APPENDICES
Long-span Timber Roof Structure
for The New Feyenoord stadium

Master Thesis
Structural Engineering

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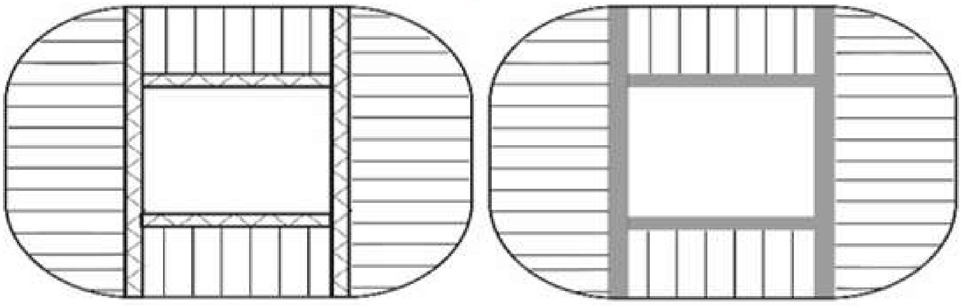
A

Rough calculations global design phase

Preconditions		
Strength class	GL32c	
Loads	Selfweight + snow load	
Supports	12	
Material factor	γ_M = 1,25	
Consequence class	CC 3: γ_G=1,3 ; γ_Q=1,65	
Service class (load duration)	SC 2 (short) k_{mod}=0.9 ; k_{def}=0.8	
Self-weight timber	$\rho_{G,tim}$ = 4.4 kN/m^3	
Selfweight polycarbonate panel	$q_{G,pc}$ = 0.15 kN/m^2	
Snow load	$q_{Q,snow}$=0.56 kN/m^2	
length	l = 246m	
width	b = 206m	
Longitudinal main girders	1500 x 1500 mm	Square cross sections.
Bracing main girders	600 x 600 mm	Dimensions are inspired by preliminary design of RHDHV
Longitudinal secondary girders	500 x 500 mm	
Bracing secondary girders	200 x 200 mm	

A.1 Single span

Single span



Calculation of primary girder

Dimensions of these girders are estimated from the steel design of RHDHV. This results in the following dimensions for the primary, secundary and tertaire girders:

<u>Tertiary girders (100x)</u>

h_3 (m) =	4	Longitudinal beams =	500 × 500 mm =	0.25 m^2
l_3 (m) =	60	cross girders =	200 × 200 mm =	0.04 m^2
b_3 (m) =	1			
s (m)=	6 [h.o.h.]			

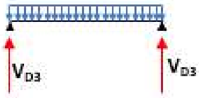
$q_{G,sw3}$ = $((4 \times 0{,}25) \times 5 \times p_{G,lim} + (2 \times 4 + 2 \times 5 + 3 \times 6{,}5) \times 0{,}04 \times p_{G,lim}) / 5$ = **8.6 kN/m**

$q_{Gk,PC}$ = $s \times q_{G,PC}$ = **0.9 kN/m**

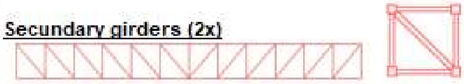
$q_{Qk,snow}$ = $s \times q_{Q,snow}$ = **3.4 kN/m**

q_{d3} = $1{,}3 \times (q_{G,sw3} + q_{Gk,PC}) + 1{,}65 \times q_{Qk,snow}$ = **17.9 kN/m**

V_{D3} = $0{,}5 * q_{d3} * l_3$ = **537 kN**



<u>Secundary girders (2x)</u>



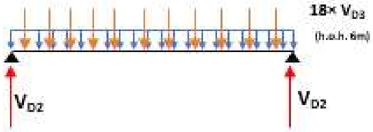
h_2 (m) =	12	Longitudinal beams (b*h) [mm] =	1500	1500	2.25 m^2
l_2 (m) =	120	cross girders (b*h) [mm] =	600	600	0.36 m^2
b_2 (m) =	10				

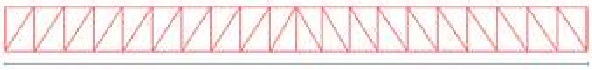
$q_{G,sw2}$ = $((4 \times 2{,}25) \times 10 \times p_{G,lim} + (2 \times 10 + 2 \times 12 + 3 \times 15{,}5) \times 0{,}36 \times p_{G,lim}) / 10$ = **89.6 kN/m**

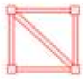
q_{d2} = $1{,}3 \times q_{G,sw2}$ = **116.5 kN/m**

V_{D3} = **537 kN**

V_{D2} = $0{,}5 \times (q_{d2} \times l_2 + (l_2/s - 2) \times V_{D3})$ = **11821 kN**







Primary girders (2x)

h_1 (m) =	14	Longitudinal beams (b*h) [mm] =	1500	1500	2.25 m^2
l_1 (m) =	206	cross girders (b*h) [mm] =	600	600	0.36 m^2
b_1 (m) =	10	$E_{0,d}$ = $(E_{0,mean} / (1 + \Psi_2 \times k_{def})) / \gamma_m$ =	11360000 kN/m²		

Conservative estimation of the moment of inertia of a truss.

(most influental cross sections are those of the longitudinal beams)

I_y = $4 \times (A_{L,T} \times (½h)^2 \times 0{,}7)$ = **308.7** m^4

EI = 3.51E+09 EA = 1.02E+08

$q_{G,sw1}$ = $((4 \times 2{,}25) \times 10 \times \rho_{G,sm} + (2 \times 10 + 2 \times 14 + 3 \times 17) \times 0{,}36 \times \rho_{G,sm}) / 10$ = **91.9 kN/m**

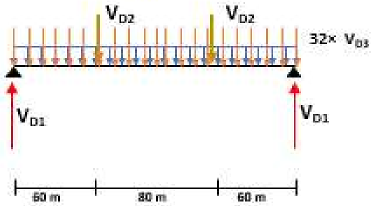
q_{d1} = $1{,}3 \times q_{G,sw1}$ = **119 kN/m**

V_{D2} = **11821 kN**

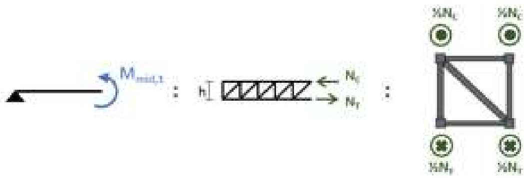
V_{D3} = **537 kN**

V_{D1} = $0{,}5 \times (q_{d1} \times l_1 + (l_1/s-2) \times V_{D3} + 2 \times V_{D2})$ = **29762 kN**

$M_{mid,1}$ = $1/8 \times (q_{d1} + 21 \times V_{D3}/l_1) \times l_1^2 + V_{D2} \times 60$ **1633244 kNm**



Values of interest



$N_C = N_T$ = $M_{mid,1} / h$ 116660 **kN**

Deflection at mid span

w = $(5/384) * (q_{d1}+(l_1/s-2)*V_{d3}/l_1) * l_1^4 / EI + (1/24) * (V_{D2}*l_3*(3*l_1^2-4*l_3^2)) / EI)$ = **2.31 m**

$\leq$ w_{max} = 0.82 m **NIET OK**

Forces

Longitudinal compression bar

$N_{Lt,C}$ =	$N_C / 2$	**58330 kN**	U.C.	**1.13**	**NIET OK**
$\sigma_{Lt,C}$ =	$N_{LT,C} / A$	**25.9 N/mm²**			
$f_{c,0,d}$ =		23.04 N/mm²			

Longitudinal tension bar

$N_{Lt,T}$ =	$N_T / 2$	**58330 kN**	U.C.	**1.41**	**NIET OK**
$\sigma_{Lt,T}$ =	$N_{Lt,T} / A$	**25.9 N/mm²**			
$f_{t,0,d}$ =		18.432 N/mm²			

Total weight of the timber structure

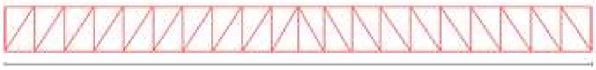
$(q_{G,sw1} \times l_1) \times 2 + (q_{G,sw2} \times l_2) \times 2 + (q_{G,sw3} \times l_3) \times 100$ = **110991 kN = 1.11E+07 kg**

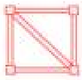
Support reactions

Vertical support reaction	V_{ED} =	**29762 kN**
Horizontal support reaction	H_{ED} =	**0 kN**

U.C. below 1.0

Primary girders (2x)





h_1 (m) =	18	Longitudinal beams (b*h) [mm] =	1500	1500	2.25	m^2
l_1 (m) =	206	cross girders (b*h) [mm] =	600	600	0.36	m^2
b_1 (m) =	10	$E_{0,d} = (E_{0,mean} / (1 + \Psi_2 \times k_{def})) / \gamma_m =$	11360000	kN/m^2		

Conservative estimation of the moment of inertia of a truss.
(most influental cross sections are those of the longitudinal beams)

$I_y = 4 \times (A_{LT} \times (½h)^2 \times 0{,}7) =$ **510.3** m^4

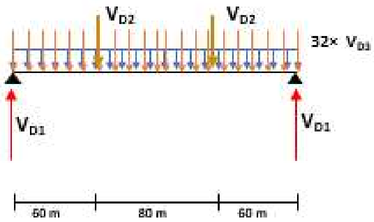
EI = 5.80E+09 EA = 1.02E+08

$q_{G,sw1} = ((4 \times 2{,}25) \times 10 \times \rho_{G,lam} + (2 \times 10 + 2 \times 14 + 3 \times 17) \times 0{,}36 \times \rho_{G,lam}) / 10 =$ **96.7 kN/m**

$q_{d1} = 1{,}3 \times q_{G,sw1} =$ **126 kN/m**

$V_{D2} =$ **11821 kN**

$V_{D3} =$ **537 kN**



$V_{D1} = 0{,}5 \times (q_{d1} \times l_1 + (l_1/s\text{-}2) \times V_{D3} + 2 \times V_{D2}) =$ **30402 kN**

$M_{mid,1} = 1/8 \times (q_{d1} + 21 \times V_{D3}/l_1) \times l_1^2 + V_{D2} \times 60$ **1666154 kNm**

U.C. below 1.0

$N_C = N_T = M_{mid,1} / h$ 92564 **kN**

Deflection at mid span

$w = (5/384) * (q_{d1}+(l_1/s\text{-}2)*V_{d3}/l_1) * l_1^4 / EI + (1/24) * (V_{D2}*l_3*(3*l_1^2-4*l_3^2)) / EI) =$ **1.42 m**

$\leq w_{max} =$ 0.82 m **NIET OK**

Forces

Longitudinal compression bar

N_{LLC} =	$N_C / 2$	**46282**	**kN**	U.C.	**0.89**	**OK**
σ_{LLC} =	$N_{LT,C} / A$	**20.6**	**N/mm^2**			
$f_{c,0,d}$ =		23.04	N/mm^2			

Longitudinal tension bar

N_{LLT} =	$N_T / 2$	**46282**	**kN**	U.C.	**1.12**	**NIET OK**
σ_{LLT} =	N_{LLT} / A	**20.6**	**N/mm^2**			
$f_{t,0,d}$ =		18.432	N/mm^2			

Total weight of the timber structure

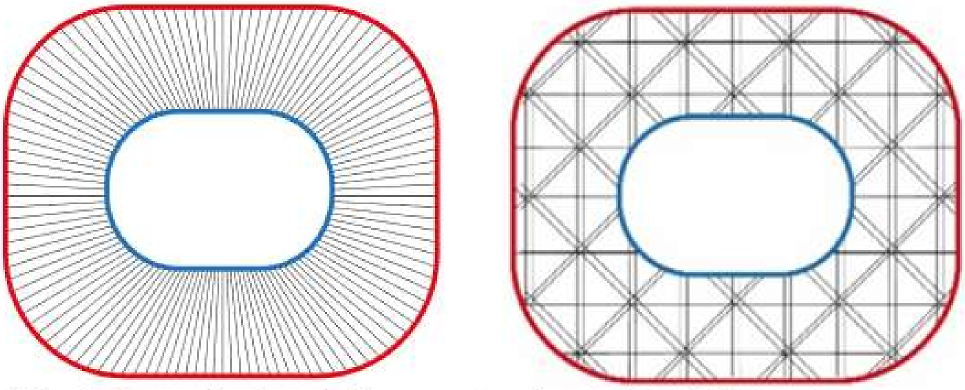
$(q_{G,sw1} \times l_1) \times 2 + (q_{G,sw2} \times l_2) \times 2 + (q_{G,sw3} \times l_3) \times 100 =$ **112957 kN = 1.13E+07 kg**

Support reactions

Vertical support reaction	V_{ED} =	**30402**	**kN**
Horizontal support reaction	H_{ED} =	**0**	**kN**

A.2 Tension/compression ring

Tension / Compression ring



Calculation of primary girder done by Rhinoceros - Grasshopper - Karamba3D

Inner Ring

h_{IR} (m) =	14	Longitudinal beams (b*h) [mm] =	1500	1500	A_{IRlt} (m) =	2.25	m^2
b_{IR} (m) =	0	Bracing (b*h) [mm]=	600	600	A_{IRbr} (m) =	0.36	m^2
l_{IR} (m) =	320				$W_{OR} = W_{IR}$	0.5625	m^3

Outer ring

h_{OR} (m) =	4	Longitudinal beams (b*h) [mm] =	1500	1500	A_{ORlt} =	2.25	m^2
b_{OR} (m) =	0	Bracing (b*h) [mm]=	600	600	A_{ORbr} =	0.36	m^2
l_{OR} (m) =	780				$W_{OR} = W_{IR}$	0.5625	m^3

Secondary girders (100x)

h_{2IR} (m) =	14		Longitudinal beams =	500 × 500 mm =	A_{2glt} (m) =	0.25 m^2
h_{2OR} (m) =	4		Bracing =	200 × 200 mm =	A_{2gbr} (m) =	0.04 m^2
l_2 (m) =	75					
b_2 (m) =	0					
s_{IR} (m) =	3.2	[h.o.h.]				
s_{OR} (m) =	7.8	[h.o.h.]				

combined bending ans axial compression $(\sigma_{c,0,d} / f_{c,0,d})^2 + k_m \times (\sigma_{m,y,d} / f_{m,y,d}) + (\sigma_{m,z,d} / f_{m,z,d}) \leq 1$

$(\sigma_{c,0,d} / f_{c,0,d})^2 + (\sigma_{m,y,d} / f_{m,y,d}) + k_m \times (\sigma_{m,z,d} / f_{m,z,d}) \leq 1$

Combined bending and axial tension $(\sigma_{t,0,d} / f_{t,0,d}) + k_m \times (\sigma_{m,y,d} / f_{m,y,d}) + (\sigma_{m,z,d} / f_{m,z,d}) \leq 1$

$(\sigma_{t,0,d} / f_{t,0,d}) + (\sigma_{m,y,d} / f_{m,y,d}) + k_m \times (\sigma_{m,z,d} / f_{m,z,d}) \leq 1$

Values of interest

Deflection at mid span

w =	**1.06 m**	≤	w_{max} =	0.82 m	**NIET OK**

Forces

Longitudinal Inner ring top [Compression + Bending] {point 25}

double truss ring?

$N_{IR,C}$ =		43106 **kN**				
$M_{IR,y}$ =		941 **kNm**				
$M_{IR,z}$ =		3043 **kNm**				
$\sigma_{IR,C}$ =	$N_{IR,C}$ / A	**19.2 N/mm²**				
$\sigma_{IR,My}$ =	$M_{IR,y}$ / W_{IR}	**1.67 N/mm²**	1.67	U.C.	**0.98**	**OK**
$\sigma_{IR,Mz}$ =	$M_{IR,z}$ / W_{IR}	**5.41 N/mm²**	5.41			
$f_{c,0,d}$ =		23.04 N/mm²				
$f_{m,0,d}$ =		23.04 N/mm²				

Longitudinal Outer ring bottom [Tension + Bending] {point 43}

Besista Rod as a solution?

Or a Double Truss ring

$N_{OR,T}$ =		**27247 kN**				
$M_{OR,y}$ =		2189 **kNm**				
$M_{OR,z}$ =		730 **kNm**				
$\sigma_{OR,T}$ =	$N_{OR,T}$ / A	**12.1 N/mm²**				
$\sigma_{OR,My}$ =	$M_{OR,y}$ / W_{OR}	3.89 **N/mm²**	1.30	U.C.	**0.83**	**OK**
$\sigma_{OR,Mz}$ =	$M_{OR,z}$ / W_{OR}	1.30 **N/mm²**	3.89			
$f_{t,0,d}$ =		18.432 N/mm²				
$f_{m,0,d}$ =		23.04 N/mm²				

Longitudinal Inner ring top [Compression + Bending] {point 50}

$N_{IR,C}$ =		35390 **kN**		
$M_{IR,y}$ =		796 **kNm**		
$M_{IR,z}$ =		9817 **kNm**		
$\sigma_{IR,C}$ =	$N_{IR,C}$ / A	**15.7 N/mm²**		
$\sigma_{IR,My}$ =	$M_{IR,y}$ / W_{IR}	**1.42 N/mm²**	1.42	U.C.
$\sigma_{IR,Mz}$ =	$M_{IR,z}$ / W_{IR}	**17.45 N/mm²**	17.45	
$f_{c,0,d}$ =		23.04 N/mm²		
$f_{m,0,d}$ =		23.04 N/mm²		

Total weight of the timber structure

kN = 5.23E+06 kg

Support reactions

Vertical support reaction	V_{ED} =	**12563 kN**	(support in the corner)
Horizontal support reaction	H_{ED} =	**22765 kN**	

U.C. below 1.0

Inner Ring

h_{IR} (m) =	18	Longitudinal beams (b*h) [mm] =	1900	1900	A_{IRl} (m) =	3.61 m²
b_{IR} (m) =	0	Bracing (b*h) [mm]=	600	600	A_{IRbr} (m) =	0.36 m²
l_{IR} (m) =	320				W_{OR} = W_{IR}	1.14317 m³

U.C. below 1.0

Deflection at mid span

w =	**0.72 m**	≤	w_{max} =	0.82 m	**OK**

Forces

Longitudinal Inner ring top [Compression + Bending] **{point 25}** double truss ring?

