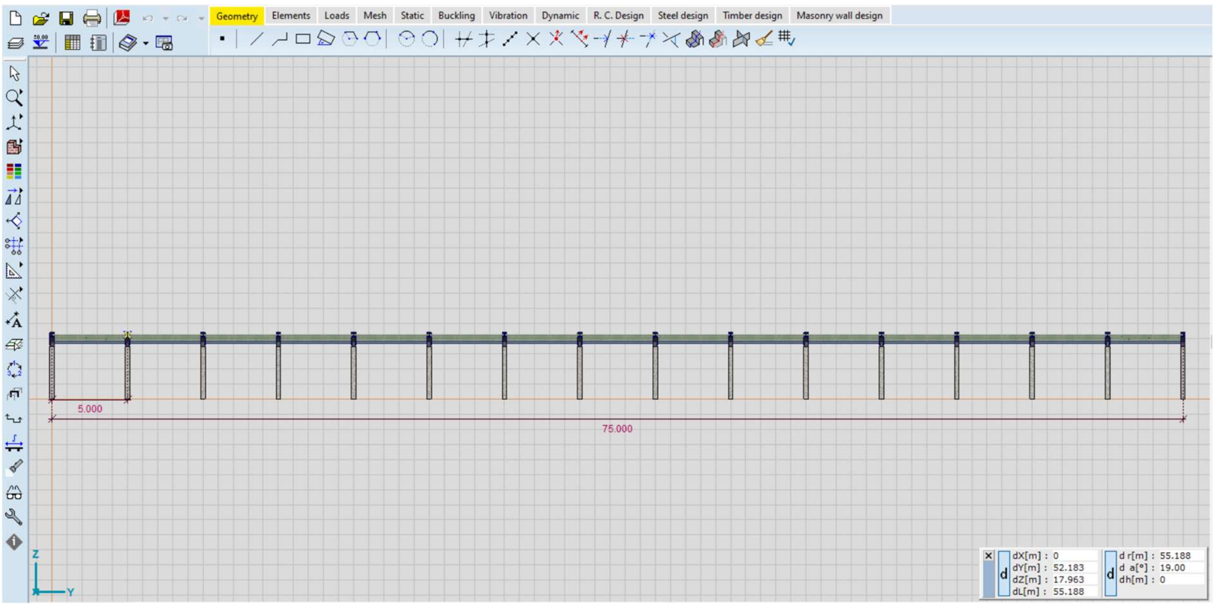


Fig. 15 Side View of the structure

2.1.3. Blockage:

2.2.

The degree of blockage under the canopy roof as defined by the EN 1991-1-4 (2005) (English) depends on the blockage φ which is the ratio of the area of the feasible and actual obstruction (vehicles) under the canopy roof divided by the cross-sectional area under the canopy.

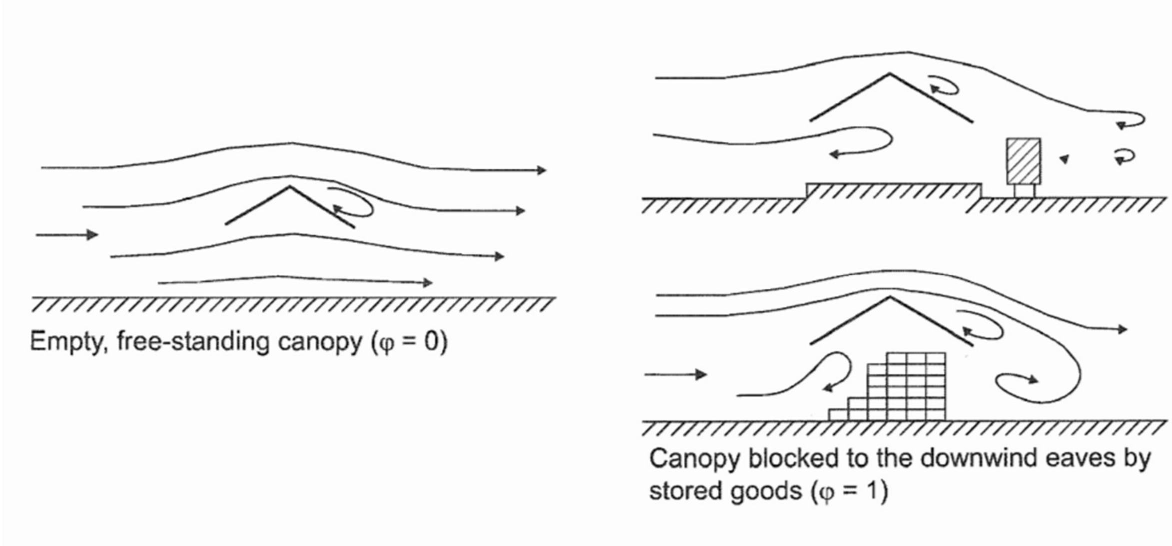


Fig. 16– Airflow over canopy roofs ([11], p. 55)

For the project, the blockage φ was taken as 0.5 with the assumption that even at full capacity, half of the wind will be obstructed by the vehicles and half of the wind will not be obstructed by the vehicles.

2.3. Loads:

Loading fields were determined using Lindab Structural Software. These loading fields are imperative in determining the subsequent loads the structure will be subjected to. A brief result of the output is shown below.

2.3.1. Purlin:

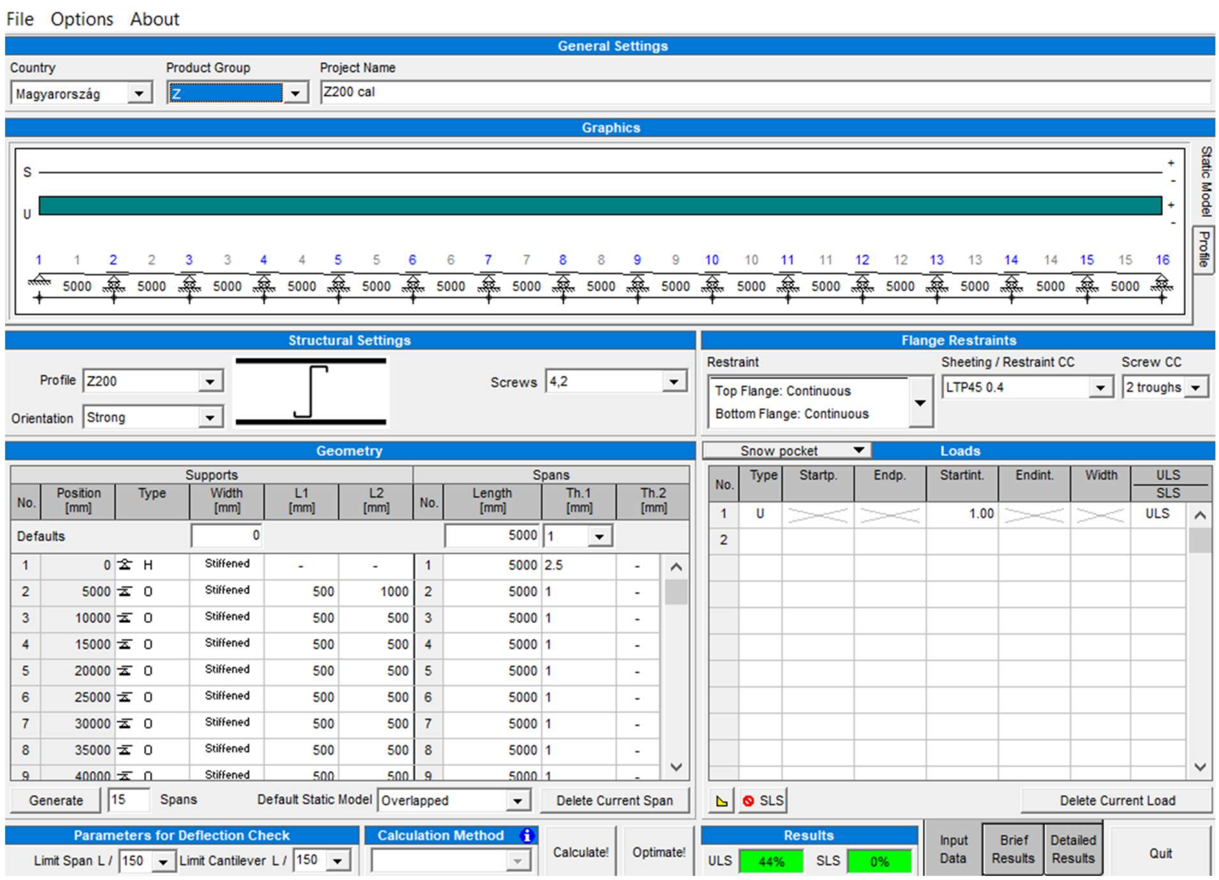


Fig. 17– Results from Lindab

After, the dead loads on the beams, snow load, and accidental snow load is calculated. Because of the symmetry of the structure, the beams on only one half of the structure are accounted for. Loads on the other half were mirrored.