$N_{IR,C}$ =		39417	**kN**				
$M_{IR,y}$ =		1757	**kNm**				
$M_{IR,z}$ =		5555	**kNm**				
$\sigma_{IR,C}$ =	$N_{IR,C}$ / A	**10.9**	**N/mm²**				
$\sigma_{IR,My}$ =	$M_{IR,y}$ / W_{IR}	**1.54**	**N/mm²**	1.54	U.C.	**0.48**	**OK**
$\sigma_{IR,Mz}$ =	$M_{IR,z}$ / W_{IR}	**4.86**	**N/mm²**	4.86			
$f_{c,0,d}$ =		23.04	N/mm²				
$f_{m,o,d}$ =		23.04	N/mm²				

Longitudinal Inner ring top [Compression + Bending] **{point 50}**

$N_{IR,C}$ =		32019	**kN**		
$M_{IR,y}$ =		1140	**kNm**		
$M_{IR,z}$ =		18578	**kNm**		
$\sigma_{IR,C}$ =	$N_{IR,C}$ / A	**8.9**	**N/mm²**		
$\sigma_{IR,My}$ =	$M_{IR,y}$ / W_{IR}	**1.00**	**N/mm²**	1.00	U.C.
$\sigma_{IR,Mz}$ =	$M_{IR,z}$ / W_{IR}	**16.25**	**N/mm²**	16.25	
$f_{c,0,d}$ =		23.04	N/mm²		
$f_{m,o,d}$ =		23.04	N/mm²		

Longitudinal Outer ring bottom [Tension + Bending] **{point 43}** Besista Rod as a solution? Or a Double Truss ring

$N_{OR,T}$ =		**22888**	**kN**				
$M_{OR,y}$ =		1925	**kNm**				
$M_{OR,z}$ =		345	**kNm**				
$\sigma_{OR,T}$ =	$N_{OR,T}$ / A	**10.2**	**N/mm²**				
$\sigma_{OR,My}$ =	$M_{OR,y}$ / W_{OR}	3.42	**N/mm²**	0.61	U.C.	**0.68**	**OK**
$\sigma_{OR,Mz}$ =	$M_{OR,z}$ / W_{OR}	0.61	**N/mm²**	3.42			
$f_{t,0,d}$ =		18.432	N/mm²				
$f_{m,o,d}$ =		23.04	N/mm²				

Total weight of the timber structure

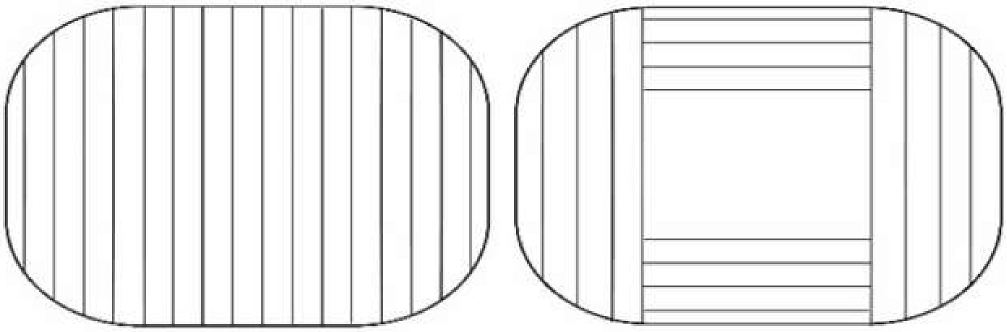
kN = 5.71E+06 kg

Support reactions

Vertical support reaction	V_{ED} =	**13828 kN**	(support in the corner)
Horizontal support reaction	H_{ED} =	**17992 kN**	

A.3 Stress ribbon

Stress ribbon

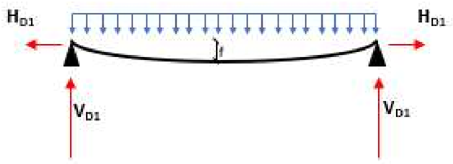


The slenderness of this system is very high and thus results in a catenary system. (bending is neglected in this rough calculation)
The sag-to-span ratio is given by:
f/L = 0.024272 < 1:8 and therefore the uniform 'cable' hanging under its own weight between two supports at the same level can be accurately described by the parabolic assumption.
The parabolic assumption for flat profile cables is accurate enough even with ratios sag to span up to 1:5. [Dictaat slender structures: Angelo Simeone]

Primairy girders

Beams =								
b (mm) =	1200	A (m) =	0.96	m^2	$E_{0,d}$ =	$(E_{0,mean} / (1 + \Psi_2 \times k_{def})) / \Upsilon_m$ =	**1.14E+07**	**kN/m^2**
h (mm) =	800	A_{totaal} =	46400	m^2	I_y =	$1/12 \times b \times h^3$ =	**0.08**	**m^4**
l (m) =	206				EI =	9.09E+05	EA =	1.09E+07
s (m) =	6 [h.o.h]							
f (m) =	5							

$q_{G,sw}$ =	$A \times \rho_{G,tim}$ =	**7.0**	**kN/m**
q_{Gd} =	$1{,}3 \times (q_{G,sw} + s \times q_{G,pc})$ =	**10.2804**	**kN/m**
q_{Qd} =	$1{,}65 \times q_{Q,snow} \times s$ =	**7.0**	**kN/m**
q_d =		**17.3**	**kN/m**
V_{D1} =	$0{,}5 * q_{d1} * l$	**1783**	**kN**
H_{D1} =	$q_d \times l^2 / (8 \times f)$	**18364**	**kN**
L_{girder} =	$l + (8 \times f^2) / 3 \times l$	**206**	**m**



Values of interest

Deflection at mid span

w(0) = $3\times\Delta H\times l^2 / (16\times f\times EA)$ = **2.68 m** ≤ w_{max} = 0.82 m **NIET OK**

Interne trekkracht is gelijk aan H_{D1}

Forces

$N_{Lt,T}$ =	H_{D1}	18364	**kN**	U.C.	**1.04**	**NIET OK**
$\sigma_{Lt,T}$ =	$N_{Lt,T}$ / A	19.13	**N/mm²**			
$f_{t,0,d}$ =		18.432	N/mm²			

Total weight of the timber structure (conservative weight calculation due to spans in the corner of super ellipse)

Width of the structure divided into 3 parts: w_1, w_2, w_3.

w_2 is the middle area which spans the entire l. The other two width areas only have a span of 0.85*l

w_1 (m) = 60

w_2 (m) = 125

w_3 (m) = 60

$(q_{G,sw3} * L_{girder}) * (0,85 * (w_1 + w_3) + w_2) / s$ = 54704 **kN = 5.47E+06 kg**

Support reactions

Supports in the middle of the stadium take up the largest loads due to width between other supports.

Width taken up by the supports in the middle is [m] = 60

the amount of ribbons carried by the supports in the middle is the width divided by the spacing of the ribbons =

10 ribbons

Therefore, the vertical support reaction of the mid support points V_{ED} = **17829 kN**

Therefore, the horizontal support reaction of the mid support points H_{ED} = **183635 kN**

Weight calculation with steel assumption and roof panels for uplift wind check

The ribbons will have a steel node every *30* m. The length of this node is 0.1 m.

The height and the width of the node is the same as 50 % of that of the beam.

The entire weight of the **nodes** is as following:

$V * \rho_{G,steel}$ * number of nodes = **1945 kN**

		unfavourable value
New conservative weight calculation including nodes and roof panels =	**56649 kN**	50984 NIET OK

U.C. below 1.0

Primairy girders

Beams =						
b (mm) =	400	A (m) =	0.16 m^2	$E_{0,d}$ =	$(E_{0,mean} / (1 + \Psi_2 \times k_{def})) / \Upsilon_m$ =	**1.14E+07** **kN/m²**
h (mm) =	400	A_{totaal} =	46400 m^2	I_y =	$1/12 \times b \times h^3$ =	**0.013333333** **m⁴**
l (m) =	206			EI =	1.51E+05 EA =	1.82E+06
s (m) =	6 [h.o.h]					
f (m) =	18					

$q_{G,sw3}$ =	$A \times p_{G,tim}$ =	**1.2 kN/m**
q_{Gd} =	$1{,}3 \times (q_{G,sw} + s \times q_{G,pc})$ =	**2.6884 kN/m**
q_{Qd} =	$1{,}65 \times q_{Q,snow} \times s$ =	**5.5 kN/m**
q_d =		**8.2 kN/m**
V_{D1} =	$0{,}5 * q_{d1} * l$	**848 kN**
H_{D1} =	$q_d \times l^2 / (8 \times f)$	**2426 kN**
L_{girder} =	$l + (8 \times f^2) / 3 \times l$	**210 m**

Maximale horizontaal kracht

Is er een manier om te rekenen wat dat doet en te kijken of je er onder kan blijven?

U.C. below 1.0

Deflection at mid span

w(0) = $3 \times \Delta H \times l^2 / (16 \times f \times EA)$ = **0.59 m** ≤ w_{max} = 0.82 m **OK**

Interne trekkracht is gelijk aan H_{D1}

Forces

$N_{t,t,T}$ =	H_{D1}	2426 **kN**	**U.C.** **0.82**	**OK**
$\sigma_{t,t,T}$ =	$N_{t,t,T} / A$	15.16 **N/mm²**		
$f_{t,0,d}$ =		18.432 N/mm²		

Total weight of the timber structure (conservative weight calculation due to spans in the corner of super ellipse)

Width of the structure divided into 3 parts: w_1, w_2, w_3.

w_2 is the middle area which spans the entire l. The other two width areas only have a span of 0.85*l

w_1 (m) = 60

w_2 (m) = 125

w_3 (m) = 60

$(q_{G,sw3} * L_{girder}) * (0{,}85 * (w_1 + w_3) + w_2) / s$ = 9288 **kN =** **9.29E+05 kg**

Support reactions

Supports in the middle of the stadium take up the largest loads due to width between other supports.

Width taken up by the supports in the middle is [m] = 60

the amount of ribbons carried by the supports in the middle is the width divided by the spacing of the ribbons = 10 ribbons

Therefore, the vertical support reaction of the mid support points V_{ED} = **8479 kN**

Therefore, the horizontal support reaction of the mid support points H_{ED} = **24260 kN**

Weight calculation with steel assumption and roof panels for uplift wind check

The ribbons will have a steel node every *30* m. The length of this node is 0.1 m.

The height and the width of the node is the same as 50 % of that of the beam.

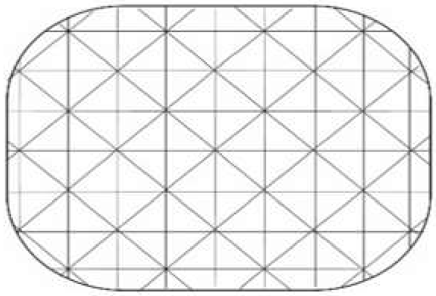
The entire weight of the **nodes** is as following:

$V * p_{G,steel}$ * number of nodes = **324 kN**

New conservative weight calculation including nodes and roof panels = **9613 kN** — unfavourable value 8651 NIET OK

A.4 Grid shell of trusses

Gid shell



Maatvoering en dimensies

Trusses

h (m) =	14	Longitudinal beams (b*h) [mm] =	600	600 A_{Tlt} (m) =	0.36	m^2
l (m) =	7	Bracing (b*h) [mm]=	200	200 A_{Tbr} (m) =	0.04	m^2
b (m) =	0					
s (m)=	6 [h.o.h.]	Atotaal =	46407 m^2			

Values of interest

Deflection at mid span

w =	**1.6 m**	≤	w_{max} =	0.82 m	**NIET OK**

Forces

Longitudinal compression bar {point 1747}

$N_{Lt,C}$ =		**7365 kN**	U.C.	**0.89**	**OK**
$\sigma_{Lt,C}$ =	$N_{LT,C}$ / A	**20.5 N/mm²**			
$f_{c,0,d}$ =		23.04 N/mm²			

Longitudinal tension bar {point 192}

$N_{Lt,T}$ =		**2622 kN**	U.C.	**0.40**	**OK**
$\sigma_{Lt,T}$ =	$N_{Lt,T}$ / A	**7.3 N/mm²**			
$f_{t,0,d}$ =		18.432 N/mm²			

Total weight of the timber structure

51717 kN = 5.17E+06 kg

Support reactions

It is estimated that due to the rigid shell the vertical load is evenly distributed to 8 supports
(In this estimation the two supports near the corners work together as one)

Total support reaction =		119208 kN
Vertical support reaction	V_{ED} =	**14901 kN**
Horizontal support reaction	H_{ED} =	**0 kN**

U.C. below 1.0

Trusses

h (m) =	14	Longitudinal top beams (b*h) [mr	700	700	$A_{tlt,top}$ (m)	0.49 m^2
l (m) =	7	Longitudinal bottom beams (b*h)	400	400	$A_{tlt,bot}$ (m)	0.16 m^2
b (m) =	0	Bracing (b*h) [mm]=	200	200	A_{Tbr} (m) =	0.04 m^2
s (m)=	6 [h.o.h.]	Atotaal =	46407 m^2			

U.C. below 1.0

Deflection at mid span

w =	**1.24 m**	≤	w_{max} =	0.82 m	**NIET OK**

Forces

Longitudinal compression bar		**{point 1749}**			
$N_{Lt,C}$ =		**7862 kN**	U.C.	**0.70**	**OK**
$\sigma_{Lt,C}$ =	$N_{LT,C}$ / A	**16.0 N/mm²**			
$f_{c,0,d}$ =		23.04 N/mm²			
Longitudinal tension bar		**{point 661}**			
$N_{Lt,T}$ =		**1687 kN**	U.C.	**0.57**	**OK**
$\sigma_{Lt,T}$ =	$N_{Lt,T}$ / A	**10.5 N/mm²**			
$f_{t,0,d}$ =		18.432 N/mm²			

Total weight of the timber structure

48195 kN = 4.82E+06 kg

Support reactions

It is estimated that due to the rigid shell the vertical load is evenly distributed to 8 supports
(In this estimation the two supports near the corners work together as one)

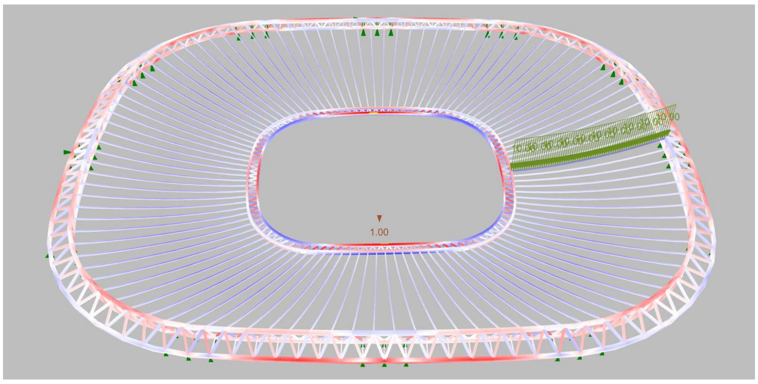
Total support reaction =		114628 kN
Vertical support reaction	V_{ED} =	**14329 kN**
Horizontal support reaction	H_{ED} =	**0 kN**

B

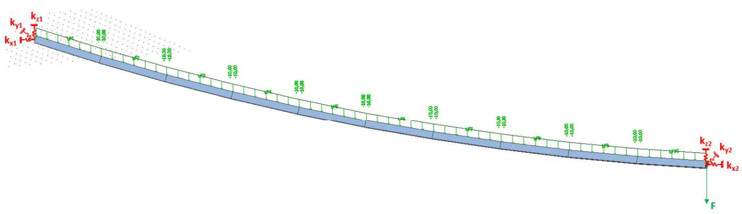
Model verification

As Karamba3D is not a certified FEM model it is of interest if the acquired results are reliable. The behaviour of a single ribbon which is loaded by a unity load is verified. A single ribbon is chosen in the Grasshopper model and a unity load of 10 kN/m is applied on only this ribbon. The same is done on a 2D schematisation of a single ribbon in the software programSCIA Engineer which is based on the finite element method. This program is used because a hand calculation is to complex due to the non-linear behaviour of the system in combination with the different radians that make up the rings.

A ribbon on the short side above a supporting point in a core is chosen for the quantification. See figure 4.29a. The ribbon is supported in z-direction at the location of the outer ring, which minimises the complexity of the system. The ribbon in SCIA is modelled with spring supports in all global directions at both endpoints. The material characteristics and non-linear analysis as well as the model discretization is kept the same as much as possible. For instance, the curves in the Grasshopper model consist of 10 straight elements so the ribbon in SCIA also consist of 10 straight elements.



(a) Unity load on a ribbon at the short side in Grasshopper



(b) Unity load on spring supported ribbon in SCIA

Figure B.1: Model verification by means of a unity load on a single ribbon

B.1 Model in SCIA

The x-, y- and z-coordination's of the single ribbon in Grasshopper are copied and used as input in SCIA to obtain the exact similar dimensions. The behaviour of the ring elements is simulated by three spring supports per end-point. The relation between its spring stiffness, its displacement and the internal forces in the ribbons cannot be approached with simple hand sums. This is because it is a system that knows a huge number of factors that determine its initial behaviour and that vary again to determine its subsequent behaviour. For example, initial displacements (due to self-weight) are needed to give the system rigidity. The more it moves, the greater its resistance and the stiffer the system. This is called the 2nd order effect which again is not easy to approach due to a free support that stiffens itself non-linear. It might even be better described as the 3rd order effect due to the large initial displacements.

The unit load will result in a displacement in x-, y- and mostly z-direction in the Grasshopper model due to the radial plan of the ribbons. This displacement is used to calculate the spring stiffness of the inner and outer ring. Especially the spring stiffness of the inner ring is hard to determine, because it is a free body element that attains stiffness form behaviour in two directions. The stiffness in these two directions is influenced by several different behaving ribbons due to the different radians of the circle.

Also, the self-weight is needed to stabilise the system. The self-weight of the ribbons initiate a deflection that in turn activates the ring action. The weight of the ring itself also contributes to the ring effect and lengthens the ribbons. Hence it is added and the effect of the unit load is found by extracting the difference in deflections between self-weight and self-weight with the unit load.

The supporting spring stiffness will be determined in the following manner to address its complicated influence and due to limitations of the FEM programs. It is possible to determine the influence of the inner ring and the stiffening of the ribbons due to self-weight in the following manner in grasshopper:

- The x,y,z coordinates of the initial geometry is taken for two points at the top of the ribbon and two points at the bottom of the ribbon. Namely point 0 and 1, and 9 and 10.

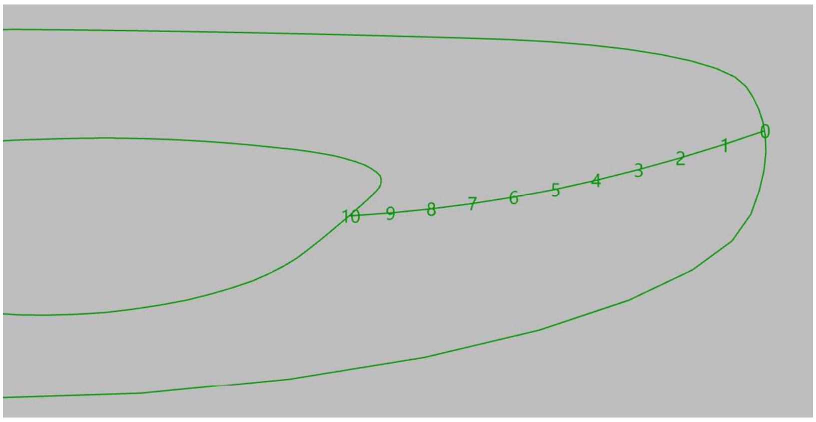


Figure B.2: Points along ribbon due to discretization

- After applying only self-weight the displacement of these points in x,y,z is taken as well as the resulting normal force in the reference ribbon.

- After applying self-weight and a unity load of 10 kN/m, the displacements and normal force are taken again.

- The initial coordinates with the displacements after the self-weight and unity load give the final position of the mentioned points. These points make it possible to construct unity vectors of the deformed state of the ribbons to determine the resulting forces in x,y,z-direction of the normal force. See figures.

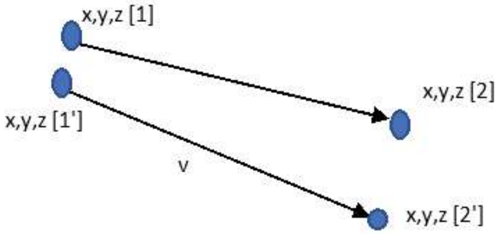


Figure B.3: Principle to get the unity vector for displaced situation

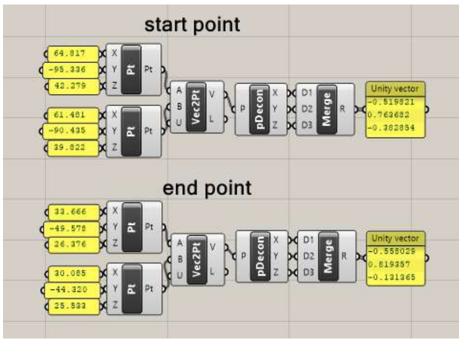


Figure B.4: Determining a unity vector in Grasshopper

- The used normal force is the additional normal force due to the unity load only
$$\triangle N = N_1 - N_0$$
- These resulting forces are divided by the additional displacement due to the unity load only to obtain the stiffness values of the start- and end point of the ribbon in x,y,z-direction.

Start point ribbon							
	point [0]			point [1]			
	x	y	z	x	y	z	
v_0	64.92	-95.35	42.28	61.43	-90.49	39.98	
	x_1	y_1	z_1	x_2	y_2	z_2	N_0
u_1	-0.091	-0.054	0	0.018	0.049	0.045	588.5
	x_1'	y_1'	z_1'	x_2'	y_2'	z_2'	N_1
u_2	-0.098	0.012	-0.001	0.051	0.051	-0.155	2627.1
	dx_1	dy_1	dz_1	dx_2	dy_2	dz_2	ΔN
Vector coordinates	64.817	-95.336	42.279	61.481	-90.435	39.822	2038.6
unitized vector	-0.519821	0.763682	-0.382854				
	Fx	Fy	Fz				
Forces F	-1059.707	1556.8421	-780.4862				
	u_x	u_y	u_z				
Displacement u	-0.007	0.066	-0.001				
	kx=Fx /ux	ky=Fy/uy	kz=Fz/uz				
Stiffness values	1.51E+05	2.36E+04	7.80E+05	kN/m			

Figure B.5: Determining the stiffness values of the support provided by the outer truss

End point ribbon							
	point [9]			point [10]			
	x	y	z	x	y	z	
v_0	32.50	-50.12	27.71	28.78	-44.94	27.00	
	x_1	y_1	z_1	x_2	y_2	z_2	N_0
u_1	1.094	0.632	-0.831	1.236	0.697	-1.111	561.5
	x_1'	y_1'	z_1'	x_2'	y_2'	z_2'	N_1
u_2	1.171	0.537	-1.333	1.301	0.617	-1.467	2440.4
	dx_1	dy_1	dz_1	dx_2	dy_2	dz_2	ΔN
Vector coordinates	33.666	-49.578	26.376	30.085	-44.320	25.533	1878.9
unitized vector	-0.558029	0.819357	-0.131365				
	Fx	Fy	Fz				
Forces F	-1048.481	1539.48987	-246.8217				
	u_x	u_y	u_z				
Displacement u	0.065	-0.08	-0.356				
	kx=Fx /ux	ky=Fy/uy	kz=Fz/uz				
Stiffness values	-1.61E+04	-1.92E+04	6.93E+02	kN/m			

Figure B.6: Determining the stiffness values of the support provided by the inner truss

The same geometry and coordinates of the ribbon after the self-weight is applied is implemented in a SCIA model. The loading is the same unity load of 10kN/m, a point load at the end point, and an initial tensile stress is applied. The point load symbolises the weight of the inner ring hanging at this point, and the tensile stress is the present initial stress due to the self-weight. All these forces are present in the Grasshopper model as well before the unity load is applied. Hence to compare the behaviour in both models due to the unity load the initial restraints need to be the same. It is now of interest if the ribbon in SCIA will give the same resulting forces as the Grasshopper model. The analysation in SCIA is of the 3rd order as this is recommended by the manual for cable structures. Just as it is recommended by the Karamba3D manual to use second order theory analysation to determine the behaviour of the cables. The amount of iterative steps is kept the same for both models.

B.2 Results

The influence of tensile stresses that stiffen the system and compressive stresses that weaken the system is in this way included. However, in SCIA this effect only works on the ribbon itself and the supporting springs keep the same stiffness. In Grasshopper the inner ring goes into more compression, which in turn weakens the system so that the end point of the ribbon deflects more and the ribbon itself gets straightened and thus results in less deflection half way. Also, the straightening of the ribbon results in more internal tension and less bending moment as it already follows an inclined curve.

Results Grasshopper

Δux [mm]	Δuy [mm]	Δuz [mm]	ΔN	ΔV	ΔM
-48	-21	-1	1925	21	13.13
32	-19	-223	1900	21	9.23
96	-17	-419	1876	23	30.57
142	-16	-577	1855	26	56.70
171	-14	-689	1836	33	93.94
184	-13	-753	1818	34	93.94
186	-12	-773	1803	27	54.15
177	-11	-742	1790	24	25.72
161	-11	-658	1779	23	2.70
141	-10	-528	1770	25	17.42
121	-8	-364			

(a) Resulting values from unity load in Grasshopper

Results SCIA

	ux [mm]	uy [mm]	uz [mm]	N [kN]	V [kN]	M [kNm]
1	-45	-20	-1	1836	38	86
2	62	-13	-281	1811	31	138
3	148	-7	-524	1787	26	171
4	207	-3	-712	1766	22	187
5	241	-1	-831	1746	26	179
6	251	-1	-879	1729	27	181
7	244	0	-860	1714	22	195
8	222	2	-765	1702	28	185
9	189	2	-592	1692	30	154
10	151	4	-352	1684	44	104
	116	8	-62			

(b) Resulting values from unity load in SCIA Engineer

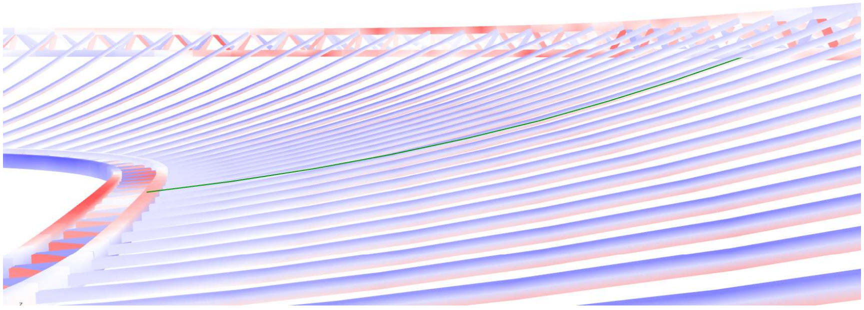
Figure B.7: Resulting values of the model verification

It can be seen that both models show similar behaviour and that their values differ slightly. The difference lies in the amount of cable vs beam action that both ribbons use. The SCIA ribbon shows higher deflections with a higher internal moment, but a lower axial tensile force. It is assumed that the spring stiffness in z-direction in SCIA is modelled to stiff. Which is the reason that the ribbon deflects more at midspan resulting in more beam behaviour. In case of the Grasshopper model the ribbon can distribute more of its force through displacements near the inner ring and therefore show more cable and ring action. This is probably due the fact that the stiffness of the inner ring changes during the loading process in Grasshopper and therefore gradually stiffens. In contrast to the SCIA model were the final stiffness, which is the highest, is applied from the start. To really verify the results of the Karamba3D analysis, the entire structural system needs to be modelled into SCIA so that the stiffening influence of the tension and compression ring can be really incorporated. It is thus assumed that the

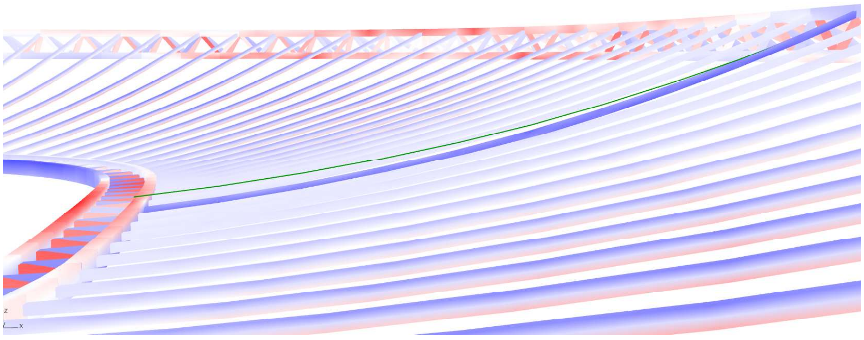
Grasshopper model gives reliable results for now.

B.3 Extra information

The structural utilisation of the different load steps in Grasshopper is shown in two figures. Also, the input for the SCIA model is given.



(a) GH model after applying self-weight



(b) GH model after applying self-weight and the unity load

Figure B.8: Behaviour of the Grasshopper model under self-weight and the unity load

1. Project

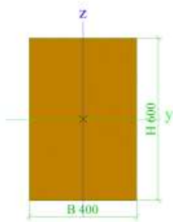
Licence name	Royal HaskoningDHV
Project	-GH check with cable tensioning
Part	-
Description	-
Author	-
Date	08. 08. 2019
Structure	Frame XYZ
No. of nodes :	11
No. of beams :	10
No. of slabs :	0
No. of solids :	0
No. of used profiles :	1
No. of load cases :	1
No. of used materials :	1
Acceleration of gravity [m/s^2]	9,810
National code	EC - EN

2. Materials

Timber EC5

Name	Type of timber	μ	E_{mod} [MPa]	$f_{m.k}$ [MPa]	$f_{t.0.k}$ [MPa]	$f_{t.90.k}$ [MPa]	$f_{c.0.k}$ [MPa]	$f_{c.90.k}$ [MPa]	$f_{v.k}$ [MPa]	Colour
	ρ [kg/m^3]	α [m/mK]	G_{mod} [MPa]							
GL75	Glued, laminated	0	1,6800e+04	60,0	60,0	60,0	60,0	60,0	60,0	■
	730,0	0,00	5,6000e+03							

3. Cross-sections

CS1		
Type	RECT	
Detailed	400; 600	
Shape type	Thick-walled	
Item material	GL75	
Fabrication	timber	
Colour		
A [m^2]	2,4000e-01	
A_y [m^2], A_z [m^2]	2,0000e-01	2,0000e-01
A_L [m^2/m], A_D [m^2/m]	2,0000e+00	2,0000e+00
$c_{Y.UCS}$ [mm], $c_{Z.UCS}$ [mm]	200	300
α [deg]	0,00	
I_y [m^4], I_z [m^4]	7,2000e-03	3,2000e-03
i_y [mm], i_z [mm]	173	115
$W_{el.y}$ [m^3], $W_{el.z}$ [m^3]	2,4000e-02	1,6000e-02
$W_{pl.y}$ [m^3], $W_{pl.z}$ [m^3]	3,6000e-02	2,4000e-02
$M_{pl.y.+}$ [Nm], $M_{pl.y.-}$ [Nm]	2,16e+06	2,16e+06
$M_{pl.z.+}$ [Nm], $M_{pl.z.-}$ [Nm]	1,44e+06	1,44e+06
d_y [mm], d_z [mm]	0	0
I_t [m^4], I_w [m^6]	7,5061e-03	1,5315e-05
$β_y$ [mm], $β_z$ [mm]	0	0
Picture		

Explanations of symbols	
A	Area
A_y	Shear Area in principal y-direction - Calculated by 2D FEM analysis
A_z	Shear Area in principal z-direction - Calculated by 2D FEM analysis
A_L	Circumference per unit length
A_D	Drying surface per unit length
$c_{Y.UCS}$	Centroid coordinate in Y-direction of Input axis system
$c_{Z.UCS}$	Centroid coordinate in Z-direction of Input axis system
$I_{Y.LCS}$	Second moment of area about the YLCS axis
$I_{Z.LCS}$	Second moment of area about the

Explanations of symbols	
	ZLCS axis
$I_{YZ.LCS}$	Product moment of area in the LCS system
α	Rotation angle of the principal axis system
I_y	Second moment of area about the principal y-axis
I_z	Second moment of area about the principal z-axis
i_y	Radius of gyration about the principal y-axis
i_z	Radius of gyration about the principal z-axis
$W_{el.y}$	Elastic section modulus about the

Explanations of symbols	
	principal y-axis
$W_{el.z}$	Elastic section modulus about the principal z-axis
$W_{pl.y}$	Plastic section modulus about the principal y-axis
$W_{pl.z}$	Plastic section modulus about the principal z-axis
$M_{pl.y.+}$	Plastic moment about the principal y-axis for a positive My moment
$M_{pl.y.-}$	Plastic moment about the principal y-axis for a negative My moment
$M_{pl.z.+}$	Plastic moment about the principal z-axis for a positive Mz moment

Explanations of symbols	
$M_{pl.z.-}$	Plastic moment about the principal z-axis for a negative Mz moment
d_y	Shear center coordinate in principal y-direction measured from the centroid - Calculated by 2D FEM analysis
d_z	Shear center coordinate in principal z-direction measured from the centroid - Calculated by 2D FEM analysis
I_t	Torsional constant - Calculated by 2D FEM analysis
I_w	Warping constant - Calculated by 2D FEM analysis
β_y	Mono-symmetry constant about the principal y-axis
β_z	Mono-symmetry constant about the principal z-axis

4. Nonlinear combinations

Name	Type	Load cases	Coeff. [-]
NC1	Ultimate	LC1 - unity load	1,00

4. Nonlinear combinations

Name	Type	Load cases	Coeff. [-]
NC1	Ultimate	LC1 - unity load	1,00

5. Mesh setup

Name	MeshSetup1
Generation of eccentric elements on members with variable height	×
Generation of nodes in connections of beam elements	×
Generation of nodes under concentrated loads on beam elements	✓
Hanging nodes for prestressing	✓
Use automatic mesh refinement	×
Division on haunches and arbitrary members	5
Division for 2D-1D upgrade	50
Average number of tiles of 1d element	10
Average size of 2d element/curved element [m]	1,000
Minimal length of beam element [m]	0,100
Maximal length of beam element [m]	1000,000
Average size of cables, tendons, elements on subsoil, nonlinear soil spring [m]	1,000
Minimal distance between two points [m]	0.001
Average size of panel element [m]	1,000
Mesh refinement following the beam type	None
Definition of mesh element size for panels	Manual

6. Solver setup

Name	SolverSetup1
Stress from member nonlinearity data	✓
Neglect shear force deformation (Ay, Az >> A)	×
Initial stress	✓
Maximum iterations	60
Number of increments	5
Number of sections on average member	10
Coefficient for reinforcement	1
Warning when maximal translation is greater than [mm]	1000,0
Warning when maximal rotation is greater than [mrad]	100,0
Solver precision ratio	1
Type of solver	Direct
Method of calculation	Newton-Raphson

7. Nodes

Name	Coord X [m]	Coord Y [m]	Coord Z [m]
N1	-0,110	-0,120	0,000
N2	-6,160	-0,300	-2,230
N3	-12,260	-0,480	-4,310
N4	-18,400	-0,660	-6,250
N5	-24,590	-0,840	-8,060
N6	-30,810	-1,020	-9,740
N7	-37,080	-1,200	-11,230
N8	-43,390	-1,390	-12,580
N9	-49,720	-1,570	-13,790
N10	-56,090	-1,760	-14,830
N11	-62,480	-1,950	-15,710

8. Nodal supports

Name	Node	System	Type	X	Y	Z	Rx	Ry	Rz
Sn1	N1	GCS	Standard	Flexible	Flexible	Flexible	Rigid	Free	Free
Sn2	N11	GCS	Standard	Flexible	Flexible	Flexible	Free	Free	Free

9. Members

Name	CrossSection	Material	Length [m]	Beg. node	End node	Type
B1	CS1 - RECT (400; 600)	GL75	6,450	N1	N2	general (0)
B2	CS1 - RECT (400; 600)	GL75	6,447	N2	N3	general (0)
B3	CS1 - RECT (400; 600)	GL75	6,442	N3	N4	general (0)
B4	CS1 - RECT (400; 600)	GL75	6,452	N4	N5	general (0)
B5	CS1 - RECT (400; 600)	GL75	6,445	N5	N6	general (0)
B6	CS1 - RECT (400; 600)	GL75	6,447	N6	N7	general (0)
B7	CS1 - RECT (400; 600)	GL75	6,456	N7	N8	general (0)
B8	CS1 - RECT (400; 600)	GL75	6,447	N8	N9	general (0)
B9	CS1 - RECT (400; 600)	GL75	6,457	N9	N10	general (0)
B10	CS1 - RECT (400; 600)	GL75	6,453	N10	N11	general (0)

10. Beam nonlinearity

Name	Member	Type	Normal force [kN]
BN1	B1	Initial stress	539,70
BN2	B2	Initial stress	536,00
BN3	B3	Initial stress	532,40
BN4	B4	Initial stress	529,10
BN5	B5	Initial stress	526,00
BN6	B6	Initial stress	523,00
BN7	B7	Initial stress	520,40
BN8	B8	Initial stress	517,90
BN9	B9	Initial stress	515,70
BN10	B10	Initial stress	513,70

11. Line force

Name	Member	Type	Dir	Value - P_1 [kN/m]	Pos x_1	Coor	Orig	Ecc ey [m]
	Load case	System	Distribution	Value - P_2 [kN/m]	Pos x_2	Loc		Ecc ez [m]
LF1	B1	Force	Z	-10,00	0.000	Rela	From start	0,000
	LC1 - unity load	GCS	Uniform		1.000	Length		0,000
LF2	B2	Force	Z	-10,00	0.000	Rela	From start	0,000
	LC1 - unity load	GCS	Uniform		1.000	Length		0,000
LF3	B3	Force	Z	-10,00	0.000	Rela	From start	0,000
	LC1 - unity load	GCS	Uniform		1.000	Length		0,000
LF4	B4	Force	Z	-10,00	0.000	Rela	From start	0,000
	LC1 - unity load	GCS	Uniform		1.000	Length		0,000
LF5	B5	Force	Z	-10,00	0.000	Rela	From start	0,000
	LC1 - unity load	GCS	Uniform		1.000	Length		0,000
LF6	B6	Force	Z	-10,00	0.000	Rela	From start	0,000
	LC1 - unity load	GCS	Uniform		1.000	Length		0,000
LF7	B7	Force	Z	-10,00	0.000	Rela	From start	0,000
	LC1 - unity load	GCS	Uniform		1.000	Length		0,000
LF8	B8	Force	Z	-10,00	0.000	Rela	From start	0,000
	LC1 - unity load	GCS	Uniform		1.000	Length		0,000
LF9	B9	Force	Z	-10,00	0.000	Rela	From start	0,000
	LC1 - unity load	GCS	Uniform		1.000	Length		0,000
LF10	B10	Force	Z	-10,00	0.000	Rela	From start	0,000
	LC1 - unity load	GCS	Uniform		1.000	Length		0,000

C

Cross section optimisation

In this appendix are the results from the iterative cross section optimisation presented. The width and height of the different element groups are changed and the resulting average- and maximum utilisation ratios according to Eurocode 3: Steel structures provided by Karamba3D are documented. The goal is to find a set of cross sections with as much unity between similar element groups while having a maximum utilisation below 60%. Furthermore, it is wanted to have ribbons with some cross sectional area to incorporate the connections and because it is beneficial for the discussion regarding uplift forces and asymmetrical loading.