2.3.2. Dead load:
2.3.3.

Loading field:

Static model of purlin: multisupport

Beams:

$t_{b1} := 1.91\ m$ $t_{b2} := 5.76\ m$ $t_{b3} := 4.78\ m$

$t_{b4} := 5.06\ m$ $t_{b5} := 4.98\ m$ $t_{b6} := 5.01\ m$

$t_{b7} := 5\ m$ $t_{b8} := 5\ m$

- distance between purlins: $t_{r\_pur} := 1.16\ m$

Roof panel: $g_{r\_pan} := 15\ \frac{kg}{m^2}$

Purlin: $g_{r\_pur} := 7.24\ \frac{kg}{m} \cdot \frac{1}{t_{r\_pur}} = 6.2414\ \frac{kg}{m^2}$

Installation load: $g_{inst} := 15\ \frac{kg}{m^2}$

Gravitational acceleration: $g := 9.81\ \frac{m}{s^2}$

- Dead load on beams:

$$g_{b1} := \left(g_{r\_pan} + g_{r\_pur} + g_{inst}\right) \cdot g \cdot t_{b1} = 0.6791\ \frac{kN}{m}$$

$$g_{b2} := \left(g_{r\_pan} + g_{r\_pur} + g_{inst}\right) \cdot g \cdot t_{b2} = 2.0478\ \frac{kN}{m}$$

$$g_{b3} := \left(g_{r\_pan} + g_{r\_pur} + g_{inst}\right) \cdot g \cdot t_{b3} = 1.6994\ \frac{kN}{m}$$

$$g_{b4} := \left(g_{r\_pan} + g_{r\_pur} + g_{inst}\right) \cdot g \cdot t_{b4} = 1.799\ \frac{kN}{m}$$

$$g_{b5} := \left(g_{r\_pan} + g_{r\_pur} + g_{inst}\right) \cdot g \cdot t_{b5} = 1.7705\ \frac{kN}{m}$$

$$g_{b6} := \left(g_{r\_pan} + g_{r\_pur} + g_{inst}\right) \cdot g \cdot t_{b6} = 1.7812\ \frac{kN}{m}$$

$$g_{b7} := \left(g_{r\_pan} + g_{r\_pur} + g_{inst}\right) \cdot g \cdot t_{b7} = 1.7776\ \frac{kN}{m}$$

$$g_{b8} := \left(g_{r\_pan} + g_{r\_pur} + g_{inst}\right) \cdot g \cdot t_{b8} = 1.7776\ \frac{kN}{m}$$

2.3.4. Snow Load:

- Snow load on the ground - characteristic value: $s_k := 1.25\ \frac{kN}{m^2}$ (A<400 m)
- Slope of the roof: $\alpha := 5\ °$
- Roof shape coefficient: $\mu_1 := 0.8$ 0°<α<30°
- Snow load on the roof - characteristic value:

$C_e := 1.0$ Exposure coefficient.

$C_t := 1.0$ Thermal coefficient.

$$s := C_e \cdot C_t \cdot \mu_1 \cdot s_k = 1\ \frac{kN}{m^2}$$

- Snow load on the beams:

$$q_{s1} := s \cdot t_{b1} = 1.91\ \frac{kN}{m}$$

$$q_{s2} := s \cdot t_{b2} = 5.76\ \frac{kN}{m}$$

$$q_{s3} := s \cdot t_{b3} = 4.78\ \frac{kN}{m}$$

$$q_{s4} := s \cdot t_{b4} = 5.06\ \frac{kN}{m}$$

$$q_{s5} := s \cdot t_{b5} = 4.98\ \frac{kN}{m}$$

$$q_{s6} := s \cdot t_{b6} = 5.01\ \frac{kN}{m}$$

$$q_{s7} := s \cdot t_{b7} = 5\ \frac{kN}{m}$$

$$q_{s8} := s \cdot t_{b8} = 5\ \frac{kN}{m}$$

2.3.4.1. Accidental Snow:

- Coefficient for exceptional snow load:

$s_{Ad} := C_{est} \cdot s_k$ $\qquad$ $C_{est} := 2.0$

- Accidental snow load on the roof:

$$s_{exc} := C_e \cdot C_t \cdot \mu_1 \cdot s_{Ad} = 2\ \frac{kN}{m^2}$$

- Accidental snow load on the beams:

$$q_{s1} := s_{exc} \cdot t_{b1} = 3.82\ \frac{kN}{m}$$

$$q_{s2} := s_{exc} \cdot t_{b2} = 11.52\ \frac{kN}{m}$$

$$q_{s3} := s_{exc} \cdot t_{b3} = 9.56\ \frac{kN}{m}$$

$$q_{s4} := s_{exc} \cdot t_{b4} = 10.12\ \frac{kN}{m}$$

$$q_{s5} := s_{exc} \cdot t_{b5} = 9.96\ \frac{kN}{m}$$

$$q_{s6} := s_{exc} \cdot t_{b6} = 10.02\ \frac{kN}{m}$$

$$q_{s7} := s_{exc} \cdot t_{b7} = 10\ \frac{kN}{m}$$

$$q_{s8} := s_{exc} \cdot t_{b8} = 10\ \frac{kN}{m}$$

2.3.5. Wind Load:

LoCa STATIKSOFTWARE

Duopitch canopies (trough roof)		
Company:	Student	locastatik.at
Project:	Wind Load	Page: 1
Projectnr.:	TS0S7Q	Date: May 08, 2022
Load calculation:	Sopron	

Wind Load

Gk = II $q_{b;0}$ = 0,35kNm^2 $v_{b;0}$ = 23,66ms

H = 202,90m

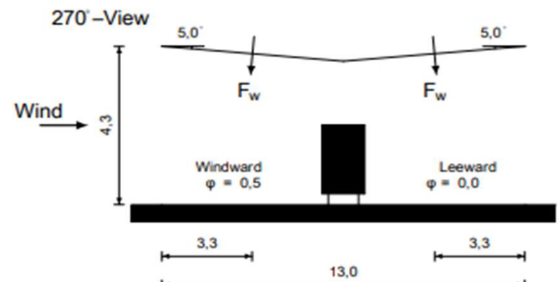
EN 1991-1-4 (2011-05) & ÖNORM B 1991-1-4 (2019-07)

Duopitch canopies (trough roof)

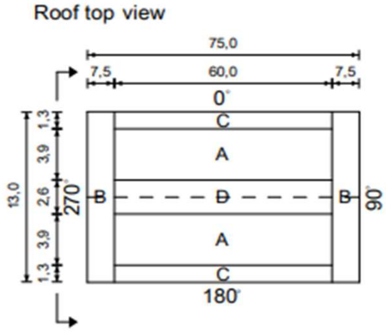
Sopron

h = 4,30m	α = 5,0°	$c_s c_d$ = 1,00
l_0 = 75,00m	z_e = 4,30m	A_{ref} = 489,36m^2
l_{90} = 13,00m	$c_0(z_e)$ = 1,00	
φ = 0,50	$q_p(z_e)$ = 0,62kNm^2	