1st iteration

Element	h [mm]	b [mm]	Average	Maximum
Out curve [OutTruss]	1200.0	1400.0	15.7	35.1
In curve bottom [OutTruss]	1200.0	1400.0	16.5	32.5
In curve top [OutTruss]	1200.0	1400.0	18.7	36.8
Sloped diagonal [OutTruss]	800.0	800.0	7.0	20.6
Vertical diagonals [OutTruss]	600.0	600.0	11.3	32.6
Horizontal diagonals [OutTruss]	400.0	400.0	12.2	42.2
Stress ribbons [144x]	600.0	300.0	26.5	54.9
In curve [InTruss]	1600.0	1000.0	26.0	43.0
Out curve [InTruss]	1600.0	800.0	27.7	41.6
Diagonals [InTruss]	600.0	400.0	14.4	39.9
Weight [total] , [load area]	6.65E+06		28227.5 kN	
Maximum displacement	1736.8 mm			

2nd iteration

Element	h [mm]	b [mm]	Average	Maximum
Out curve [OutTruss]	1000.0	1200.0	26.3	54.8
In curve bottom [OutTruss]	1200.0	1000.0	23.8	49.0
In curve top [OutTruss]	1000.0	1000.0	26.5	58.1
Sloped diagonal [OutTruss]	800.0	800.0	6.7	20.4
Vertical diagonals [OutTruss]	600.0	600.0	11.0	31.1
Horizontal diagonals [OutTruss]	400.0	400.0	11.9	44.2
Stress ribbons [144x]	600.0	300.0	27.2	58.5
In curve [InTruss]	1400.0	1000.0	27.7	45.7
Out curve [InTruss]	1400.0	800.0	29.6	44.1
Diagonals [InTruss]	600.0	400.0	13.5	37.9
Weight [total] , [load area]	5.66E+06		27436.3 kN	
Maximum displacement	1729.2 mm			

3rd iteration

Element	h [mm]	b [mm]	Average	Maximum
Out curve [OutTruss]	1000.0	1200.0	24.5	48.4
In curve bottom [OutTruss]	1200.0	1000.0	23.2	48.9
In curve top [OutTruss]	1000.0	1000.0	28.3	61.2
Sloped diagonal [OutTruss]	600.0	600.0	12.6	41.3
Vertical diagonals [OutTruss]	500.0	500.0	15.4	43.6
Horizontal diagonals [OutTruss]	400.0	400.0	10.9	41.2
Stress ribbons [144x]	600.0	300.0	28.2	61.9
In curve [InTruss]	1400.0	1000.0	27.6	43.7
Out curve [InTruss]	1400.0	800.0	29.3	43.3
Diagonals [InTruss]	400.0	400.0	18.2	50.6
Weight [total] , [load area]	4.93E+06		26798.0 kN	
Maximum displacement	1692.7 mm			

4th iteration

Element	h [mm]	b [mm]	Average	Maximum
Out curve [OutTruss]	1000.0	1200.0	26.1	53.1
In curve bottom [OutTruss]	1200.0	1000.0	23.3	48.5
In curve top [OutTruss]	1000.0	1000.0	28.6	62.4
Sloped diagonal [OutTruss]	600.0	600.0	13.4	43.6
Vertical diagonals [OutTruss]	600.0	600.0	10.8	30.0
Horizontal diagonals [OutTruss]	400.0	400.0	11.5	43.4
Stress ribbons [144x]	600.0	300.0	27.5	59.1
In curve [InTruss]	1000.0	1200.0	29.7	49.0
Out curve [InTruss]	1000.0	1200.0	32.9	47.1
Diagonals [InTruss]	600.0	600.0	7.8	20.1
Weight [total] , [load area]	5.19E+06		28107.1 kN	
Maximum displacement	1802.7 mm			

5th iteration

Element	h [mm]	b [mm]	Average	Maximum
Out curve [OutTruss]	1200.0	1200.0	16.7	40.5
In curve bottom [OutTruss]	1200.0	1200.0	16.5	34.8
In curve top [OutTruss]	1200.0	1200.0	17.3	34.3
Sloped diagonal [OutTruss]	800.0	800.0	6.7	19.5
Vertical diagonals [OutTruss]	600.0	600.0	9.9	28.9
Horizontal diagonals [OutTruss]	400.0	400.0	10.9	36.1
Stress ribbons [144x]	300.0	200.0	41.6	54.7
In curve [InTruss]	1200.0	1000.0	27.3	49.0
Out curve [InTruss]	1200.0	1000.0	31.1	45.8
Diagonals [InTruss]	400.0	400.0	20.2	53.4
Weight [total] , [load area]	5.26E+06		19292.8 kN	
Maximum displacement	1925.3 mm			

6th iteration

Element	h [mm]	b [mm]	Average	Maximum
Out curve [OutTruss]	1000.0	1200.0	23.6	43.9
In curve bottom [OutTruss]	1200.0	1000.0	20.9	43.0
In curve top [OutTruss]	1000.0	1000.0	24.6	53.2
Sloped diagonal [OutTruss]	600.0	600.0	13.8	43.9
Vertical diagonals [OutTruss]	600.0	600.0	9.7	28.0
Horizontal diagonals [OutTruss]	400.0	400.0	10.9	39.2
Stress ribbons [144x]	300.0	200.0	42.8	59.9
In curve [InTruss]	1000.0	1200.0	27.4	49.1
Out curve [InTruss]	1000.0	1200.0	31.3	45.3
Diagonals [InTruss]	600.0	600.0	8.1	20.5
Weight [total] , [load area]	4.38E+06		20888.5 kN	
Maximum displacement	2155.0 mm			

7th iteration

Element	h [mm]	b [mm]	Average	Maximum
Out curve [OutTruss]	1000.0	1200.0	22.7	46.1
In curve bottom [OutTruss]	1200.0	1000.0	21.6	45.5
In curve top [OutTruss]	1200.0	1200.0	24.7	48.0
Sloped diagonal [OutTruss]	600.0	600.0	13.1	43.6
Vertical diagonals [OutTruss]	600.0	600.0	11.0	30.1
Horizontal diagonals [OutTruss]	400.0	400.0	10.7	39.6
Stress ribbons [144x]	600.0	400.0	25.3	58.0
In curve [InTruss]	1200.0	1200.0	28.1	42.8
Out curve [InTruss]	1200.0	1200.0	31.0	44.7
Diagonals [InTruss]	400.0	400.0	17.9	47.0
Weight [total] , [load area]	5.76e+06 kg		31171.2 kN	
Maximum displacement	1661.5 mm			

D

Calculations Structural Design

		Characteristics			
k_{mod}	=	short	0.9		
k_{def}	=	short	0.8		
k_h	=	min{ (600/h)^0,1 ; 1,1 }	1.0	assume h>600 mm	
γ_M	=		1.25		
$k_{h,m}$	=	min{ (600/h)^0,1 ; 1,1 }	1.0	assume h>600 mm	
k_m	=		0.7	rectangular c.s.	
$f_{m,g,k}$	=		75	N/mm^2	
$f_{t,0,g,k}$	=		60	N/mm^2	
$f_{t,90,g,k}$	=		0.6	N/mm^2	
$f_{c,0,g,k}$	=		49.5	N/mm^2	
$f_{c,90,g,k}$	=		12.3	N/mm^2	
$f_{v,g,k}$	=		4.5	N/mm^2	
$E_{0,g,mean}$	=		16800	N/mm^2	
$E_{0,g,05}$	=		15300	N/mm^2	
$E_{90,g,mean}$	=		470	N/mm^2	
$G_{g,mean}$	=		850	N/mm^2	
$\rho_{g,k}$	=		730	kg/m^3	
$\rho_{g,mean}$	=		800	kg/m^3	
$f_{c,0,d}$	=	$k_{mod} \times f_{c,0,k} / \gamma_m$	35.64	N/mm^2	
$f_{t,0,d}$	=	$k_h \times k_{mod} \times f_{t,0,k} / \gamma_m$	43.20	N/mm^2	$k_h = 1$
$f_{m,o,d}$	=	$k_{h,m} \times k_{mod} \times f_{m,0,k} / \Upsilon_m$	54.00	N/mm^2	$k_{h,m} = 1$
$f_{v,0,d}$	=	$k_{mod} \times f_{v,0,k} / \Upsilon_m$	3.24	N/mm^2	
$E_{0,d}$	=	$(E_{0,mean} / (1 + \Psi_2 \times k_{def})) / \Upsilon_m$	13440	N/mm^2	
$E_{0,05}$	=		15300	N/mm^2	
$G_{0,05}$	=		850	N/mm^2	

ULS strength verification checks

Load combination: Selfweight + Secondary structure + Architectural finishing + Downward wind (short term)
Unity check for: Bending, tension, compression. Shear, torsion, stability
It is assumed that the roof can be categorised into Consequence Class (CC) 3:

Resistance	R_d	=	$k_{mod} \times R_k / \gamma_M$	
Tension parallel to the grain	$\sigma_{t,0,d}$	≤	$f_{t,0,d}$	
Compression parallel to the grain	$\sigma_{c,0,d}$	≤	$f_{c,0,d}$	
Bending	$(\sigma_{m,y,d} / f_{m,y,d}) + k_m \times (\sigma_{m,z,d} / f_{m,z,d})$			≤ 1
	$(\sigma_{m,z,d} / f_{m,z,d}) + k_m \times (\sigma_{m,y,d} / f_{m,y,d})$			≤ 1
shear	τ_d	≤	$f_{v,d}$	
Combined bending and axial tension	$(\sigma_{t,0,d} / f_{t,0,d}) + k_m \times (\sigma_{m,y,d} / f_{m,y,d}) + (\sigma_{m,z,d} / f_{m,z,d})$			≤ 1
	$(\sigma_{t,0,d} / f_{t,0,d}) + (\sigma_{m,y,d} / f_{m,y,d}) + k_m \times (\sigma_{m,z,d} / f_{m,z,d})$			≤ 1
combined bending and axial compression	$(\sigma_{c,0,d} / f_{c,0,d})^2 + k_m \times (\sigma_{m,y,d} / f_{m,y,d}) + (\sigma_{m,z,d} / f_{m,z,d})$			≤ 1
	$(\sigma_{c,0,d} / f_{c,0,d})^2 + (\sigma_{m,y,d} / f_{m,y,d}) + k_m \times (\sigma_{m,z,d} / f_{m,z,d})$			≤ 1
Biaxial shear	$(\tau_{y,d}/f_{v,d})^2 + (\tau_{z,d}/f_{v,d})^2$			≤ 1
Torsion	$\tau_{tor,d}/ (k_{shape} * f_{v,d})$			≤ 1
Torsion + Biaxial shear	$\tau_{tor,d}/ (k_{shape} * f_{v,d}) + (\tau_{y,d}/f_{v,d})^2 + (\tau_{z,d}/f_{v,d})^2$			≤ 1

$A = h*b$

$I_y = 1/12*b*h^3$

$I_z = 1/12*h*b^3$

$I_t = 1/3*h*b^3*(1-0.63*b/h)$

$S_y = h * (½ b)^2$

$S_z = b * (½ h)^2$

$W_y = 1/6\, h*b^2$

$W_z = 1/6\, b*h^2$

$W_t = \alpha*h*b^2$

$\alpha =$ depend on h/b

$k_{shape} = \min\{2.0 ; 1+0.15*h/b\}$

<u>Compression + Bending</u>

$\sigma_C = N_C / A$

$\sigma_{Mz} = M_z / W_y$

$\sigma_{My} = M_y / W_z$

<u>Tension + Bending</u>

$\sigma_T = N_T / A$

$\sigma_{Mz} = M_z / W_y$

$\sigma_{My} = M_y / W_z$

<u>Shear</u>

$\tau_{z,d} = V_{d,z}*S_z / (b*I_y)$

$\tau_{y,d} = V_{d,y}*S_y / (h*I_z)$

<u>Torsion</u>

$\tau_{tor} = M_t / W_t$

<u>Stability</u>

$l_{eff} =$ length of element * 1.0 (Truss elements)

$i_z = \sqrt{(I_z / A)}$

$\lambda_z = l_{eff} / i_z$

$\lambda_{rel,z} = \lambda_z / \pi * \sqrt{(f_{c,0,k} / E_{0,05})}$

$k = 0.5*(1+\beta_c*(\lambda_{rel,z}-0.3)+\lambda_{rel,z}^2)$

$k_c = 1/(k+\sqrt{(k^2 - \lambda_{rel,z}^2)})$

$\sigma_{m,crit} = \pi/(W_y*l_{ef})*\sqrt{(E_{0,05}*I_z*G_{0,05}*I_t)}$

$\lambda_{rel} = \sqrt{(f_{m,k}/\sigma_{m,crit})}$

$$k_{crit} = \begin{cases} 1, & \text{for } \lambda_{rel} \le 0.75 \\ 1.56 - 0.75*\lambda_{rel}, & \text{for } 0.75 \ge \lambda_{rel} \le 1.4 \\ 1 / \lambda_{rel}^2, & \text{for } 1.4 \le \lambda_{rel} \end{cases}$$

$U.C. = (\sigma_{m,d} / (k_{crit}*f_{m,d}))^2 + \sigma_{c,0,d}/(k_c*f_{c,0,d}) \le 1.0$

D.1 Maximum force combinations

Forces are taken at the start-, mid-, and end point of the modelled elements. Therefore, similar element labels can have different force combinations.

All forces are in kN or kNm

Outer Truss			Max N (trek)	Max N (druk	Max M	Max My	Max Mz	Max Mt	Max V					
elements forces														
Out Curve		id	{79}	{118}	{64}	{64}	{65}	{64}	{64}	A [mm^2]	1.20E+06		**Max U.C.**	{id}
h * b [mm]		length		5810 mm						I_y [mm^4]	1.00E+11			
1000	N	Trek	2384.58							I_z [mm^4]	1.44E+11	Bending + tension	0.09	{79}
1200		Druk		-19357.74	-3458.47		-2191.58	-3456.47		I_t [mm^4]	1.41E+11	Bending + compression	0.33	{118}
	M	z-as	467.56	218.04	1549.14		1549.14	65.60		S_y [mm^3]	3.60E+08	Stability	0.47	{118}
		y-as	172.80	1230.50	2448.77		2448.77	1197.69		S_z m[m^3]	3.00E+08			
		t	36.53	1.61	100.53		100.53	100.53		W_y [mm^3]	2.40E+08			
	V	z-as	24.92	280.46	407.81		503.20	452.33		W_z [mm^3]	2.00E+08	Torsion + biaxial shear	0.39	{64}
		y-as	189.99	127.49	553.79		333.82	556.87		W_t [mm^3]	3.12E+08			
In Curve bottom		id	{55}	{94}	{163}	{46}	{65}	{72}	{88}	A [mm^2]	1.20E+06			
h * b [mm]		length					5150 mm			I_y [mm^4]	1.44E+11			
1200	N	Trek	773.52							I_z [mm^4]	1.00E+11	Bending + tension	0.07	{55}
1000		Druk		-15260.58	-13559.36	-10055.34	-13085.77	-12253.19	-13437.98	I_t [mm^4]	1.90E+11	Bending + compression	0.32	{65}
	M	z-as	221.83	2.21	2391.94	865.55	1454.95	1924.60	953.07	S_y [mm^3]	3.00E+08	Stability	0.32	{65}
		y-as	557.41	1855.41	380.31	1942.00	1714.15	541.59	1612.37	S_z m[m^3]	3.60E+08			
		t	5.06	9.69	1.92	5.68	64.72	91.39	36.77	W_y [mm^3]	2.00E+08			
	V	z-as	10.33	434.81	2.79	458.07	412.89	460.88	422.87	W_z [mm^3]	2.40E+08	Torsion + biaxial shear	1.09	{88}
		y-as	16.43	33.05	1112.04	82.79	150.23	878.31	1258.52	W_t [mm^3]	2.60E+08			
In Curve Top		id		{81}	{87}	{5}	{10}	{286}	{223}	A [mm^2]	1.44E+06			
h * b [mm]		length			5150 mm					I_y [mm^4]	1.73E+11			
1200	N	Trek								I_z [mm^4]	1.73E+11	Bending + tension	0.00	
1200		Druk		-27180.81	-19760.14	-25731.14	-25304.10	-14043.55	-26933.27	I_t [mm^4]	2.56E+11	Bending + compression	0.41	{81}
	M	z-as		1250.24	2054.54	1283.20	1333.66	41.57	1622.64	S_y [mm^3]	4.32E+08	Stability	0.53	{81}
		y-as		1188.24	424.49	1231.24	1227.89	652.9	3.81	S_z m[m^3]	4.32E+08			
		t		5.11	1.16	8.23	0.80	73.74	4.73	W_y [mm^3]	2.88E+08			
	V	z-as		167.56	268.97	176.71	147.40	85.36	286.27	W_z [mm^3]	2.88E+08	Torsion + biaxial shear	0.16	{223}
		y-as		547.67	545.27	533.57	516.37	376.36	554.66	W_t [mm^3]	3.59E+08			
Sloped diagonal			{69}	{47}	{47}	{47}			{47}	A [mm^2]	3.60E+05			
h x b [mm]		length		9380 mm						I_y [mm^4]	1.08E+10			
600	N	Trek	5779.79							I_z [mm^4]	1.08E+10	Bending + tension	0.39	{69}
600		Druk		-4691.77					-4684.82	I_t [mm^4]	1.60E+10	Bending + compression	0.16	{47}
	M	z-as	0.00	0.00					0.00	S_y [mm^3]	5.40E+07	Stability	0.47	{47}
		y-as	26.63	44.30					0.00	S_z m[m^3]	5.40E+07			
		t	0.00	0.00					0.00	W_y [mm^3]	3.60E+07			
	V	z-as	0.00	0.00					18.08	W_z [mm^3]	3.60E+07	Torsion + biaxial shear	0.00	{47}
		y-as	0.02	0.02					0.04	W_t [mm^3]	4.49E+07			
Vertical diagonal			{176}	{32}	{32}	{32}			{32}	A [mm^2]	3.60E+05			
h x b [mm]		length		4760 mm						I_y [mm^4]	1.08E+10			
600	N	Trek	4107.82							I_z [mm^4]	1.08E+10	Bending + tension	0.27	{176}
600		Druk		-5350.35					-5343.41	I_t [mm^4]	1.60E+10	Bending + compression	0.18	{32}
	M	z-as	0.00	0.00					0.00	S_y [mm^3]	5.40E+07	Stability	0.43	{32}
		y-as	5.03	5.73					0.00	S_z m[m^3]	5.40E+07			
		t	0.00	0.00					0.00	W_y [mm^3]	3.60E+07			
	V	z-as	0.01	0.00					4.74	W_z [mm^3]	3.60E+07	Torsion + biaxial shear	0.00	{32}
		y-as	0.02	0.03					0.05	W_t [mm^3]	4.49E+07			
Horizontal diagonal			{27}	{44}	{44}	{44}			{44}	A [mm^2]	1.60E+05			
h x b [mm]		length		7980 mm						I_y [mm^4]	2.13E+09			
400	N	Trek	19.50							I_z [mm^4]	2.13E+09	Bending + tension	0.02	{27}
400		Druk		-1345.50					-1345.49	I_t [mm^4]	3.16E+09	Bending + compression	0.08	{44}
	M	z-as	0.00	0.00					0.00	S_y [mm^3]	1.60E+07	Stability	0.42	{44}
		y-as	12.29	16.35					0.00	S_z m[m^3]	1.60E+07			
		t	0.00	0.00					0.00	W_y [mm^3]	1.07E+07			
	V	z-as	0.00	0.00					7.77	W_z [mm^3]	1.07E+07	Torsion + biaxial shear	0.00	{44}
		y-as	0.00	0.00					0.00	W_t [mm^3]	1.33E+07			

Inner Truss

elements		forces	Max N (trek)	Max N (druk)	Max M	Max My	Max Mz	Max Mt	Max V					
In Curve		id	{127}	None	{141}	{67}	{141}	{100}	{117}	A [mm2]	1.44E+06		**Max U.C.**	{id}
h x b [mm]		length	2410 mm							Iy [mm4]	1.73E+11			
1200	N	Trek	24948.64		10162.07	13695.16		13455.90	16608.00	Iz [mm4]	1.73E+11	Bending + tension	**0.54**	{127}
1200		Druk								It [mm4]	2.56E+11	Bending	**0.18**	{141}
	M	z-as	1673.15		2126.76	1710.21		221.16	1361.26	Sy [mm3]	4.32E+08	Stability	**0**	{141}
		y-as	758.33		962.88	1224.07		28.86	1047.74	Sz m[m3]	4.32E+08			
		t	12.23		79.95	50.21		153.74	65.51	Wy [mm3]	2.88E+08			
	V	z-as	23.64		112.70	79.67		119.82	74.79	Wz [mm3]	2.88E+08	Torsion + biaxial shear	**0.16**	{117}
		y-as	23.02		52.36	486.27		272.26	507.05	Wt [mm3]	3.59E+08			
Out Curve		id	{0}	none	{142}	{21}	{142}	{103}	{140}	A [mm2]	1.44E+06			
h x b [mm]		length		2220 mm						Iy [mm4]	1.73E+11			
1200	N	Trek	22224.68		21829.68	8053.72		17117.60	19883.67	Iz [mm4]	1.73E+11	Bending + tension	**0.56**	{0}
1200		Druk								It [mm4]	2.56E+11	Bending	**0.21**	{142}
	M	z-as	2555.65		2746.55	1606.67		1560.16	2147.91	Sy [mm3]	4.32E+08	Stability	**0.03**	{142}
		y-as	582.31		714.72	1642.83		72.49	944.34	Sz m[m3]	4.32E+08			
		t	107.10		30.52	33.29		329.82	71.50	Wy [mm3]	2.88E+08			
	V	z-as	34.45		70.86	19.73		102.18	14.68	Wz [mm3]	2.88E+08	Torsion + biaxial shear	**0.25**	{103}
		y-as	140.15		78.89	6.78		62.31	517.17	Wt [mm3]	3.59E+08			
Diagonals		id	{284}	{139}	{140}	{140}			{262}	A [mm2]	1.60E+05			
h x b [mm]		length		4700 mm						Iy [mm4]	2.13E+09			
400	N	Trek	3165.04							Iz [mm4]	2.13E+09	Bending + tension	**0.44**	{284}
400		Druk		-3112.23	-2995.66				-2964.90	It [mm4]	3.16E+09	Bending + compression	**0.31**	{139}
	M	z-as	0.00	0.00	0.00				0.00	Sy [mm3]	1.60E+07	Stability	**0.59**	{139}
		y-as	2.20	4.70	4.92				0.00	Sz m[m3]	1.60E+07			
		t	0.00	0.00	0.00				0.00	Wy [mm3]	1.07E+07			
	V	z-as	1.06	0.51	0.50				4.73	Wz [mm3]	1.07E+07	Torsion + biaxial shear	**0.00**	{262}
		y-as	0.19	0.10	0.10				0.18	Wt [mm3]	1.33E+07			

Ribbons

elements		forces	Max N (trek)	Max N (druk)	Max M	Max My	Max Mz	Max Mt	Max V					
		id	{380}	None	{1303}	{25}	{1334}	{1330}	{1300}	A [mm2]	2.40E+05		**Max U.C.**	{id}
Tendons		length								Iy [mm4]	7.20E+09			
h x b [mm]	N	Trek	2291.78		498.38	2092.81	553.51	644.86	577.83	Iz [mm4]	3.20E+09	Bending + tension	**0.65**	{380}
600		Druk								It [mm4]	7.42E+09	Bending	**0.60**	{1303}
400	M	z-as	0.50		4.53	2.42	5.41	0.00	0.00	Sy [mm3]	2.40E+07	Stability	**0.36**	{1303}
		y-as	11.75		778.02	142.01	701.07	0.00	0.00	Sz m[m3]	3.60E+07			
		t	0.39		0.59	0.23	0.60	1.11	0.89	Wy [mm3]	1.60E+07			
	V	z-as	0.03		16.24	17.86	3.42	59.44	65.27	Wz [mm3]	2.40E+07	Torsion + biaxial shear	**0.07**	{1300}
		y-as	0.22		0.14	0.23	0.11	0.75	0.67	Wt [mm3]	2.22E+07			

D.2 Strength verifications

D.2.1 Outer truss ring

	Out Curve			In curve bottom			In curve top		
h =	1000	mm		1200	mm		1200	mm	
b =	1200	mm		1000	mm		1200	mm	
A =	1.20E+06	mm^2		1.20E+06	mm^2		1.44E+06	mm^2	
I_y =	1.00E+11	mm^4		1.44E+11	mm^4		1.73E+11	mm^4	
I_z =	1.44E+11	mm^4		1.00E+11	mm^4		1.73E+11	mm^4	
I_t =	1.41E+11	mm^4		1.90E+11	mm^4		2.56E+11	mm^4	
S_y =	3.60E+08	mm^3		3.00E+08	mm^3		4.32E+08	mm^3	
S_z =	3.00E+08	mm^3		3.60E+08	mm^3		4.32E+08	mm^3	
W_y =	2.40E+08	mm^3		2.00E+08	mm^3		2.88E+08	mm^3	
W_z =	2.00E+08	mm^3		2.40E+08	mm^3		2.88E+08	mm^3	
W_t =	3.12E+08	mm^3		2.60E+08	mm^3		3.59E+08	mm^3	
α =	0.217			0.217			0.208		
k_h =	1.00			1.00			1.00		
$k_{h,m}$ =	1.00			1.00			1.00		
Compression + Bending									
N_C =	19357.74	kN		13085.77	kN		27180.81	kN	
M_z =	218.0	kNm		1454.95	kNm		1250.2	kNm	
M_y =	1230.5	kNm		1714.15	kNm		1188.2	kNm	
σ_C =	16.1	N/mm^2		10.9	N/mm^2		18.9	N/mm^2	
σ_{Mz} =	0.91	N/mm^2	0.91	7.27	N/mm^2	7.14	4.34	N/mm^2	4.13
σ_{My} =	6.15	N/mm^2	6.15	7.14	N/mm^2	7.27	4.13	N/mm^2	4.34
$f_{c,0,d}$ =	35.64	N/mm^2		35.64	N/mm^2		35.64	N/mm^2	
$f_{m,o,d}$ =	54.00	N/mm^2		54.00	N/mm^2		54.00	N/mm^2	
U.C.	0.33	OK		0.32	OK		0.41	OK	
Tension + Bending									
N_T =	2385	kN		774	kN			kN	
M_z =	467.6	kNm		221.8	kNm			kNm	
M_y =	172.8	kNm		557.4	kNm			kNm	
σ_T =	2.0	N/mm^2		0.6	N/mm^2		0.0	N/mm^2	
σ_{Mz} =	1.95	N/mm^2	0.86	1.11	N/mm^2	1.11	0.00	N/mm^2	0.00
σ_{My} =	0.86	N/mm^2	1.95	2.32	N/mm^2	2.32	0.00	N/mm^2	0.00
$f_{t,0,d}$ =	43.20	N/mm^2		43.20	N/mm^2		43.20	N/mm^2	
$f_{m,o,d}$ =	54.00	N/mm^2		54.00	N/mm^2		54.00	N/mm^2	
U.C.	0.09	OK		0.07	OK		0.00	OK	

Stability	Mz	My	
$\sigma_{m,d}$ =	0.91	6.15	
$\sigma_{c,0,d}$ =	16.1	16.1	
β_c =	0.1	0.1	
l_{eff} =	5810	5810	
i_z =	288.68	346.41	
λ_z =	20.13	16.77	
$\lambda_{rel,z}$ =	0.36440	0.30366	
k =	0.56961	0.54629	
k_c =	0.99264	0.99960	
$\sigma_{m,crit}$ =	1155.8596	1155.8596	
λ_{rel} =	0.25473	0.25473	
k_{crit} =	1		
$f_{m,0,d}$ =	54.00	N/mm^2	
$f_{c,0,d}$ =	35.64	N/mm^2	
U.C.	**0.47**	OK	
Shear			
$V_{d,z}$ =	452.3	**kN**	
$V_{d,y}$ =	556.9	**kN**	
$\tau_{z,d}$ =	1.13	**N/mm^2**	
$\tau_{y,d}$ =	1.39	**N/mm^2**	
$f_{v,0,d}$ =	3.24	N/mm^2	
U.C.	**0.31**	OK	
Torsion			
M_t =	100.53		
k_{shape} =	1.18		
τ_{tor} =	0.32	**N/mm^2**	
$f_{v,0,d}$ =	3.24	N/mm^2	
U.C.	**0.08**	OK	
Torsion + Shear			
U.C.	**0.39**	OK	

Stability	Mz	My	
$\sigma_{m,d}$ =	7.27	7.14	
$\sigma_{c,0,d}$ =	10.9	10.9	
β_c =	0.1	0.1	
l_{eff} =	5150	5150	
i_z =	346.41	288.68	
λ_z =	14.87	17.84	
$\lambda_{rel,z}$ =	0.26917	0.32300	
k =	0.53468	0.55332	
k_c =	1.00334	0.99744	
$\sigma_{m,crit}$ =	1516.159	1516.159	
λ_{rel} =	0.22241	0.22241	
k_{crit} =	1		
$f_{m,0,d}$ =	54.00	N/mm^2	
$f_{c,0,d}$ =	35.64	N/mm^2	
U.C.	**0.32**	OK	
Shear			
$V_{d,z}$ =	422.9	**kN**	
$V_{d,y}$ =	1258.5	**kN**	
$\tau_{z,d}$ =	1.06	**N/mm^2**	
$\tau_{y,d}$ =	3.15	**N/mm^2**	
$f_{v,0,d}$ =	3.24	N/mm^2	
U.C.	**1.05**	NIET OK	
Torsion			
M_t =	36.77		
k_{shape} =	1.18		
τ_{tor} =	0.14	**N/mm^2**	
$f_{v,0,d}$ =	3.24	N/mm^2	
U.C.	**0.04**	OK	
Torsion + Shear			
U.C.	**1.09**	NIET OK	

Stability	Mz	My	
$\sigma_{m,d}$ =	4.34	4.13	
$\sigma_{c,0,d}$ =	18.9	18.9	
β_c =	0.1	0.1	
l_{eff} =	5150	5150	
i_z =	346.41	346.41	
λ_z =	14.87	14.87	
$\lambda_{rel,z}$ =	0.26917	0.26917	
k =	0.53468	0.53468	
k_c =	1.00334	1.00334	
$\sigma_{m,crit}$ =	1605.757	1605.757	
λ_{rel} =	0.21612	0.21612	
k_{crit} =	1		
$f_{m,0,d}$ =	54.00	N/mm^2	
$f_{c,0,d}$ =	35.64	N/mm^2	
U.C.	**0.53**	OK	
Shear			
$V_{d,z}$ =	286.3	**kN**	
$V_{d,y}$ =	554.7	**kN**	
$\tau_{z,d}$ =	0.60	**N/mm^2**	
$\tau_{y,d}$ =	1.16	**N/mm^2**	
$f_{v,0,d}$ =	3.24	N/mm^2	
U.C.	**0.16**	OK	
Torsion			
M_t =	4.73		
k_{shape} =	1.15		
τ_{tor} =	0.01	**N/mm^2**	
$f_{v,0,d}$ =	3.24	N/mm^2	
U.C.	**0.00**	OK	
Torsion + Shear			
U.C.	**0.16**	OK	

Sloped diagonal				Vertical diagonal				Horizontal diagonal			
h =	600	mm		h =	600	mm		h =	400	mm	
b =	600	mm		b =	600	mm		b =	400	mm	
A =	3.60E+05	mm^2		A =	3.60E+05	mm^2		A =	1.60E+05	mm^2	
I_y =	1.08E+10	mm^4		I_y =	1.08E+10	mm^4		I_y =	2.13E+09	mm^4	
I_z =	1.08E+10	mm^4		I_z =	1.08E+10	mm^4		I_z =	2.13E+09	mm^4	
I_t =	1.60E+10	mm^4		I_t =	1.60E+10	mm^4		I_t =	3.16E+09	mm^4	
S_y =	5.40E+07	mm^3		S_y =	5.40E+07	mm^3		S_y =	1.60E+07	mm^3	
S_z =	5.40E+07	mm^3		S_z =	5.40E+07	mm^3		S_z =	1.60E+07	mm^3	
W_y =	3.60E+07	mm^3		W_y =	3.60E+07	mm^3		W_y =	1.07E+07	mm^3	
W_z =	3.60E+07	mm^3		W_z =	3.60E+07	mm^3		W_z =	1.07E+07	mm^3	
W_t =	4.49E+07	mm^3		W_t =	4.49E+07	mm^3		W_t =	1.33E+07	mm^3	
α =	0.208			α =	0.208			α =	0.208		
k_h =	1.00			k_h =	1.00			k_h =	1.04		
$k_{h,m}$ =	1.00			$k_{h,m}$ =	1.00			$k_{h,m}$ =	1.04		
Compression + Bending				Compression + Bending				Compression + Bending			
N_C =	4691.77	**kN**		N_C =	5350.35	**kN**		N_C =	1345.5	**kN**	
M_z =	0.0	**kNm**		M_z =	0.0	**kNm**		M_z =	0.0	**kNm**	
M_y =	44.3	**kNm**		M_y =	5.7	**kNm**		M_y =	16.4	**kNm**	
σ_C =	**13.0**	**N/mm^2**		σ_C =	**14.9**	**N/mm^2**		σ_C =	**8.4**	**N/mm^2**	
σ_{Mz} =	**0.00**	**N/mm^2**	0.00	σ_{Mz} =	**0.00**	**N/mm^2**	0.00	σ_{Mz} =	**0.00**	**N/mm^2**	0.00
σ_{My} =	**1.23**	**N/mm^2**	1.23	σ_{My} =	**0.16**	**N/mm^2**	0.16	σ_{My} =	**1.53**	**N/mm^2**	1.53
$f_{c,0,d}$ =	35.64	N/mm^2		$f_{c,0,d}$ =	35.64	N/mm^2		$f_{c,0,d}$ =	35.64	N/mm^2	
$f_{m,o,d}$ =	54.00	N/mm^2		$f_{m,o,d}$ =	54.00	N/mm^2		$f_{m,o,d}$ =	56.16	N/mm^2	
U.C.	**0.16**	OK		**U.C.**	**0.18**	OK		**U.C.**	**0.08**	OK	
Tension + Bending				Tension + Bending				Tension + Bending			
N_T =	**5780**	**kN**		N_T =	**4108**	**kN**		N_T =	**20**	**kN**	
M_z =	0.0	**kNm**		M_z =	0.0	**kNm**		M_z =	0.0	**kNm**	
M_y =	26.6	**kNm**		M_y =	5.0	**kNm**		M_y =	12.3	**kNm**	
σ_T =	**16.1**	**N/mm^2**		σ_T =	**11.4**	**N/mm^2**		σ_T =	**0.1**	**N/mm^2**	
σ_{Mz} =	**0.00**	**N/mm^2**	0.00	σ_{Mz} =	**0.00**	**N/mm^2**	0.00	σ_{Mz} =	**0.00**	**N/mm^2**	0.00
σ_{My} =	**0.74**	**N/mm^2**	0.74	σ_{My} =	**0.14**	**N/mm^2**	0.14	σ_{My} =	**1.15**	**N/mm^2**	1.15
$f_{t,0,d}$ =	43.20	N/mm^2		$f_{t,0,d}$ =	43.20	N/mm^2		$f_{t,0,d}$ =	44.93	N/mm^2	
$f_{m,o,d}$ =	54.00	N/mm^2		$f_{m,o,d}$ =	54.00	N/mm^2		$f_{m,o,d}$ =	56.16	N/mm^2	
U.C.	**0.39**	OK		**U.C.**	**0.27**	OK		**U.C.**	**0.02**	OK	

Stability	Mz	My
$\sigma_{m,d}$ =	0.00	1.23
$\sigma_{c,0,d}$ =	13.0	13.0
β_c =	0.1	0.1
l_{eff} =	9380	9380
i_z =	173.21	173.21
λ_z =	54.16	54.16
$\lambda_{rel,z}$ =	0.98050	0.98050
k =	1.01472	1.01472
k_c =	0.78370	0.78370
$\sigma_{m,crit}$ =	440.8129	440.8129
λ_{rel} =	0.41248	0.41248
k_{crit} =	1	
$f_{m,0,d}$ =	54.00	N/mm^2
$f_{c,0,d}$ =	35.64	N/mm^2
U.C.	**0.47**	OK

Shear		
$V_{d,z}$ =	18.1	**kN**
$V_{d,y}$ =	0.0	**kN**
$\tau_{z,d}$ =	0.15	**N/mm^2**
$\tau_{y,d}$ =	0.00	**N/mm^2**
$f_{v,0,d}$ =	3.24	N/mm^2
U.C.	**0.00**	OK

Torsion		
M_t =	0	
k_{shape} =	1.15	
τ_{tor} =	0.00	**N/mm^2**
$f_{v,0,d}$ =	3.24	N/mm^2
U.C.	**0.00**	OK

Torsion + Shear		
U.C.	**0.00**	OK

Stability	Mz	My
$\sigma_{m,d}$ =	0.00	0.16
$\sigma_{c,0,d}$ =	14.9	14.9
β_c =	0.1	0.1
l_{eff} =	4760	4760
i_z =	173.21	173.21
λ_z =	27.48	27.48
$\lambda_{rel,z}$ =	0.49757	0.49757
k =	0.63367	0.63367
k_c =	0.97462	0.97462
$\sigma_{m,crit}$ =	868.6608	868.6608
λ_{rel} =	0.29384	0.29384
k_{crit} =	1	
$f_{m,0,d}$ =	54.00	N/mm^2
$f_{c,0,d}$ =	35.64	N/mm^2
U.C.	**0.43**	OK

Shear		
$V_{d,z}$ =	4.7	**kN**
$V_{d,y}$ =	0.1	**kN**
$\tau_{z,d}$ =	0.04	**N/mm^2**
$\tau_{y,d}$ =	0.00	**N/mm^2**
$f_{v,0,d}$ =	3.24	N/mm^2
U.C.	**0.00**	OK

Torsion		
M_t =	0	
k_{shape} =	1.15	
τ_{tor} =	0.00	**N/mm^2**
$f_{v,0,d}$ =	3.24	N/mm^2
U.C.	**0.00**	OK

Torsion + Shear		
U.C.	**0.00**	OK

Stability	Mz	My
$\sigma_{m,d}$ =	0.00	1.53
$\sigma_{c,0,d}$ =	8.4	8.4
β_c =	0.1	0.1
l_{eff} =	7980	7980
i_z =	115.47	115.47
λ_z =	69.11	69.11
$\lambda_{rel,z}$ =	1.25124	1.25124
k =	1.33036	1.33036
k_c =	0.56107	0.56107
$\sigma_{m,crit}$ =	345.4324	345.4324
λ_{rel} =	0.46596	0.46596
k_{crit} =	1	
$f_{m,0,d}$ =	56.16	N/mm^2
$f_{c,0,d}$ =	35.64	N/mm^2
U.C.	**0.42**	OK

Shear		
$V_{d,z}$ =	7.8	**kN**
$V_{d,y}$ =	0.0	**kN**
$\tau_{z,d}$ =	0.15	**N/mm^2**
$\tau_{y,d}$ =	0.00	**N/mm^2**
$f_{v,0,d}$ =	3.24	N/mm^2
U.C.	**0.00**	OK

Torsion		
M_t =	0	
k_{shape} =	1.15	
τ_{tor} =	0.00	**N/mm^2**
$f_{v,0,d}$ =	3.24	N/mm^2
U.C.	**0.00**	OK

Torsion + Shear		
U.C.	**0.00**	OK

D.2.2 Inner truss ring

Inner truss

In curve			
h =	1200	mm	
b =	1200	mm	
A =	1.44E+06	mm^2	
I_y =	1.73E+11	mm^4	
I_z =	1.73E+11	mm^4	
I_t =	2.56E+11	mm^4	
S_y =	4.32E+08	mm^3	
S_z =	4.32E+08	mm^3	
W_y =	2.88E+08	mm^3	
W_z =	2.88E+08	mm^3	
W_t =	3.59E+08	mm^3	
α =	0.208		
k_h =	1.00		
$k_{h,m}$ =	1.00		
Compression + Bending			
N_C =	0	kN	
M_z =	2126.8	kNm	
M_y =	962.9	kNm	
σ_C =	0.0	N/mm^2	
σ_{Mz} =	7.38	N/mm^2	3.34
σ_{My} =	3.34	N/mm^2	7.38
$f_{c,0,d}$ =	35.64	N/mm^2	
$f_{m,o,d}$ =	54.00	N/mm^2	
U.C.	0.18	OK	
Tension + Bending			
N_T =	24949	kN	
M_z =	1673.2	kNm	
M_y =	758.3	kNm	
σ_T =	17.3	N/mm^2	
σ_{Mz} =	5.81	N/mm^2	2.63
σ_{My} =	2.63	N/mm^2	5.81
$f_{t,0,d}$ =	43.20	N/mm^2	
$f_{m,o,d}$ =	54.00	N/mm^2	
U.C.	0.54	OK	

Out curve			
h =	1200	mm	
b =	1200	mm	
A =	1.44E+06	mm^2	
I_y =	1.73E+11	mm^4	
I_z =	1.73E+11	mm^4	
I_t =	2.56E+11	mm^4	
S_y =	4.32E+08	mm^3	
S_z =	4.32E+08	mm^3	
W_y =	2.88E+08	mm^3	
W_z =	2.88E+08	mm^3	
W_t =	3.59E+08	mm^3	
α =	0.208		
k_h =	1.00		
$k_{h,m}$ =	1.00		
Compression + Bending			
N_C =		kN	
M_z =	2746.6	kNm	
M_y =	714.7	kNm	
σ_C =	0.0	N/mm^2	
σ_{Mz} =	9.54	N/mm^2	2.48
σ_{My} =	2.48	N/mm^2	9.54
$f_{c,0,d}$ =	35.64	N/mm^2	
$f_{m,o,d}$ =	54.00	N/mm^2	
U.C.	0.21	OK	
Tension + Bending			
N_T =	21830	kN	
M_z =	2746.6	kNm	
M_y =	714.7	kNm	
σ_T =	15.2	N/mm^2	
σ_{Mz} =	9.54	N/mm^2	2.48
σ_{My} =	2.48	N/mm^2	9.54
$f_{t,0,d}$ =	43.20	N/mm^2	
$f_{m,o,d}$ =	54.00	N/mm^2	
U.C.	0.56	OK	

Diagonals			
h =	400	mm	
b =	400	mm	
A =	1.60E+05	mm^2	
I_y =	2.13E+09	mm^4	
I_z =	2.13E+09	mm^4	
I_t =	3.16E+09	mm^4	
S_y =	1.60E+07	mm^3	
S_z =	1.60E+07	mm^3	
W_y =	1.07E+07	mm^3	
W_z =	1.07E+07	mm^3	
W_t =	1.33E+07	mm^3	
α =	0.208		
k_h =	1.04		
$k_{h,m}$ =	1.04		
Compression + Bending			
N_C =	3112.23	kN	
M_z =	0.0	kNm	
M_y =	4.7	kNm	
σ_C =	19.5	N/mm^2	
σ_{Mz} =	0.00	N/mm^2	0.00
σ_{My} =	0.44	N/mm^2	0.44
$f_{c,0,d}$ =	35.64	N/mm^2	
$f_{m,o,d}$ =	56.16	N/mm^2	
U.C.	0.31	OK	
Tension + Bending			
N_T =	3165	kN	
M_z =	0.0	kNm	
M_y =	2.2	kNm	
σ_T =	19.8	N/mm^2	
σ_{Mz} =	0.00	N/mm^2	0.00
σ_{My} =	0.21	N/mm^2	0.21
$f_{t,0,d}$ =	44.93	N/mm^2	
$f_{m,o,d}$ =	56.16	N/mm^2	
U.C.	0.44	OK	