Results



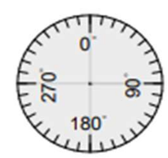
Roof top view



Net pressure coefficient φ = 0,50	Net wind pressure φ = 0,50	Net pressure coefficient φ = 0,00
$c_{p,net}$ ✣	w_{net} ✣	$c_{p,net}$ ✣
$c_{p,net,A}$ = 0,50	$w_{net,A}$ = 0,31 kNm^2	$c_{p,net,A}$ = 0,50
$c_{p,net,A}$ = −1,10	$w_{net,A}$ = −0,68 kNm^2	$c_{p,net,A}$ = −0,70
$c_{p,net,B}$ = 1,50	$w_{net,B}$ = 0,93 kNm^2	$c_{p,net,B}$ = 1,50
$c_{p,net,B}$ = −1,85	$w_{net,B}$ = −1,15 kNm^2	$c_{p,net,B}$ = −1,30
$c_{p,net,C}$ = 0,80	$w_{net,C}$ = 0,50 kNm^2	$c_{p,net,C}$ = 0,80
$c_{p,net,C}$ = −2,00	$w_{net,C}$ = −1,24 kNm^2	$c_{p,net,C}$ = −1,60
$c_{p,net,D}$ = 0,80	$w_{net,D}$ = 0,50 kNm^2	$c_{p,net,D}$ = 0,80
$c_{p,net,D}$ = −0,60	$w_{net,D}$ = −0,37 kNm^2	$c_{p,net,D}$ = −0,60

Gk	Terrain category
H	Altitude [m]
$q_{b;0}$	Basic velocity pressure †
$v_{b;0}$	Basic wind velocity †
h	Ridge height
l_0	Length of eaves side
l_{90}	Length of gable wall
φ	Blockage
α	Roof pitch
z_e	Reference height
c_o	Topography coefficient
q_p	Peak velocity pressure
$c_s c_d$	Structural factor
A_{ref}	Reference area
+	Downward wind load
−	Upward wind load
✣	Results for all wind directions

The wind pressures without blockage (φ = 0) are to be set on the leeward side of the blockage and the wind pressures with blockage (φ = 0:5) are to be set on the windward side.



– – Roof valley

All lengths in [m].

Net wind pressure $\varphi = 0{,}00$ w_{net} ✥	Force coefficient c_f ↕	Force coefficient c_f ↔
$w_{net,A} = 0{,}31$ kN m^2	$c_f = 0{,}30$	$c_f = 0{,}20$
$w_{net,A} = -0{,}44$ kN m^2	$c_f = -0{,}90$	$c_f = -0{,}90$
$w_{net,B} = 0{,}93$ kN m^2		
$w_{net,B} = -0{,}81$ kN m^2		
$w_{net;C} = 0{,}50$ kN m^2		
$w_{net,C} = -1{,}00$ kN m^2		
$w_{net,D} = 0{,}50$ kN m^2		
$w_{net,D} = -0{,}37$ kN m^2		
Global wind force F_w ↕	**Global wind force F_w ↔**	**Friction ✥**
$F_w = 91{,}37$ kN	$F_w = 60{,}91$ kN	$c_{fr} = 0{,}01$
$F_w = -274{,}10$ kN	$F_w = -274{,}10$ kN	$w_{fr} = 0{,}01$ kN m^2

The friction is to be applied to the top and bottom of the roof.

+ Downward wind load
− Upward wind load
✥ Results for all wind directions

The wind pressures without blockage ($\varphi = 0$) are to be set on the leeward side of the blockage and the wind pressures with blockage ($\varphi = 0{:}5$) are to be set on the windward side.

The wind load for the project was calculated using an online service which took into consideration the friction as well. The fundamental values of the basic wind velocity and basic velocity pressure according to the National Annex of Hungary was considered [p. 2]. Moreover, to stay on the side of safety, wind load on a free-standing wall without the return corner was considered, calculated, and applied to the structure against the wind in y direction according to the EN 1991-1-4 (2005) (English). The loads from free-standing wall were combined with the maximum pressure and suction loads obtained for the roof. This is to ensure that the arrangements with maximum effects are taken into consideration. The loads were arranged using the same national annex as shown below.

Wind Load New

Gk = II	$q_{b,0}$ = 0,35 kN m^2	$v_{b,0}$ = 23,66ms
H = 202,90m		

EN 1991-1-4 (2011-05) and ÖNORM B 1991-1-4 (2019-07).

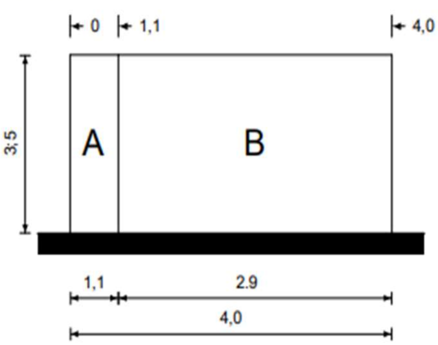
Wind loads free-standing wall

Wall

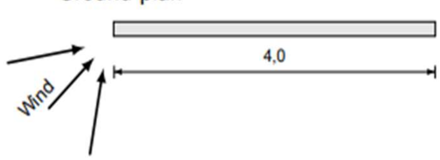
h = 3,50m	z_e = 3,50m	$c_s c_d$ = 1,00
l = 4,00m	$c_o(z_e)$ = 1,00	
φ = 1,00	$q_p(z_e)$ = 0,62kNm^2	

Results

View



Ground plan



Pressure coefficient	Wind pressure	Friction
$c_{p,net,A}$ = 2,30	$w_{net,A}$ = 1,43 kNm^2	c_{fr} = 0,02
$c_{p,net,B}$ = 1,40	$w_{net,B}$ = 0,87 kNm^2	w_{fr} = 0,01 kN m^2

Gk	Terrain category
H	Altitude [m]
$q_{b,0}$	Basic velocity pressure †
$v_{b,0}$	Basic wind velocity †
h	Height
l	Wall length
φ	Solidity
z_e	Reference height
c_o	Topography coefficient
q_p	Peak velocity pressure
$c_s c_d$	Structural factor

All lengths in [m].

Arrangement:

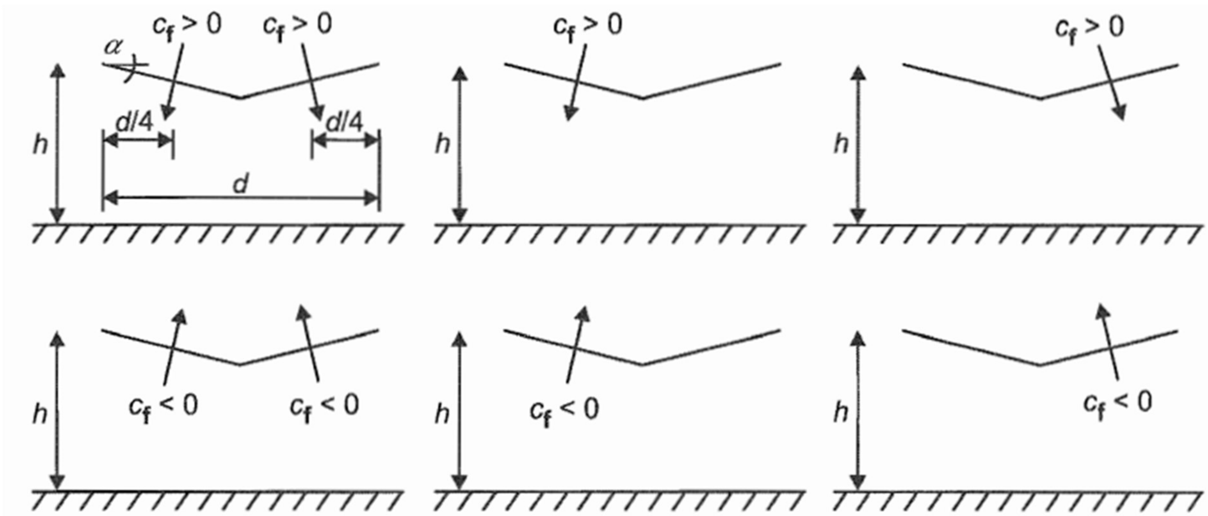


Fig.18 – Arrangements of load obtained from force coefficients for duo pitch canopies [11, p.60]