Stability	Mz	My
$\sigma_{m,d}$ =	7.38	3.34
$\sigma_{c,0,d}$ =	0.0	0.0
β_c =	0.1	0.1
l_{eff} =	2410	2410
i_z =	346.41	346.41
λ_z =	6.96	6.96
$\lambda_{rel,z}$ =	0.12596	0.12596
k =	0.49923	0.49923
k_c =	1.01801	1.01801
$\sigma_{m,crit}$ =	3431.39	3431.39
λ_{rel} =	0.14784	0.14784
k_{crit} =	1	
$f_{m,o,d}$ =	54.00	N/mm²
$f_{c,0,d}$ =	35.64	N/mm²
U.C.	**0.02**	OK
Shear		
$V_{d,z}$ =	74.8	**kN**
$V_{d,y}$ =	507.1	**kN**
$\tau_{z,d}$ =	0.16	**N/mm²**
$\tau_{y,d}$ =	1.06	**N/mm²**
$f_{v,0,d}$ =	3.24	N/mm²
U.C.	**0.11**	OK
Torsion		
M_t =	65.51	
k_{shape} =	1.15	
τ_{tor} =	0.18	**N/mm²**
$f_{v,0,d}$ =	3.24	N/mm²
U.C.	**0.05**	OK
Torsion + Shear		
U.C.	**0.16**	OK

Stability	Mz	My
$\sigma_{m,d}$ =	9.54	2.48
$\sigma_{c,0,d}$ =	0.0	0.0
β_c =	0.1	0.1
l_{eff} =	2220	2220
i_z =	346.41	346.41
λ_z =	6.41	6.41
$\lambda_{rel,z}$ =	0.11603	0.11603
k =	0.49753	0.49753
k_c =	1.01901	1.01901
$\sigma_{m,crit}$ =	3725.068	3725.068
λ_{rel} =	0.14189	0.14189
k_{crit} =	1	
$f_{m,o,d}$ =	54.00	N/mm²
$f_{c,0,d}$ =	35.64	N/mm²
U.C.	**0.03**	OK
Shear		
$V_{d,z}$ =	102.2	**kN**
$V_{d,y}$ =	62.3	**kN**
$\tau_{z,d}$ =	0.21	**N/mm²**
$\tau_{y,d}$ =	0.13	**N/mm²**
$f_{v,0,d}$ =	3.24	N/mm²
U.C.	**0.01**	OK
Torsion		
M_t =	329.82	
k_{shape} =	1.15	
τ_{tor} =	0.92	**N/mm²**
$f_{v,0,d}$ =	3.24	N/mm²
U.C.	**0.25**	OK
Torsion + Shear		
U.C.	**0.25**	OK

Stability	Mz	My
$\sigma_{m,d}$ =	0.00	0.44
$\sigma_{c,0,d}$ =	19.5	19.5
β_c =	0.1	0.1
l_{eff} =	4700	4700
i_z =	115.47	115.47
λ_z =	40.70	40.70
$\lambda_{rel,z}$ =	0.73695	0.73695
k =	0.79339	0.79339
k_c =	0.91971	0.91971
$\sigma_{m,crit}$ =	586.5	586.5
λ_{rel} =	0.35760	0.35760
k_{crit} =	1	
$f_{m,o,d}$ =	56.16	N/mm²
$f_{c,0,d}$ =	35.64	N/mm²
U.C.	**0.59**	OK
Shear		
$V_{d,z}$ =	4.7	**kN**
$V_{d,y}$ =	0.2	**kN**
$\tau_{z,d}$ =	0.09	**N/mm²**
$\tau_{y,d}$ =	0.00	**N/mm²**
$f_{v,0,d}$ =	3.24	N/mm²
U.C.	**0.00**	OK
Torsion		
M_t =	0	
k_{shape} =	1.15	
τ_{tor} =	0.00	**N/mm²**
$f_{v,0,d}$ =	3.24	N/mm²
U.C.	**0.00**	OK
Torsion + Shear		
U.C.	**0.00**	OK

D.2.3 Stress ribbons

Ribbons			
Stress ribbons			
h =	600	mm	
b =	400	mm	
A =	2.40E+05	mm^2	
I_y =	7.20E+09	mm^4	
I_z =	3.20E+09	mm^4	
I_t =	7.42E+09	mm^4	
S_y =	2.40E+07	mm^3	
S_z =	3.60E+07	mm^3	
W_y =	1.60E+07	mm^3	
W_z =	2.40E+07	mm^3	
W_t =	2.22E+07	mm^3	
α =	0.231		
k_h =	1.00		
$k_{h,m}$ =	1.00		
Compression + Bending			
N_C =	0	kN	
M_z =	4.5	kNm	
M_y =	778.0	kNm	
σ_C =	0.0	N/mm^2	
σ_{Mz} =	0.28	N/mm^2	0.28
σ_{My} =	32.42	N/mm^2	32.42
$f_{c,0,d}$ =	35.64	N/mm^2	
$f_{m,o,d}$ =	54.00	N/mm^2	
U.C.	0.60	OK	
Tension + Bending			
N_T =	498	kN	
M_z =	4.5	kNm	
M_y =	778.0	kNm	
σ_T =	2.1	N/mm^2	
σ_{Mz} =	0.28	N/mm^2	0.28
σ_{My} =	32.42	N/mm^2	32.42
$f_{t,0,d}$ =	43.20	N/mm^2	
$f_{m,o,d}$ =	54.00	N/mm^2	
U.C.	0.65	OK	

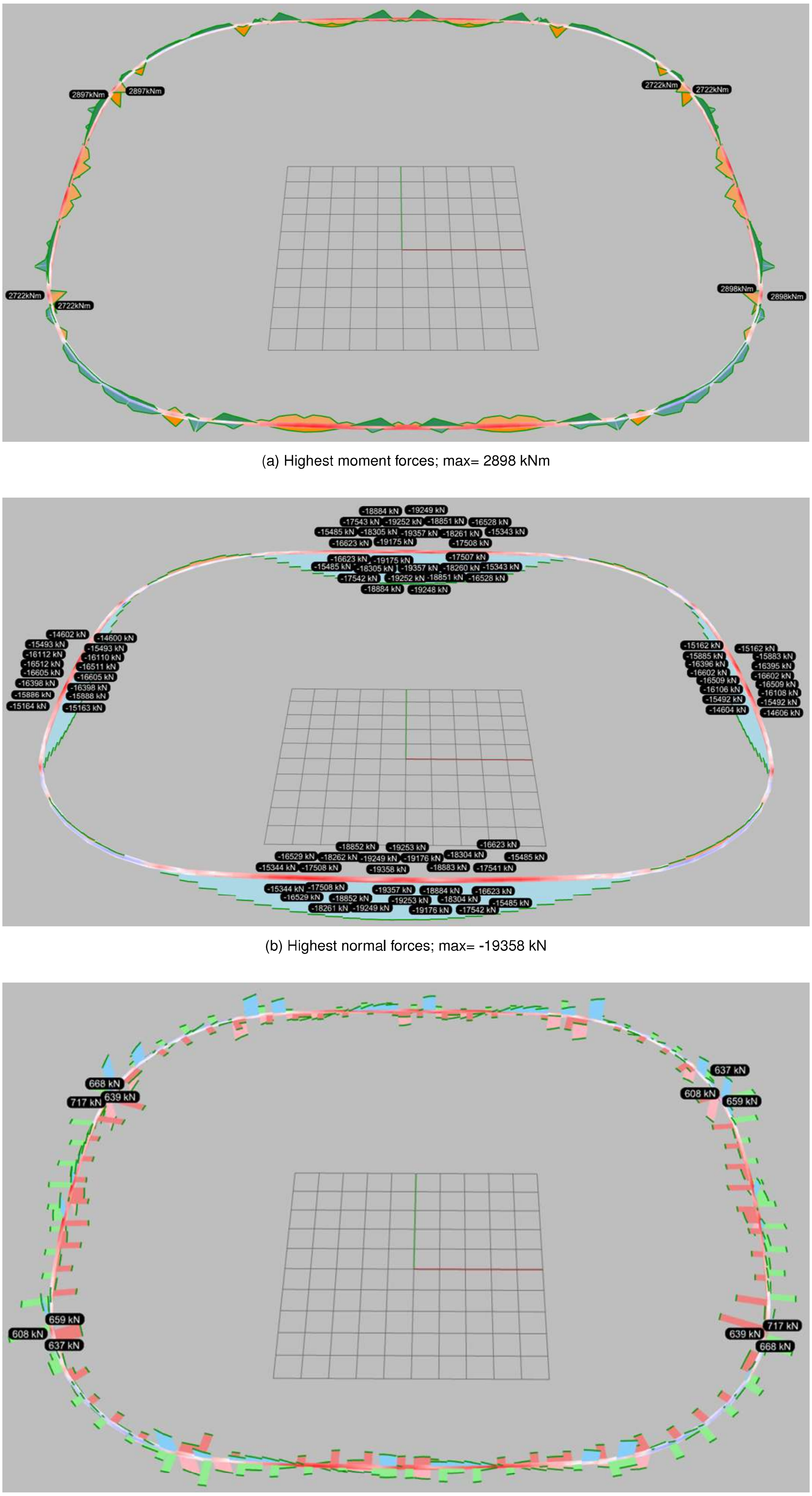
Stability	Mz	My
$\sigma_{m,d}$ =	0.28	32.42
$\sigma_{c,0,d}$ =	0.0	0.0
β_c =	0.1	0.1
l_{eff} =	2500	2500
i_z =	173.21	115.47
λ_z =	14.43	21.65
$\lambda_{rel,z}$ =	0.26133	0.39199
k =	0.53221	0.58143
k_c =	1.00417	0.98927
$\sigma_{m,crit}$ =	1380.508	1380.508
λ_{rel} =	0.23308	0.23308
k_{crit} =	1	
$f_{m,o,d}$ =	54.00	N/mm^2
$f_{c,0,d}$ =	35.64	N/mm^2
U.C.	0.36	OK
Shear		
$V_{d,z}$ =	65.3	kN
$V_{d,y}$ =	0.7	kN
$\tau_{z,d}$ =	0.82	N/mm^2
$\tau_{y,d}$ =	0.01	N/mm^2
$f_{v,0,d}$ =	3.24	N/mm^2
U.C.	0.06	OK
Torsion		
M_t =	0.89	
k_{shape} =	1.23	
τ_{tor} =	0.04	N/mm^2
$f_{v,0,d}$ =	3.24	N/mm^2
U.C.	0.01	OK
Torsion + Shear		
U.C.	0.07	OK

E

FEM Results

The 25% top values of the resulting internal forces are visually presented at their occurring locations with accompanying value. This will be done per element group for normal force (N), shear force (V), and moment (M). As mentioned, the rings consists of 288 elements per element group and as many resulting values are calculated by the FEM program. The ribbons consists of 1440 elements in total and as many resulting values are calculated by the FEM program. The figures shown below can hence be interpreted on the amount of resulting values are presented near their occurring location in the element group for the 25% top values. Many values means that the calculated unity checks can be seen as normative for the entire element group. Few values means that the maximum unity check is only valid for localised effects. This insight will help answering the main research question and pinpoint the optimisation options for a next design phase.

Outer curve [OutTruss]



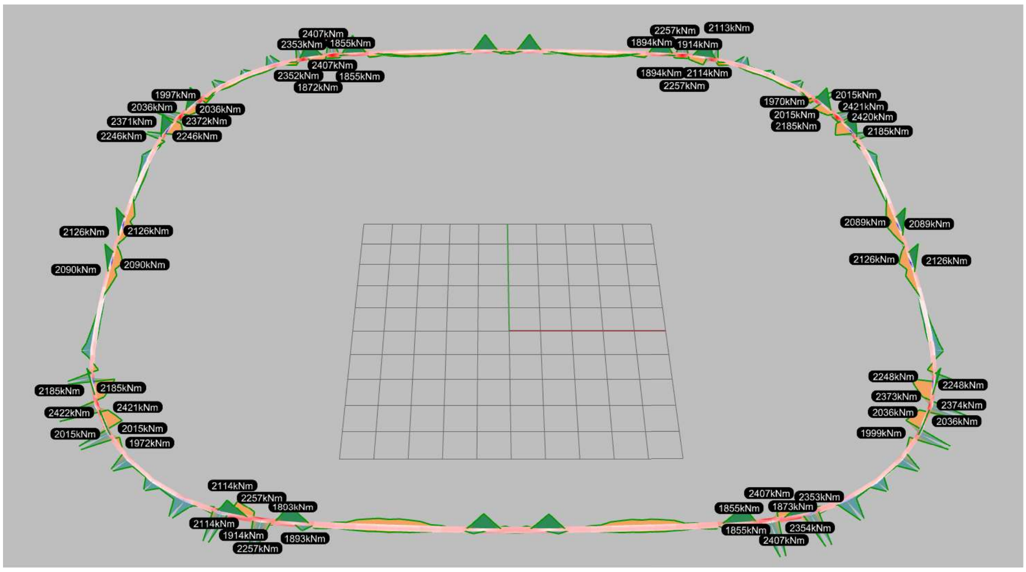
(a) Highest moment forces; max= 2898 kNm

(b) Highest normal forces; max= -19358 kN

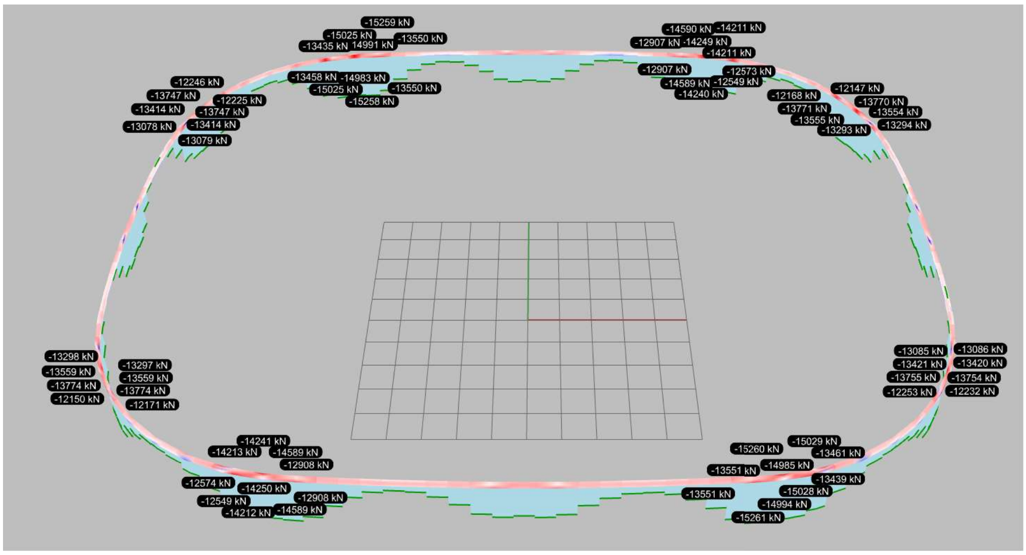
(c) Highest shear forces; max= 717 kN

Figure E.1: 25% upper values in the element group Out curve [OutTruss]

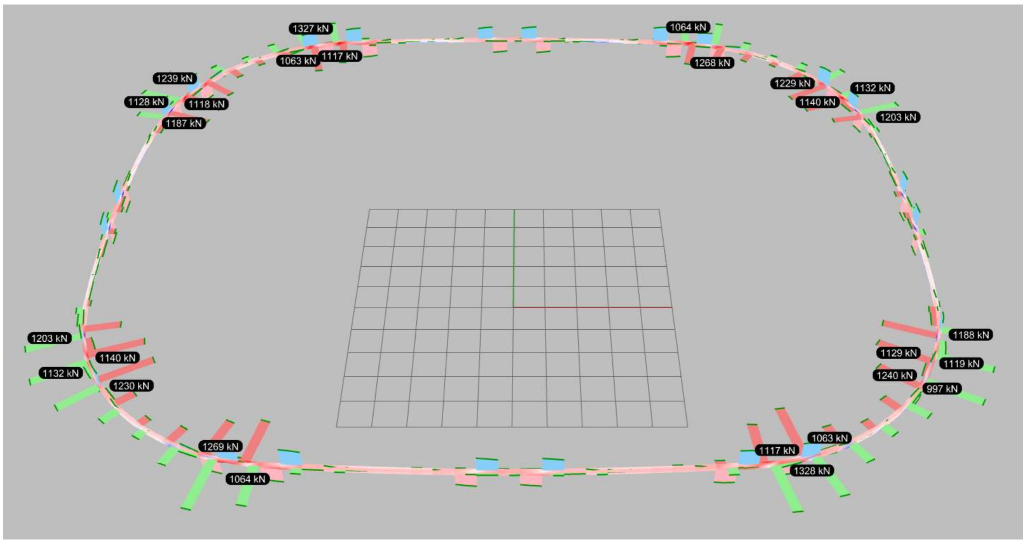
Inner curve bottom [OutTruss]



(a) Highest moment forces; max= 2422 kNm



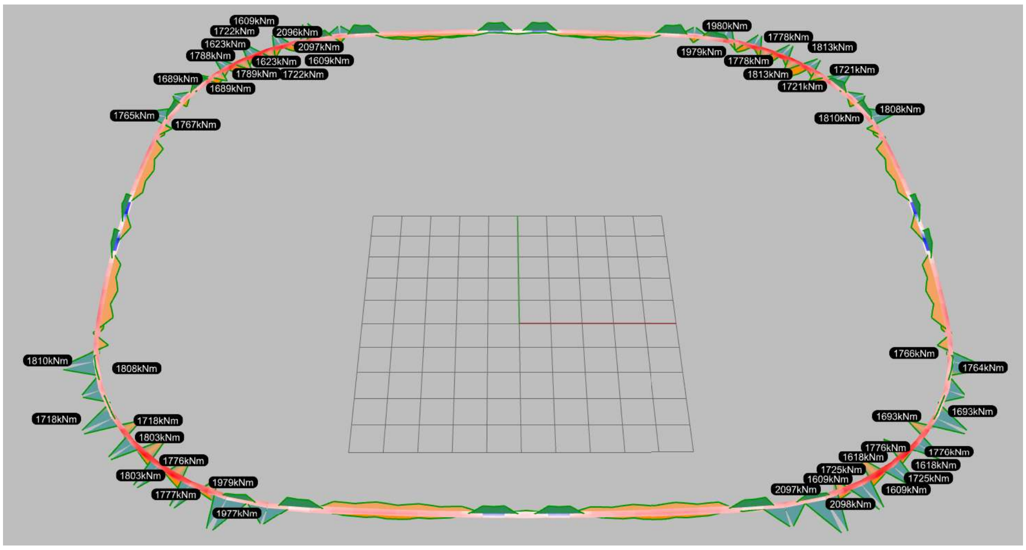
(b) Highest normal forces; max= -15261 kN



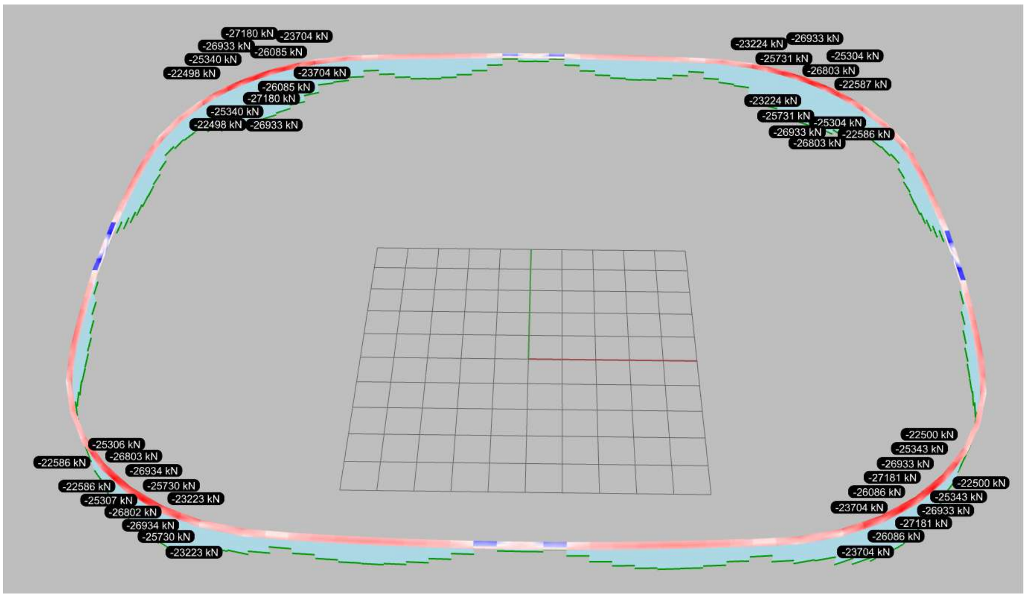
(c) Highest shear forces; max= 1328 kN

Figure E.2: 25% upper values in the element group In curve bottom [OutTruss]

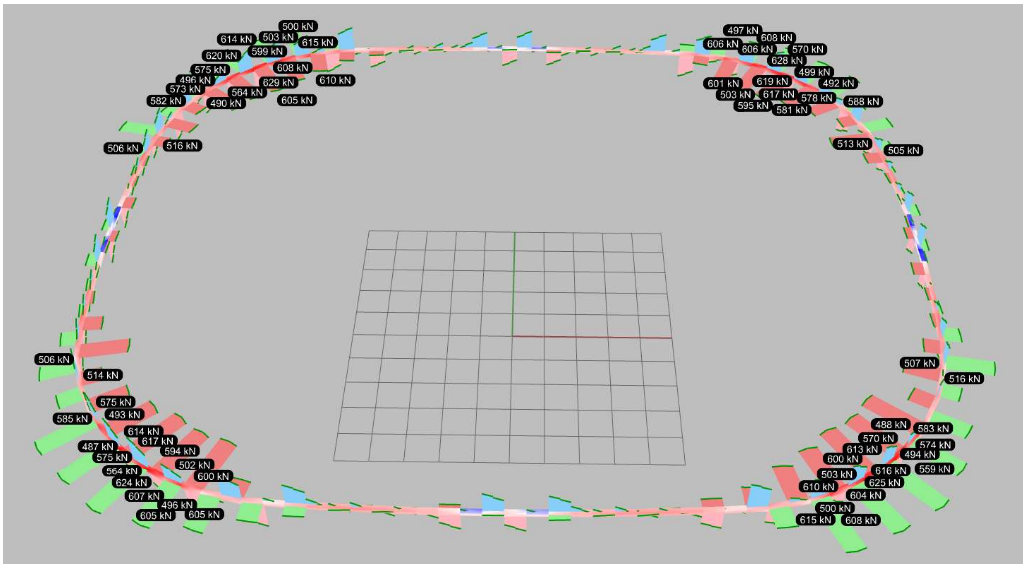
Inner curve top [OutTruss]



(a) Highest moment forces; max= 2098 kNm



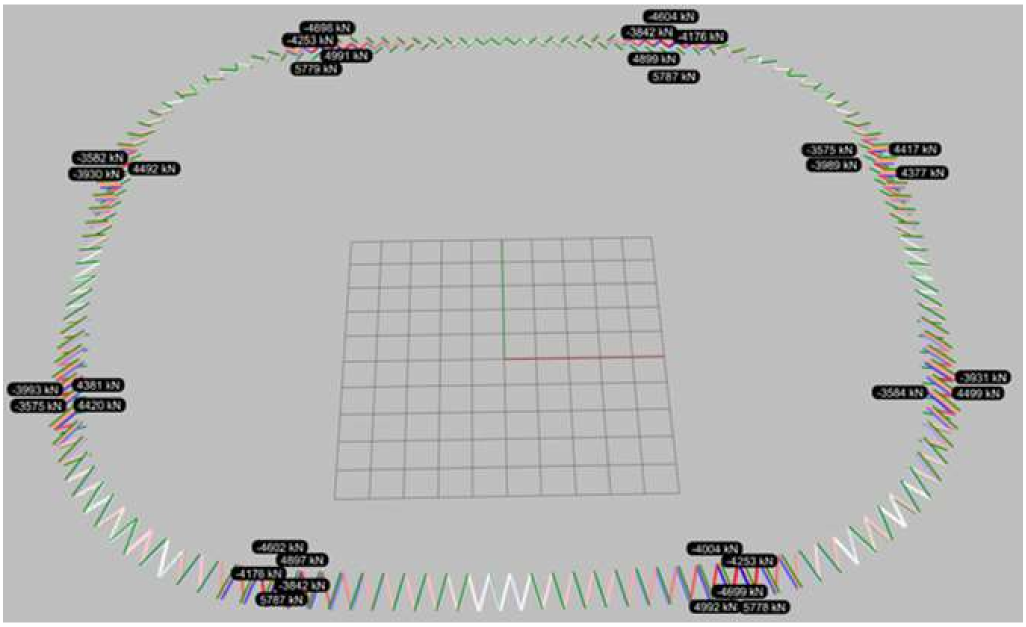
(b) Highest normal forces; max= -27181 kN



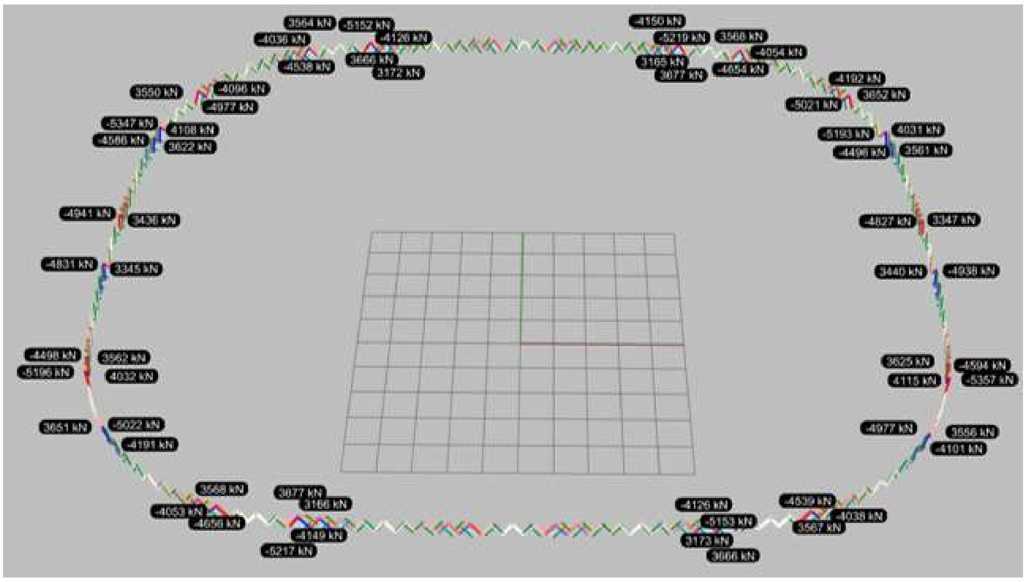
(c) Highest shear forces; max= 629 kN

Figure E.3: 25% upper values in the element group In curve top [OutTruss]

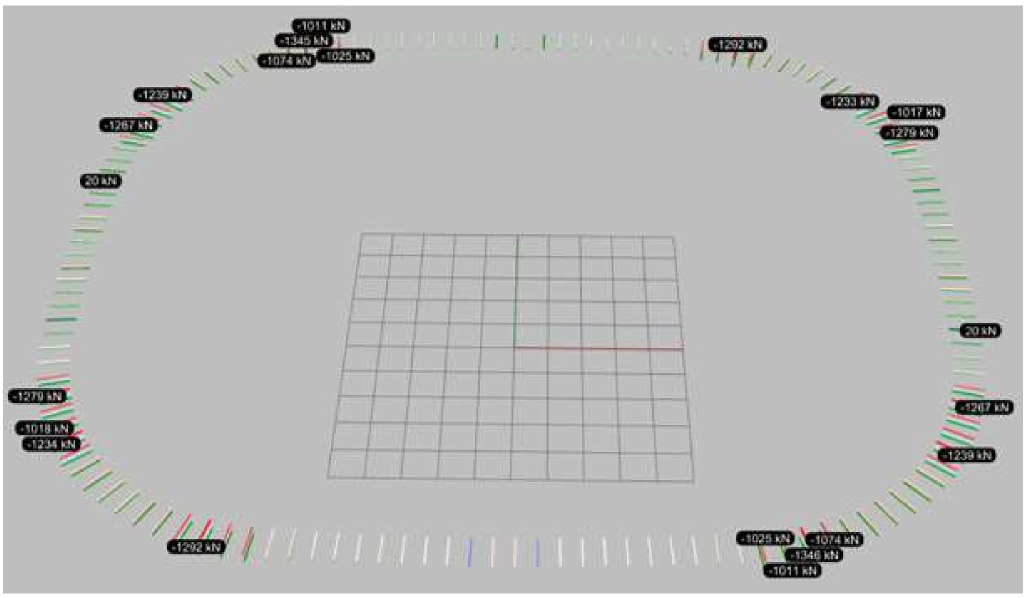
Diagonals [OutTruss]



(a) Highest normal forces in the sloped diagonals; max= -4699 kN, and 5787 kN



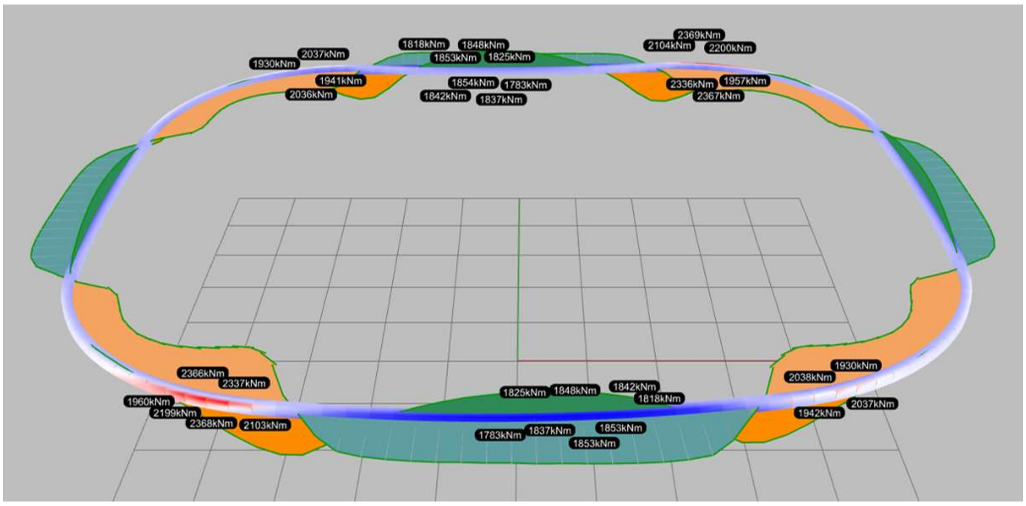
(b) Highest normal forces in the vertical diagonals; max= -5347 kN, and 4115 kN



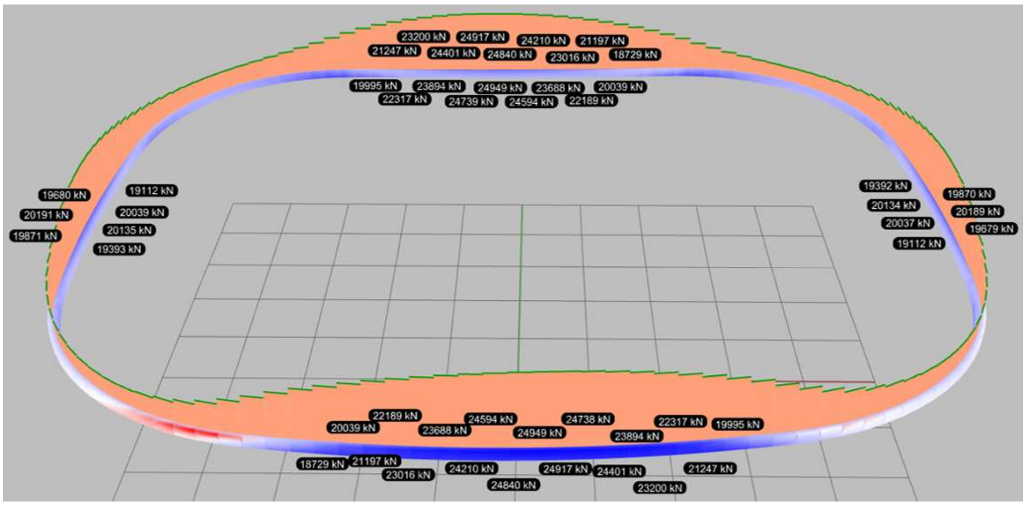
(c) Highest normal forces; max= -1346 kN

Figure E.4: 25% upper values in the element groups Sloped diagonal, Vertical diagonal, and Horizontal diagonal [OutTruss]

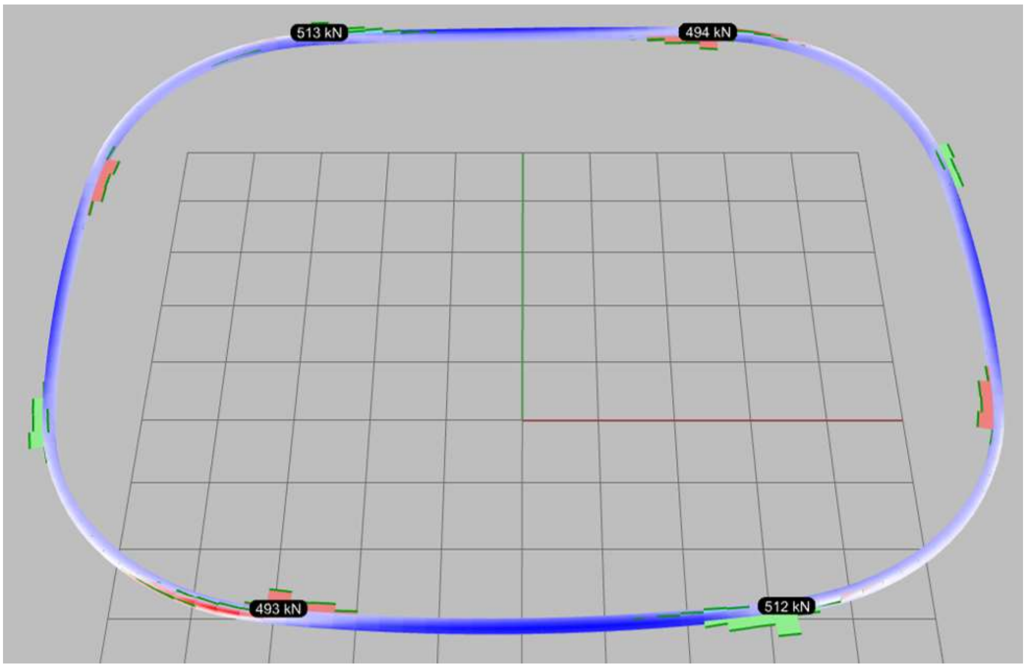
Inner curve [InTruss]



(a) Highest moment forces; max= 2369 kNm



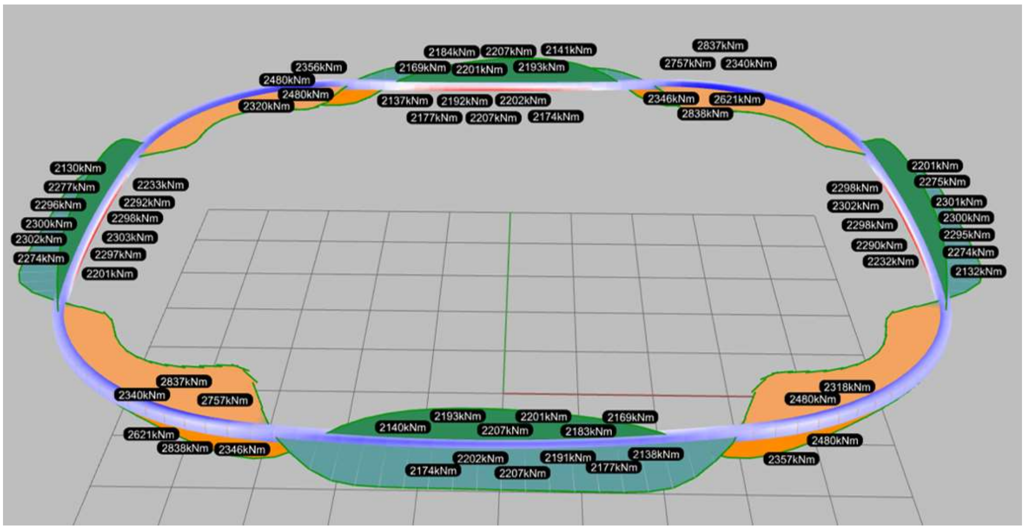
(b) Highest normal forces; max= 24949 kN



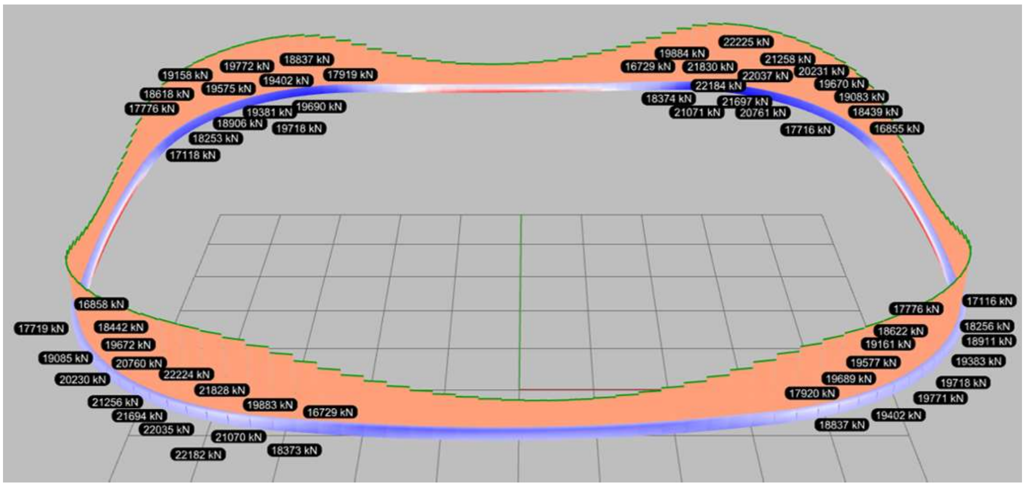
(c) Highest shear forces; max= 513 kN

Figure E.5: 25% upper values in the element group In curve [InTruss]

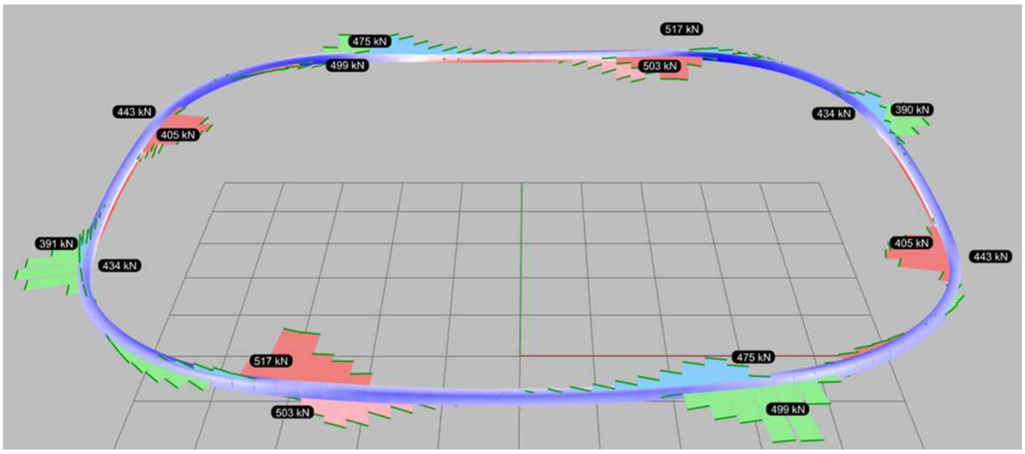
Outer curve [InTruss]