2.3.6. Load Groups:

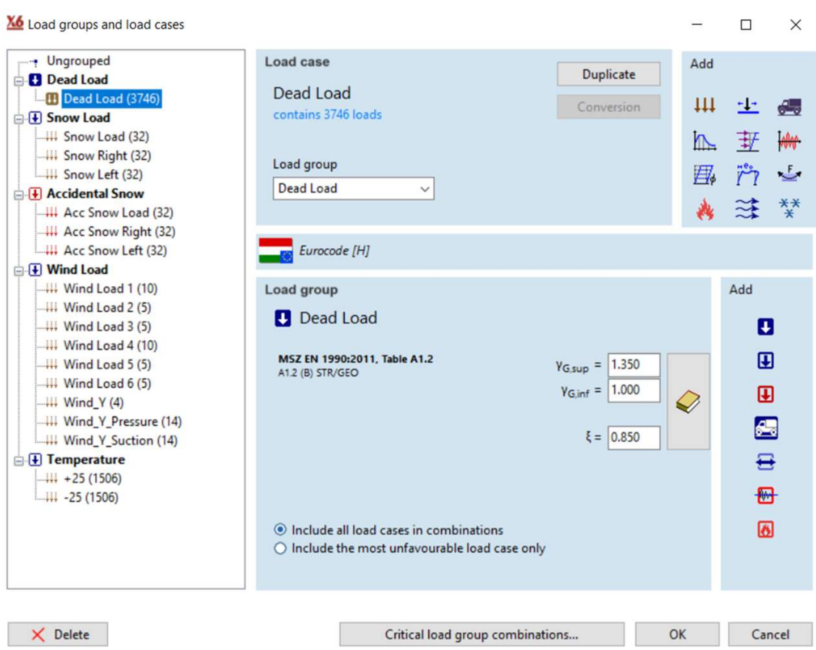


Fig. 19 – Load Groups from AxisVM

2.4. Material:

After various iterations, the right material and cross sections were chosen. Following are the material properties of the main components of the carport.

2.4.1. Beams:

Beams are one of the most important members of the carport structure. They carry and transfer most of the loads the structure is subjected to.

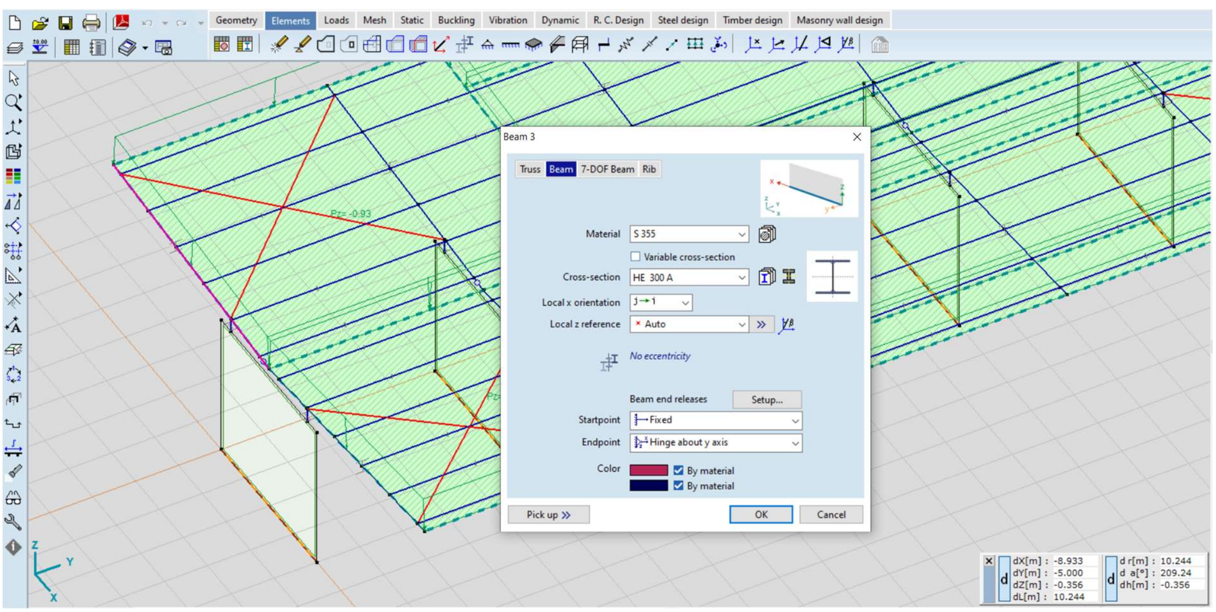


Fig. 20 – Element window for beams

2.4.2. Columns:

The vertical components transfer the loads from the roof to the RC Wall.

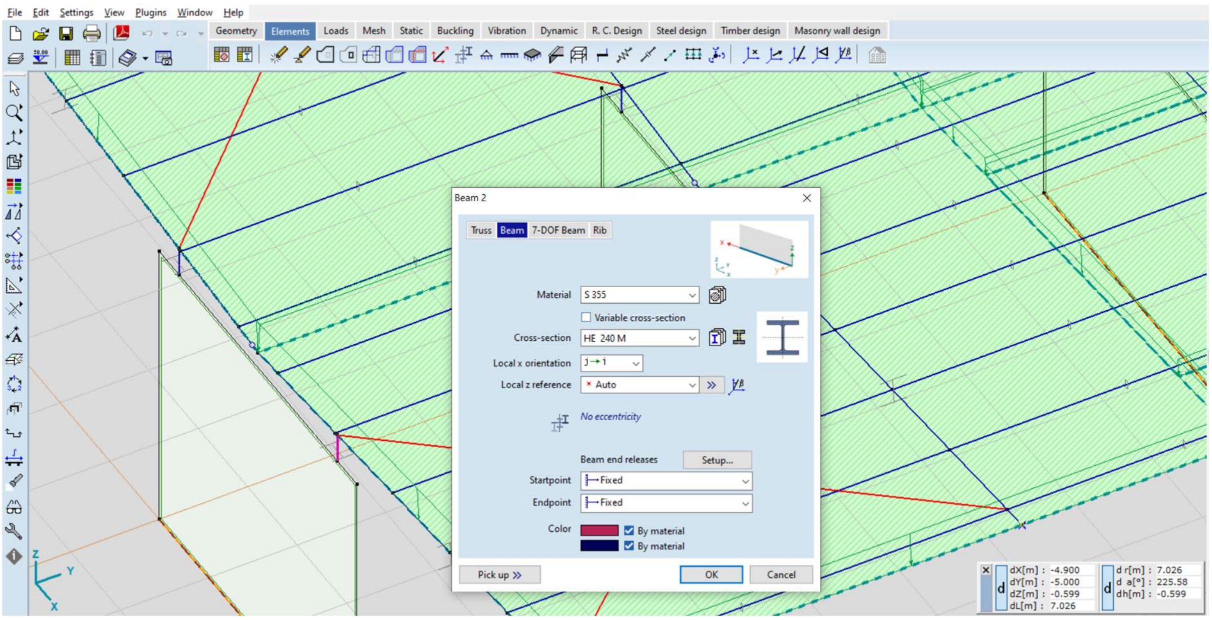


Fig. 21 – Element window for columns

2.4.2.1. Anchor:

Material properties:

Steel: $S355$ $\quad f_u := 510\ \frac{N}{mm^2}$ $\quad f_y := 355\ \frac{N}{mm^2}$ $\quad E := 210000\ \frac{N}{mm^2}$

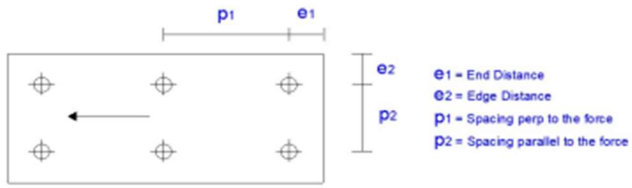
$$\varepsilon := \sqrt{\frac{235\ \frac{N}{mm^2}}{f_y}} = 0.8136$$