(a) Highest moment forces; max= 2838 kNm



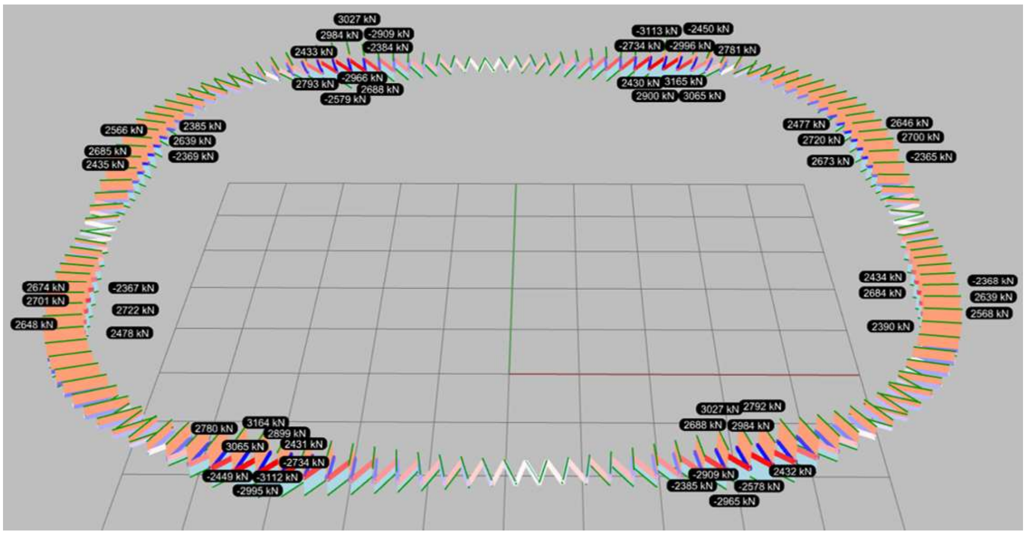
(b) Highest normal forces; max= 22224 kN



(c) Highest shear forces; max= 517 kN

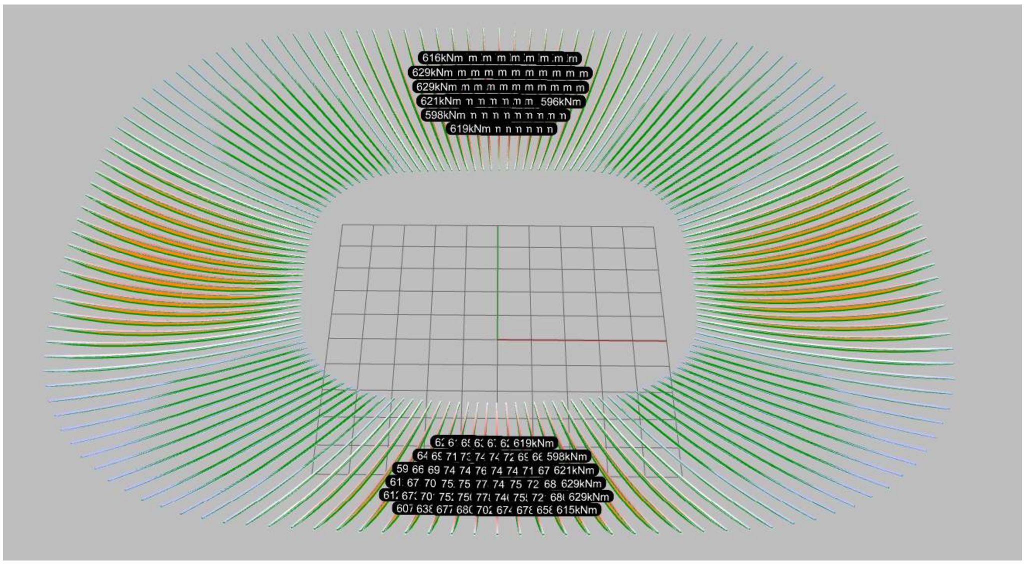
Figure E.6: 25% upper values in the element group Out curve [InTruss]

Diagonals [InTruss]

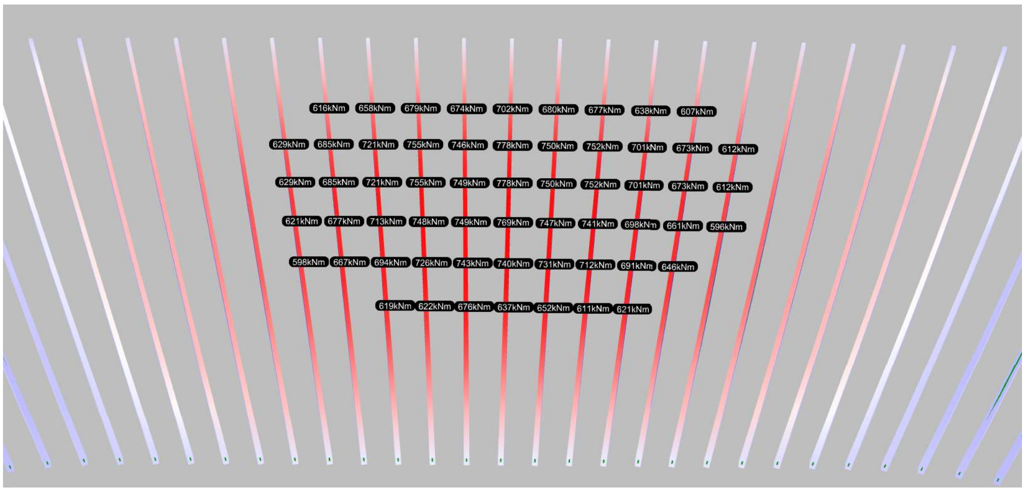


(a) Highest normal forces; max= -3113 kN, and 3165 kN

Stress Ribbons

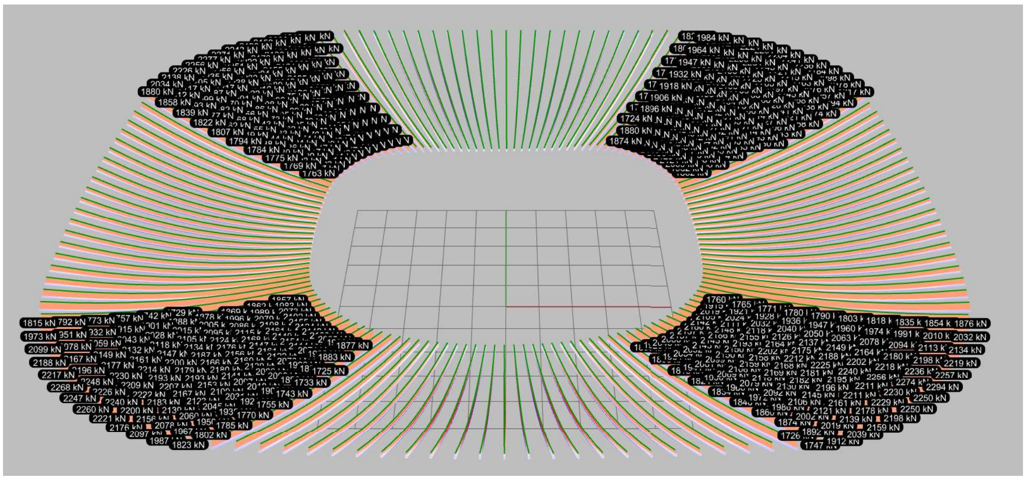


(a) Highest moment forces

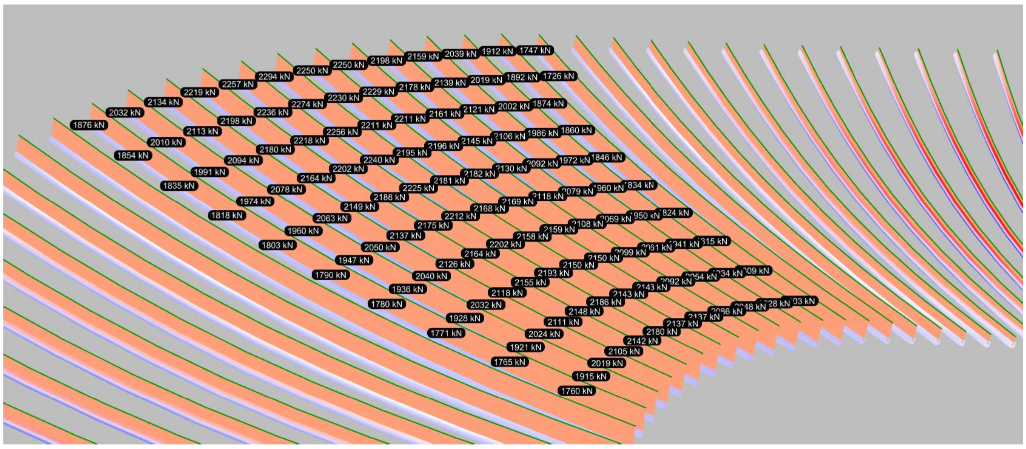


(b) max moment = 778 kNm

Figure E.8: 25% upper values in the element group Stress ribbons - Moment forces

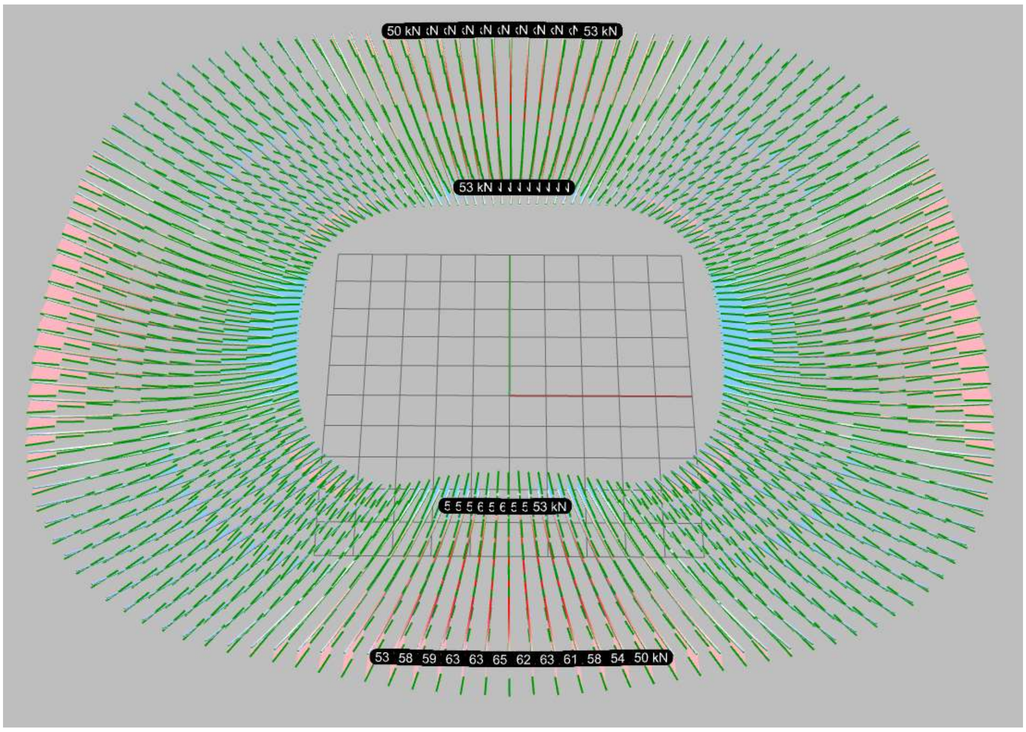


(a) Highest Normal forces

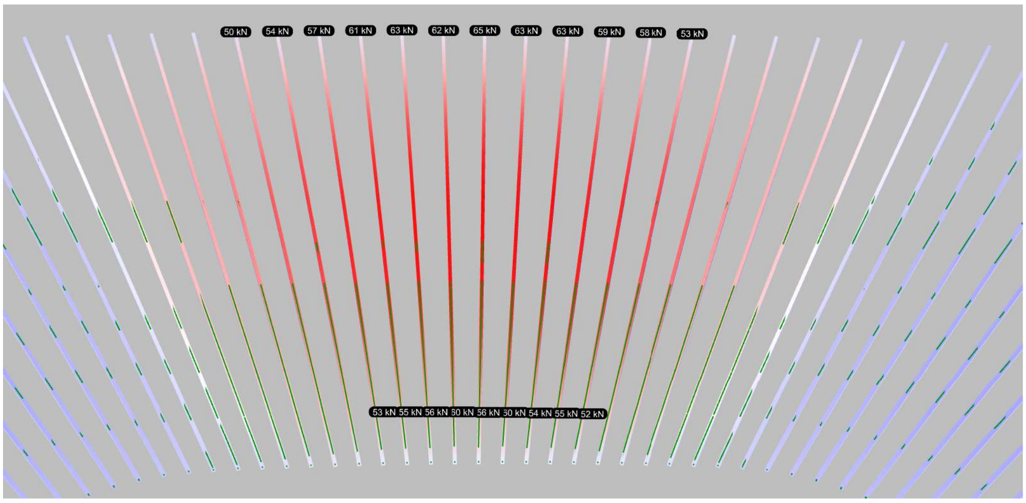


(b) max normal force = 2294 kN

Figure E.9: 25% upper values in the element group Stress ribbons - Normal forces



(a) Highest shear forces



(b) max shear force = 65 kN

Figure E.10: 25% upper values in the element group Stress ribbons - Shear forces

F

Connection calculations

Connection: Out Truss - Ribbon and Ribbon - In Truss				
Dimensions				
Out Truss		h =	1200	mm
		b =	1200	mm
Stress ribbon		h =	600	mm
		b =	400	mm
		α =	15	°
Screws	SFS Intec			
Glued-in rods	GSA			
Maximum loaded ribbon				
Design tension force		Nt,d =	2295	kN
Design shear force		Vd =	7	kN
Check load carrying capacity screws connection				
Steel plate to In curve top [Outer truss]				
Screw - WR-T-13 of carbon steel				
Nominal diameter of screw		d_1 =	13	mm
Nominal diameter of head		d_h =	22	mm
length of screw		l =	400	mm
effective length of screw		l_{ef} =	380	mm
density of timber		ρ_k=	590	kg/m^3
number of screws		n =		
thickness steel plate		t =	10	mm
thickness loaded timber in shear		t_1 =	lef	mm
k_{def} permanent for service class 2		k_{def} =	0.8	
k_{mod} short-term for service class 2		k_{mod} =	0.9	
		γ_{M1} =	1.25	
		γ_{M2} =	1.3	
characteristic yield moment		$M_{y,k}$	84600	Nmm
characteristic head pull-through capacity		$f_{head,k}$ =	13.00	N/mm^2
characteristic tensile strength fastener		$f_{u,k}$ =	600	N/mm^2
Withdrawal parameter		$f_{ax,k,90}$ =	12.9	N/mm^2
Tensile load-carrying capacity		$f_{tens,k}$ =	58.4	kN

Check capacity screws		
Check:		
Withdrawal resistance of screw		
Pull-through resistance of a screw		
Tensile load-carrying capacity		
Group effect		
Axially loaded screws		
Characteristic withdrawal capacity per screw		
$F_{ax,\alpha,Rk} = (f_{ax,k} * d * l_{ef}) /(1.2 * \cos^2\alpha + \sin^2\alpha) * (\rho_k / 350)^{0.8}$	=	80642.241 N
$F_{ax,a,Rd} = F_{ax,\alpha,Rk} * k_{mod} / \gamma_{M1}$	=	58062.413 N
$n_{ef} = N_{t,d} *1000 / F_{ax,a,Rd}$	=	39.5
Pull-through resistance of a screw		
Pull-through of the head is prevented by the steel plate and is thus not relevant.		
Tensile load-carrying capacity		
$F_{t,Rk} = f_{tens,k}$	=	58400 N
$F_{t,Rd} = F_{t,Rk} * k_{mod} / \gamma_{M}1$	=	42048 N
$n_{ef} = N_{t,d} *1000 / F_{t,Rd}$	=	54.6
$n = n_{ef}$ for a staggered configuration, at least 1d perpendicular to the grain to each other	=	56
Minimum spacing and edge distance		
a1 = 5 * d	=	65 mm
a2 = 5 * d	=	65 mm

Check load carrying glued-in rod connection				
steel plate to ribbon				
Glued-in rods GSA				
diameter of fastener	d =	16	mm	
density of timber	ρ_k=	730	kg/m^3	
number of rods	n =			
thickness steel plate	t =	10	mm	
effective cross-section steel rod	A_{ef} =	201.1	mm^2	
length of the glued-in rod	l_{ad} =	800	mm	
design strength of the bond line	$f_{k,1,d}$ =	2.3	N/mm^2	
design yield strength fastener	$f_{y,d}$ =	355	N/mm^2	
Design tensile strength of timber	$f_{t,o,d}$ =	43.2	N/mm^2	
Check tension strength (parallel to grain)				
Tensile strength steel				
$F_{ax,Rd} = A_{ef} * f_{yd}$	=	71376.985 N		
Shear strength bond line				
$F_{ax,Rd} = \pi * d * l_{ad} * f_{k1,d}$	=	92488.488 N		
Block shear failure				
Block shear failure is prevented by a lower resistance of the steel rods than the bond line				
$n_{ef} = N_{t,d} * 1000 / F_{ax,Rd}$	=	32.2		
$n = n_{ef}$ for a steel yield failure	=	34		
Minimum spacing and edge distance				
$a_2 = 3.5 * d$	=	56	mm	
$a_{2,c} = 1.75 * d$	=	28	mm	
n_{max} = Due to limited cross section of ribbons	=	70		
	Thus	OK		

Connection: Ribbon - Ribbon				
Dimensions				
Stress ribbon	h =		400	mm
	b =		200	mm
Stress ribbon	h =		400	mm
	b =		200	mm
self-drilling dowels SFS Intec				
Maximum loaded ribbon				
Design tension force	$N_{t,d}$ =		2240	kN
Design shear force	V_d =		6	kN
Check load carrying capacity dowel connection				
Dowels S235 WS-T-7				
nominal diameter of dowel	d =		7	mm
length of dowel	l =		193	mm
density of timber	ρ_k=		730	kg/m^3
number of dowels	n =			
thickness steel plate	t =		5	mm
number of steel plates	n_s =		6	
thickness loaded timber in shear	t_1 =		41	mm
k_{def} permanent for service class 2	k_{def} =		0.8	
k_{mod} short-term for service class 2	k_{mod} =		0.9	
	γ_{M1} =		1.25	
characteristic tensile strength fastener	$f_{u,k}$ =		360	N/mm^2
embedment strength reduction parallel to grain (70%)	η =		0.7	
Check capacity dowels				
Characteristic latteral capacity per dowel				
$M_{y,Rk}$ =	$0.3 * f_{u,k} * d^{2.6}$	=	17009	Nmm
$f_{h,0,k}$ =	$(0.082 * (1-0.01*d)*\rho_k) * \eta$	=	39.0	N/mm^2
$F_{v,Rk,1}$ =	$f_{h,k}*t_1*d$	=	11184.1	N
$F_{v,Rk,2}$ =	$f_{h,k}*t_1*d * (\sqrt{(2+ (4*M_{y,Rk} / (f_{h,k}*d*t_1^2))}-1)$	=	5208.8	N
$F_{v,Rk,3}$ =	$2.3 * \sqrt{(M_{y,Rk}*f_{h,k}*d)}$	=	4954.2	N
The governing failure mode is two plastic hinges per shear plane.		=	$F_{v,Rk,3}$	
$F_{v,Rd}$ =	shear planes * failure mode = 12 * $F_{v,Rk,3} * k_{mod} / \gamma_M$	=	42804.44	N
Reinforcement to eliminate splitting risk of is used (VG screws)				
Thus $n_{ef} = n$				
Dowels drilled from two sides two make use of six steel plates				
n =	$2*(N_{t,d} *1000 / F_{t,Rd})$	=	104.7	
		=	112	
Minimum spacing and edge distance				
a1 = spacing parallel		=	50	mm
a2 = spacing perpendicular		=	20	mm
a3,t = end parallel		=	80	mm
a4,c = end perpendicular		=	20	mm