Bolt: M 30 8.8 $\quad f_{yb} := 640\ \frac{N}{mm^2}$ $\quad f_{ub} := 800\ \frac{N}{mm^2}$

$d := 30\ mm$ $\quad d_o := 33\ mm$ $\quad d_m := 49.6\ mm$

$A := 707\ mm^2$ $\quad A_s := 561\ mm^2$

Factors: $\gamma_{m0} := 1$ $\quad \gamma_{m1} := 1$ $\quad \gamma_{m2} := 1.25$ $\quad t_p := 25\ mm$



$e_1 := 1.2 \cdot d_o = 39.6\ \mathrm{mm}$

$e_2 := 1.2 \cdot d_o = 39.6\ \mathrm{mm}$

$p_1 := 2.2 \cdot d_o = 72.6\ \mathrm{mm}$

$p_2 := 2.4 \cdot d_o = 79.2\ \mathrm{mm}$

Recommended Values

$e_1 := 2 \cdot d_o = 66\ \mathrm{mm}$

$e_2 := 1.5 \cdot d_o = 49.5\ \mathrm{mm}$

$p_1 := 3 \cdot d_o = 99\ \mathrm{mm}$

$p_2 := 3 \cdot d_o = 99\ \mathrm{mm}$

Number of Shear Plans $n := 1$

Plate Geometry

$e_1 := 50\ \mathrm{mm}$ $e_2 := 50\ \mathrm{mm}$

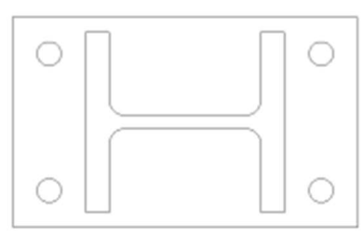
$p_1 := 370\ \mathrm{mm}$ $p_2 := 188\ \mathrm{mm}$

$$F_{v\_Rd} := n \cdot \frac{0.6 \cdot f_{ub} \cdot A}{\gamma_{m1}} = 339.36\ \mathrm{kN}$$

$$k1 := \min\left(\left[\, 2.8 \cdot \frac{e_2}{d_o} - 1.7 \quad 1.4 \cdot \frac{p_2}{d_o} - 1.7 \quad 2.5 \,\right]\right) = 2.5$$

$$\alpha_b := \min\left(\left[\, \frac{e_1}{3 \cdot d_o} \quad \frac{p_1}{3 \cdot d_o} - \frac{1}{4} \quad \frac{f_{ub}}{f_u} \quad 1 \,\right]\right) = 0.5051$$

$$F_{b.Rd} := \frac{k1 \cdot \alpha_b \cdot f_u \cdot d \cdot t_p}{1.25} = 386.3636\ \mathrm{kN}$$



$$F_{V.Rd} := \min\left(\left[\, F_{v\_Rd} \quad F_{b.Rd} \,\right]\right) = 339.36\ \mathrm{kN}$$

$$F_{t\_Rd} := \frac{0.9 \cdot f_{ub} \cdot A_s}{\gamma_{m2}} = 323.136\ \text{kN}$$

$$B_{p\_Rd} := \frac{0.6 \cdot \pi \cdot d_m \cdot t_p \cdot f_u}{\gamma_{m2}} = 953.6367\ \text{kN}$$

$$f_{cd} := \frac{20}{1.5} \frac{\text{N}}{\text{mm}^2} = 13.3333 \frac{\text{N}}{\text{mm}^2}$$

$$f_{j\_d} := 1 \cdot \frac{2}{3} \cdot f_{cd} \cdot \sqrt{3} = 15.396 \frac{\text{N}}{\text{mm}^2}$$

HE 240 M

$h := 270\ \text{mm}$ $\quad b := 248\ \text{mm}$

$t_w := 18.0\ \text{mm}$ $\quad t_f := 32.0\ \text{mm}$

$e_x := 50\ \text{mm}$

$m_x := 50\ \text{mm}$

$b_p := 288\ \text{mm}$

$w := 188\ \text{mm}$

$$e := \frac{b - w}{2} = 30\ \text{mm}$$

$$c := t_p \cdot \sqrt{\frac{f_y}{3 \cdot f_{j\_d} \cdot \gamma_{m0}}} = 69.309\ \text{mm}$$

$$l_p := 2 \cdot \left(m_x + e_x\right) + h = 470\ \text{mm}$$

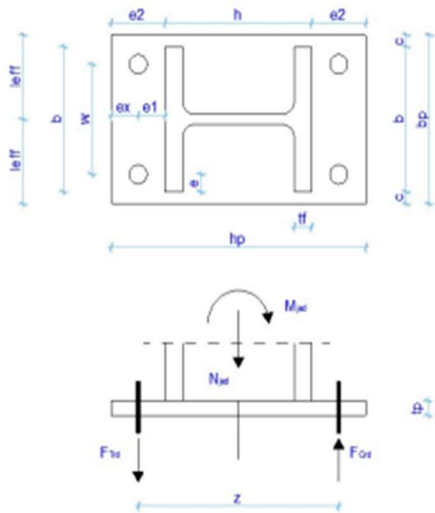
$$l_{eff\_c} := b = 248\ \text{mm}$$

$$b_{eff\_c} := 2 \cdot c + t_f = 170.618\ \text{mm}$$

$$F_{c\_Rd} := f_{j\_d} \cdot l_{eff\_c} \cdot b_{eff\_c} = 651.4552\ \text{kN}$$

1st bolt row (bolt under tension, base plate under bending, column flange under tension)

$$L_{eff\_t} := \min\left(\begin{bmatrix} 2 \cdot \pi \cdot m_x \\ \pi \cdot m_x + w \\ \pi \cdot m_x + 2 \cdot e \\ 4 \cdot m_x + 1.25 \cdot e_x \\ e + 2 \cdot m_x + 0.625 \cdot e_x \\ 0.5 \cdot b_p \\ 0.5 \cdot w + 2 \cdot m_x + 0.625 \cdot e_x \end{bmatrix}\right) = 144 \text{ mm}$$



$$F_{tRdSum} := \frac{0.9 \cdot f_{ub} \cdot A_s}{\gamma_{m2}} \cdot 2 = 646.272 \text{ kN}$$

$$M_{Pl1Rd} := \frac{L_{eff\_t} \cdot {t_p}^2 \cdot f_y}{2 \cdot m_x \cdot \gamma_{m0}} = 319.5 \text{ kN}$$

$$F_{TRd1} := \min\left(\begin{bmatrix} F_{tRdSum} \\ M_{Pl1Rd} \end{bmatrix}\right) = 319.5 \text{ kN}$$

$$z := m_x + h - \frac{t_f}{2} = 304 \text{ mm}$$

$$z_c := \frac{h}{2} - \frac{t_f}{2} = 119 \text{ mm}$$

$$z_t := \frac{h}{2} + m_x = 185 \text{ mm}$$

2.5. Non-Linear Analysis:

2.5.1. Roof Bracing:

For the roof bracing, special settings were set for the Saint Andrews bracing. The setting defined the tension-only nature of the bracing as seen in the picture below.

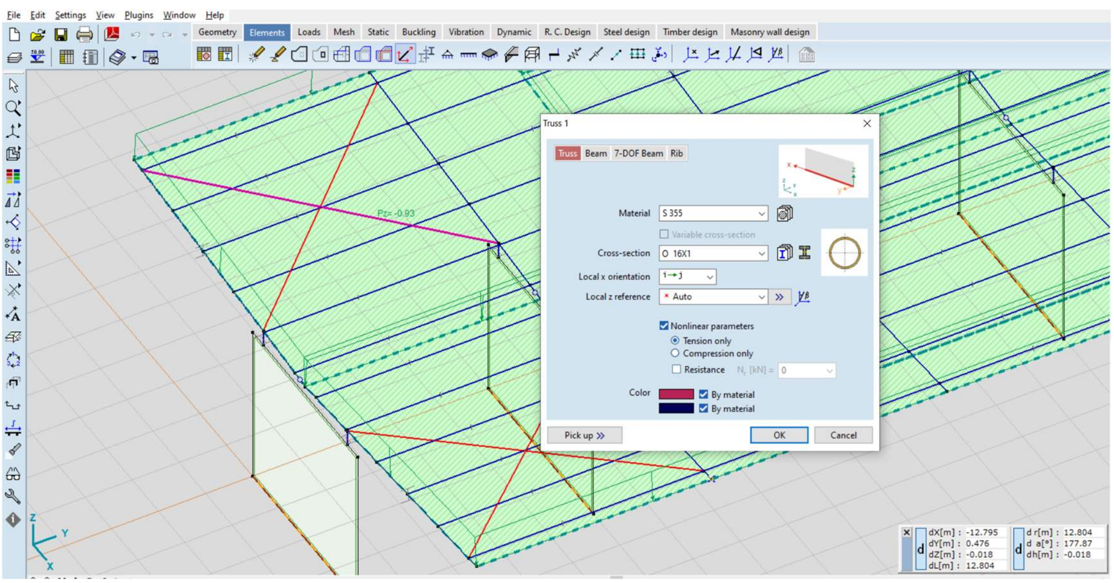


Fig. 22 – Element window for cross elements

For this purpose, a non-linear analysis was run for these elements. The load combinations were manually chosen for this task.

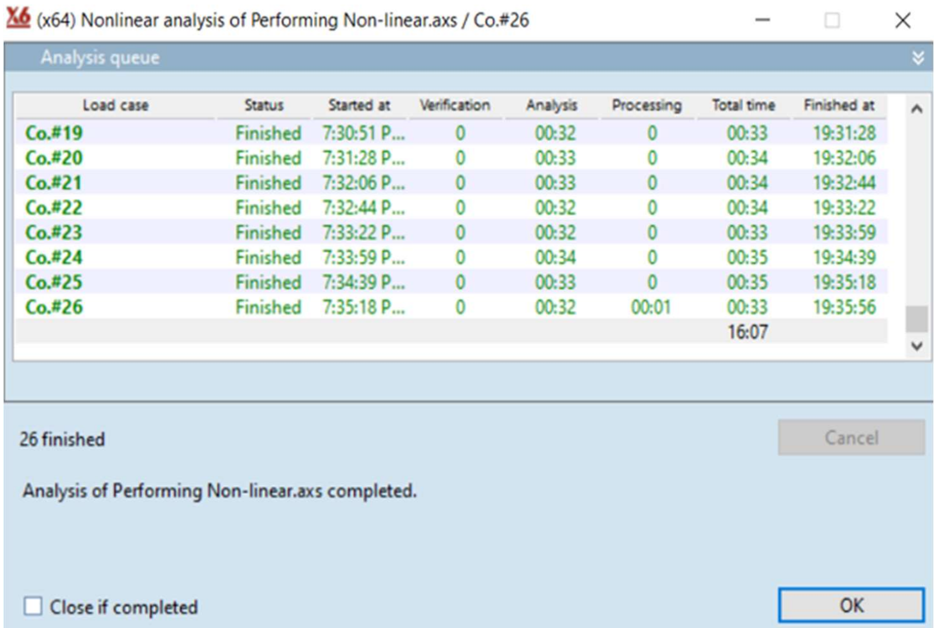


Fig. 23 – Completion of non-linear analysis

After running the non-linear analysis with manual load combinations, following results was obtained for the special elements.

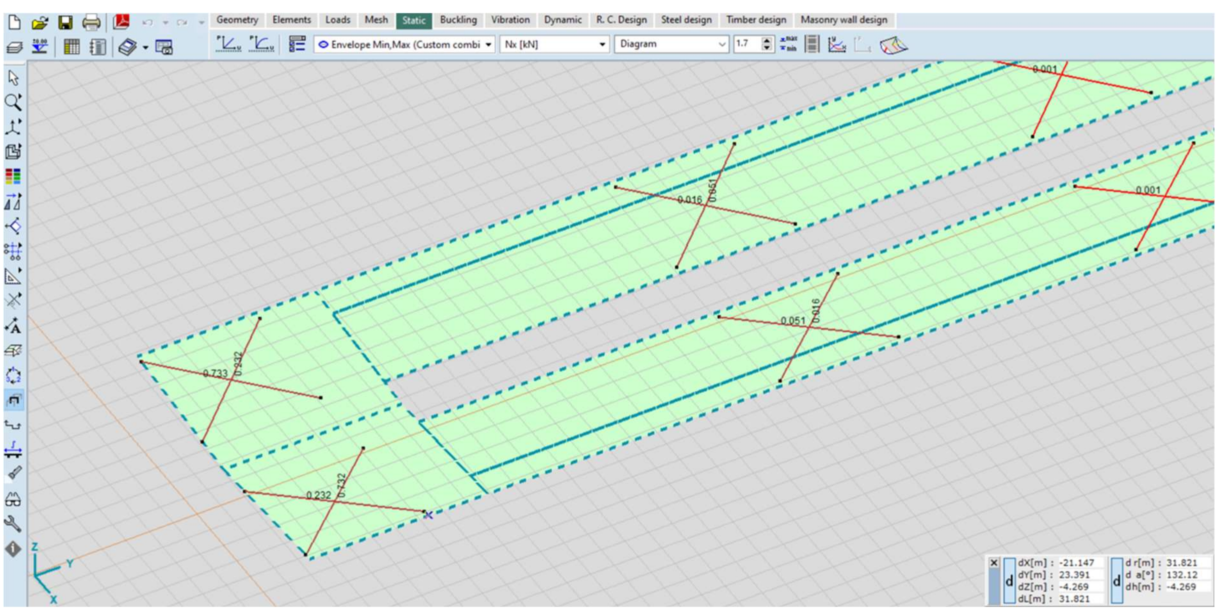
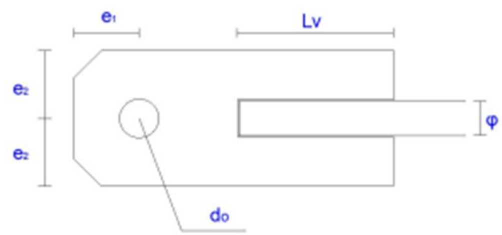


Fig. 24 – Nx Value after the non-linear analysis

Bracing Rod Connections (bars with one bolt)

Material properties:



Plate

$f_y := 355 \frac{N}{mm^2}$

$f_u := 510 \frac{N}{mm^2}$

Bolt

$f_{yb} := 640 \frac{N}{mm^2}$

$f_{ub} := 800 \frac{N}{mm^2}$

Safety factors: $\gamma_{M0} := 1$ $\gamma_{M2} := 1.25$

Resistance of the bar:

Diameter of the bar: $\varphi := 16\ mm$

The cross-sectional area of the bar for tension: $A_s := 157\ mm^2$

$$F_{tRd} := \frac{A_s \cdot f_y}{\gamma_{M0}} = 55.735\ kN$$

Resistance of the bolt:

$d := 16\ mm$	Diameter of the bolt
$d_0 := 18\ mm$	Diameter of the hole
$A := 157\ mm^2$	Considerable cross-sectional area of the bolt
$e_1 := 40\ mm$	Paralell with the direction of the force
$e_2 := 40\ mm$	Perpendicular to the direction of the force
$n := 1$	Number of shear surfaces
$t := 8\ mm$	The thickness of the thinner plate in the connection

Shear resistance:

$$F_{vRd} := \frac{n \cdot 0.6 \cdot f_{ub} \cdot A}{\gamma_{M2}} = 60.288\ kN$$

Bearing resistance:

$$k_{1sz} := \min\left(\begin{bmatrix} 2.8 \cdot \frac{e_2}{d_0} - 1.7 \\ 2.5 \end{bmatrix}\right) = 2.5 \qquad \alpha_{bsz} := \min\left(\begin{bmatrix} \frac{e_1}{3 \cdot d_0} \\ \frac{f_{ub}}{f_u} \\ 1 \end{bmatrix}\right) = 0.740741$$

$$F_{bRd} := \frac{k_{1sz} \cdot \alpha_{bsz} \cdot f_u \cdot d \cdot t}{\gamma_{M2}} = 96.711111\ kN$$

$$F_{Rd} := \min\left(\begin{bmatrix} F_{vRd} \\ F_{bRd} \end{bmatrix}\right) = 60.288\ kN$$

Plate-Bar welding check:

Throat thickness: $a := 3\ \text{mm}$

Length of the weld reduced with start and end failures: $L_w := 74\ \text{mm}$

Modification factor depending on the steel garde: $\beta_w := 0.8$

Stress components in the weld:

$$\tau_{par} := \frac{F_{tRd}}{a \cdot L_w \cdot 4} = 62.7646\ \frac{\text{N}}{\text{mm}^2} \qquad \tau_{perp} := 0\ \frac{\text{N}}{\text{mm}^2} \qquad \sigma_{perp} := 0\ \frac{\text{N}}{\text{mm}^2}$$

$$\sqrt{\sigma_{perp}^2 + 3 \cdot \left(\tau_{perp}^2 + \tau_{par}^2\right)} = 108.7115\ \frac{\text{N}}{\text{mm}^2} \quad \_\le\_ \quad \frac{f_u}{\beta_w \cdot \gamma_{M2}} = 510\ \frac{\text{N}}{\text{mm}^2}$$

$$\sigma_{perp} = 0\ \frac{\text{N}}{\text{mm}^2} \quad \_\le\_ \quad \frac{f_u}{\gamma_{M2}} = 408\ \frac{\text{N}}{\text{mm}^2}$$

Tension resistance of the connecting plate (in three different cross-sections):

$$N_{plRd} := \frac{2 \cdot e_2 \cdot t \cdot f_y}{\gamma_{M0}} = 227.2\ \text{kN}$$

$$N_{uRd\_1} := \frac{0.9 \cdot \left(2 \cdot e_2 - d_0\right) \cdot t \cdot f_u}{\gamma_{M2}} = 182.1312\ \text{kN}$$

$$N_{uRd\_2} := \frac{0.9 \cdot \left(2 \cdot e_2 - \varphi - 2\ \text{mm}\right) \cdot t \cdot f_u}{\gamma_{M2}} = 182.1312\ \text{kN}$$

Shear failure of the connecting plate:

$$\frac{\left(2 \cdot e_1\right) \cdot t \cdot f_y}{\sqrt{3} \cdot \gamma_{M0}} = 131.174\ \text{kN}$$

2.6. Linear Analysis:

2.6.1. Deflection:

Deflection in the z-axis came out at about 14 mm which is a reasonable deflection as far as the span of 13 meters is concerned. The deflection was taken from the critical min, max.

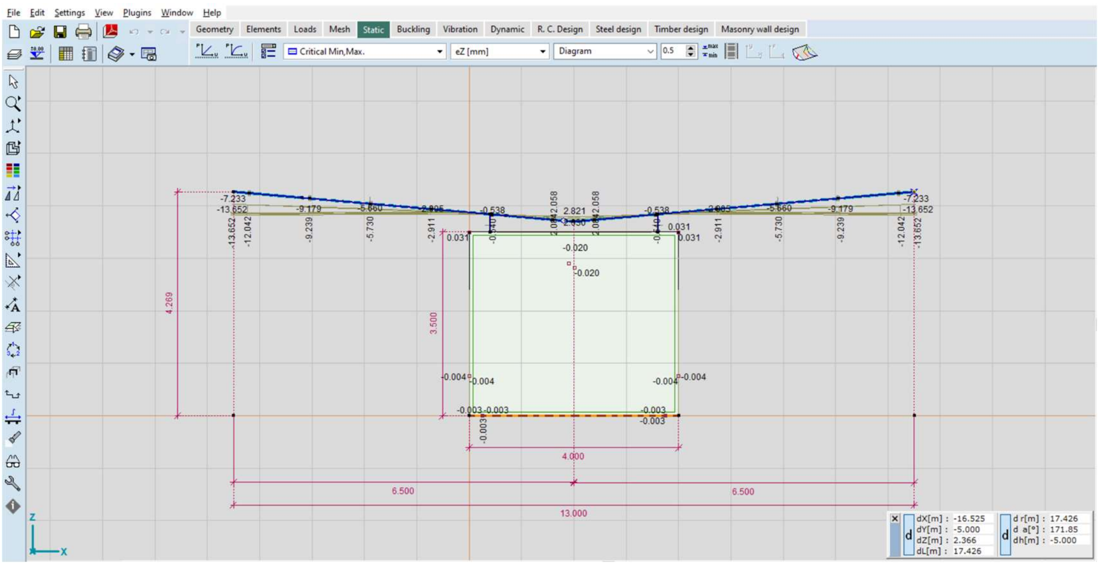


Fig. 25 – Ez Deflection from the front view according to the Critical Min Max

2.6.2. Moment:

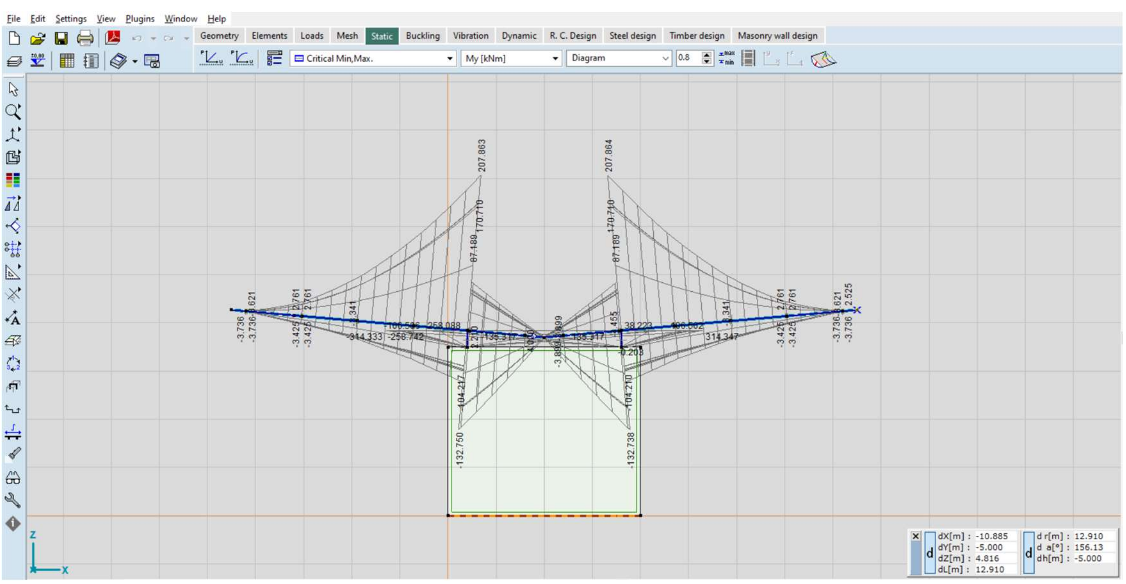


Fig. 26 – My moment from the front view according to the Critical Min Max

2.6.3. Shear Force:

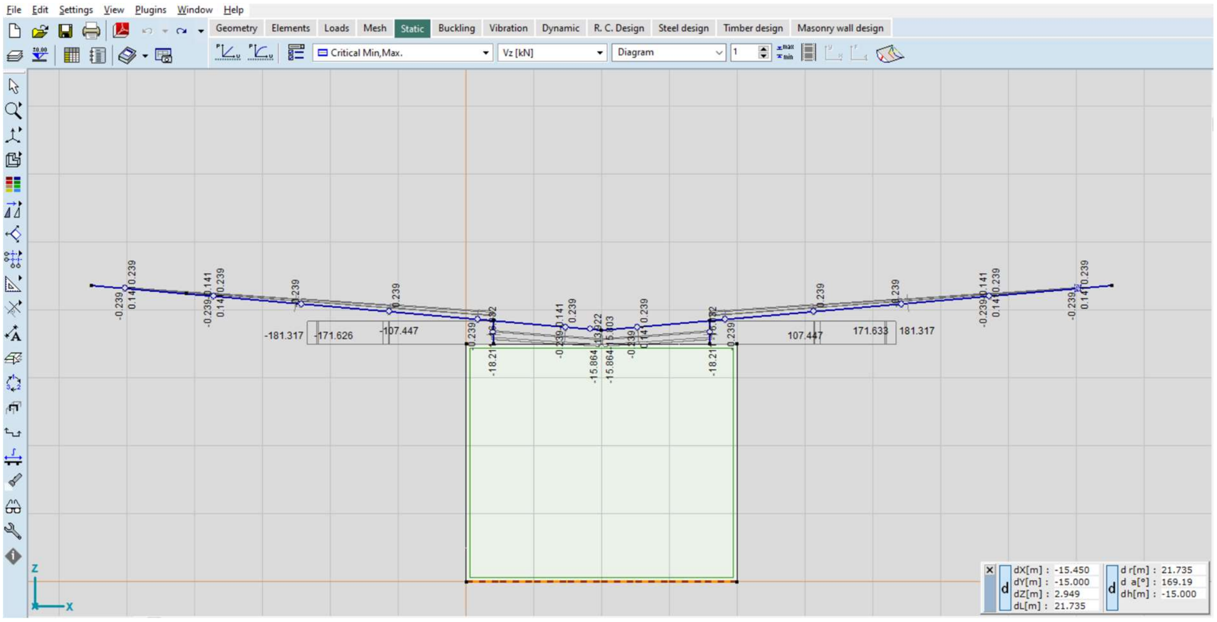


Fig. 27 – Vz moment from the front view according to the Critical Min Max

2.6.4. Normal Force:

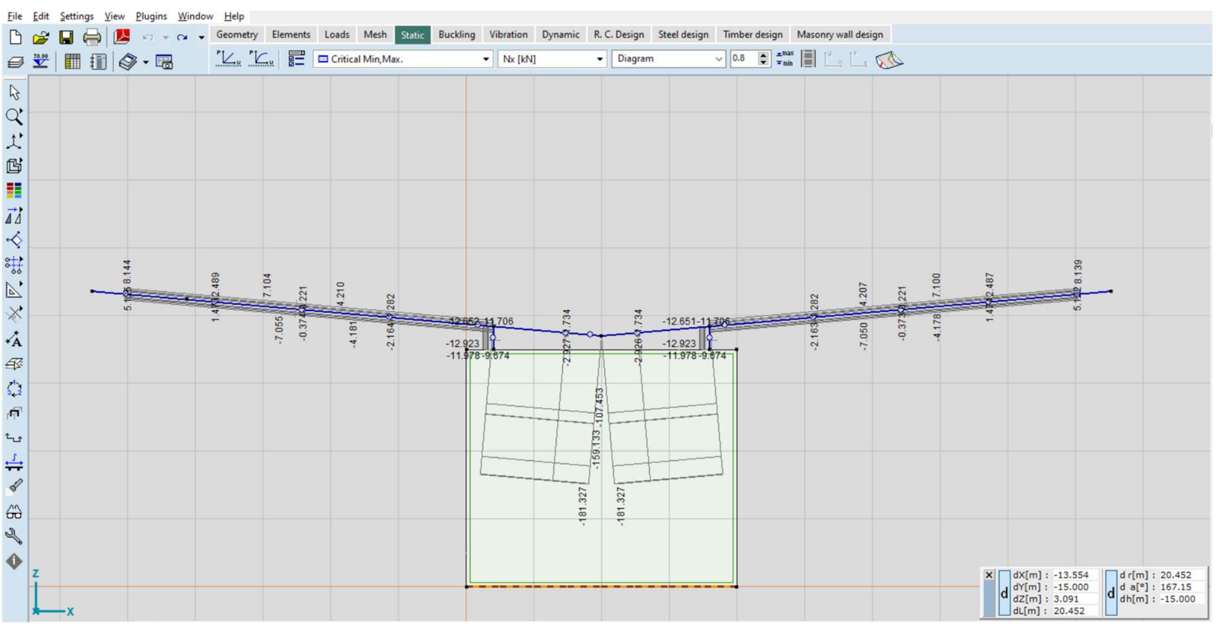


Fig. 28 – Nx force from the front view according to the Critical Min Max

2.6.5. Utilization:

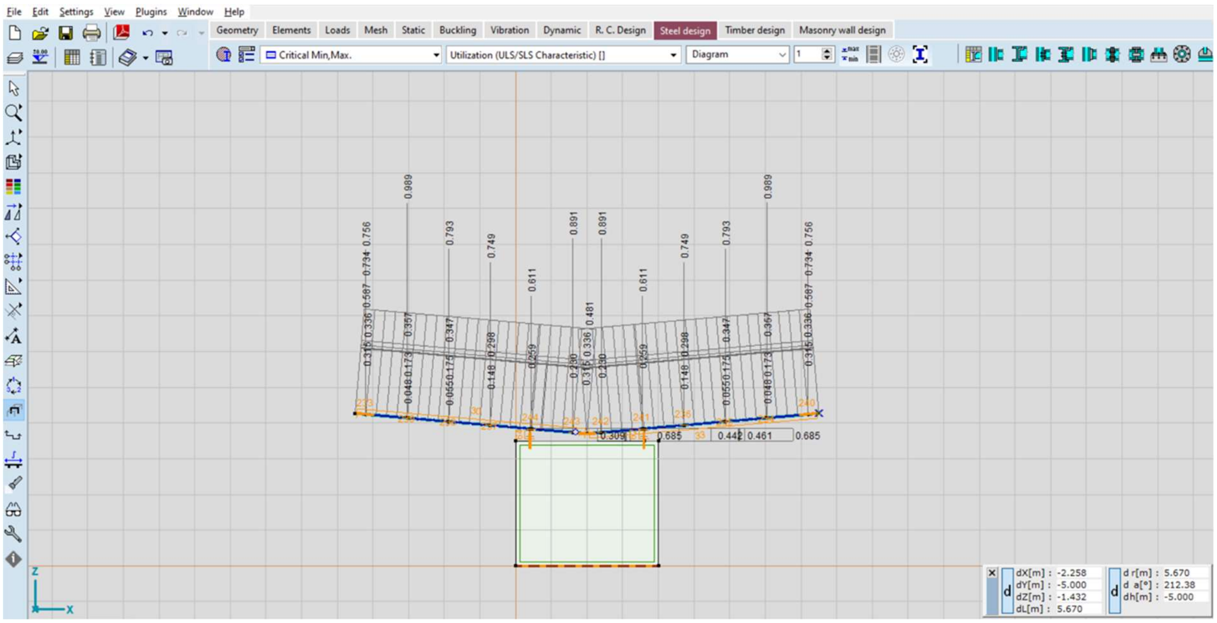


Fig. 29 – Utilization of critical max, min in Steel Design.

3. Conclusion and Discussion:

By the help of FEM and CAD software modules, a designer can efficiently and accurately produce blueprints of an assigned project. It makes it significantly easier to coincide different aspects of a project for better flow and integration of information from within. Computer-aided design allows us to extract more information after the analysis so that the design could easily be updated. We will see more collaboration between FEM and BIM software packages in the future which will allow a faster production of blueprints. While FEM software packages are efficient on their own, they can certainly be updated to automate many of the remaining aspects of a design such as determination of wind zones for various types of structures as per the national annexes. This will eliminate the introduction of human error but certainly require a quick manual check for confirmation. Advances as such will make the design discipline more integrated for better cooperation among different teams (architectural, structural, construction) tasked to complete a project. Finally, this computer-aided approach helps a designer produce an accurate list of quantity estimations which helps with better budget practices.

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