



**Politécnico  
Castelo Branco**

Escola Superior  
de Tecnologia

## **TIMBER DESIGN**

### **Reimagining Steel Pavilion with Wood**

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## **Composition of the Jury**

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## **Dedication**

I dedicate this report and my everlasting venture to become a better designer to my brother who constantly inspires me throughout my life.



## **Acknowledgement**

I would like to express my deepest gratitude to **Prof. Luis Jorge** who has constantly guided me in this project and offered me invaluable advices.

Finally, I would like to thank School of Technology of the I.P.C.B for providing me with this opportunity.



## **Abstract**

This project explores the structural redesign of an existing steel pavilion using engineered timber. The objective is to understand and apply the principles of timber construction by replacing steel elements with timber alternatives like glulam and CLT components while maintaining the original architectural design. Using Eurocode 5 as the primary design framework, the study involves a complete structural analysis under gravity and wind loads, leading to the sizing of members and design of complex joinery. Analytical tools, including 'Staad Pro', 'Robot Structural Analysis' and custom Excel-based design sheets, were employed to evaluate structural performance under compression, tension, bending, and shear forces. Additionally, critical joineries were designed for strength and stability, accounting for tension, shear, and moment transfer. Through comparative analysis, the project highlights both the opportunities and challenges in timber design, including fire resistance, durability, and connection detailing.

## **Keywords**

Timber Design, Pavilion design, Glulam, Cross Laminated Timber (C.L.T.), Connection Design,



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## **Lista de abreviaturas, siglas e acrónimos**

C.L.T.	Cross Laminated Timber
i.e.	that is
max.	maximum
min.	minimum





## 1. Introduction

This project work is carried out to understand the principles of **timber design** and construction by **reimagining and redesigning a previously designed steel pavilion with timber**.

The following is included in the scope of the project:

- Understanding timber as a material and types of timber components used in construction.
- Redesigning a previously designed steel pavilion with wood using Eurocode 5.
- To develop automated and integrated excels, for timber design.
- Analysing the pavilion under gravity and wind loads (uplift and downforce on the canopy), and designing its structural elements along with some of its critical wood joineries (wood-wood or wood-steel).
- Developing a set of overall and joinery drawings of the finalized design
- Comparing this timber pavilion design with the previous steel pavilion and drawing inferences.

## 2. Design Initiation

As mentioned earlier, the design for the wooden pavilion is taken from the previously designed steel pavilion. Its overall drawings, connection drawings and renderings are depicted in the subsections below. This will act as a starting point for redesigning it as a timber pavilion.

### 2.1. Overall Drawings

The overall drawings of the Steel Pavilion are depicted below:

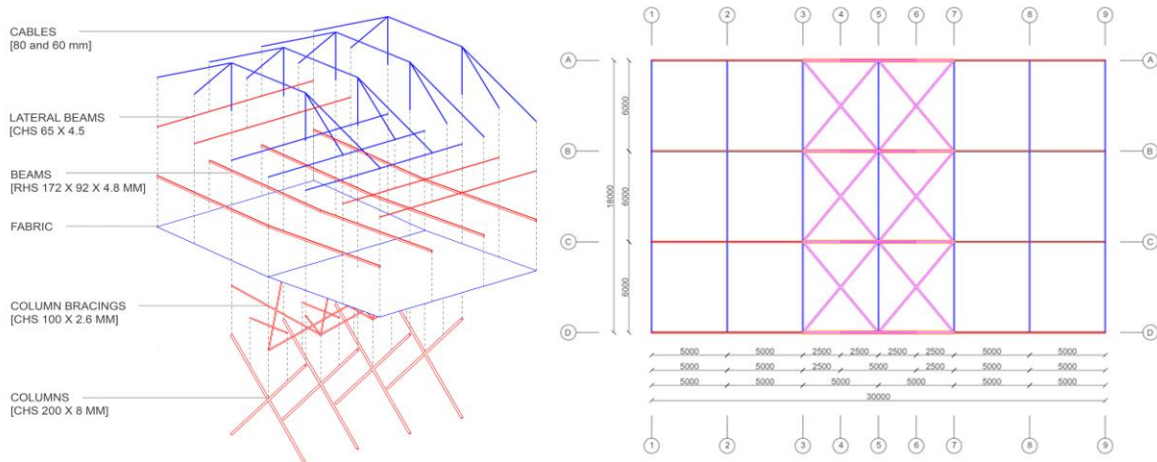


Figure 1: Exploded View and Plan

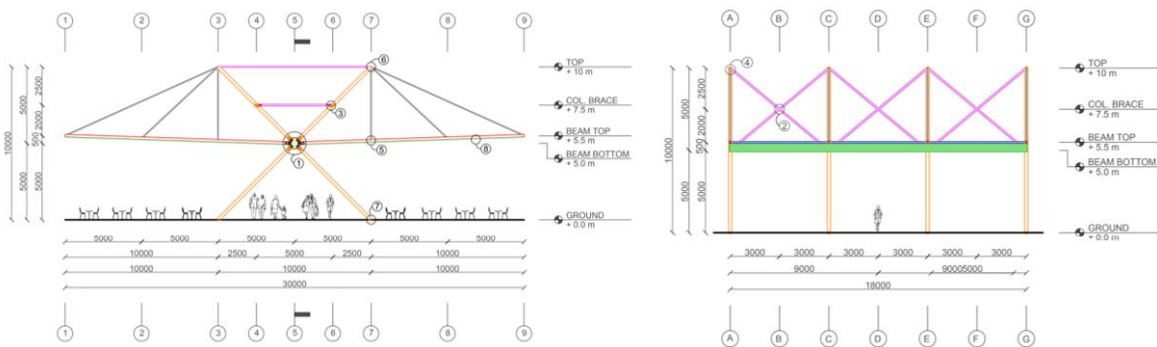


Figure 2: Front and Side Elevations

### 2.2. Joinery Drawings

Some of the important joineries of the steel pavilion are depicted in the images below:

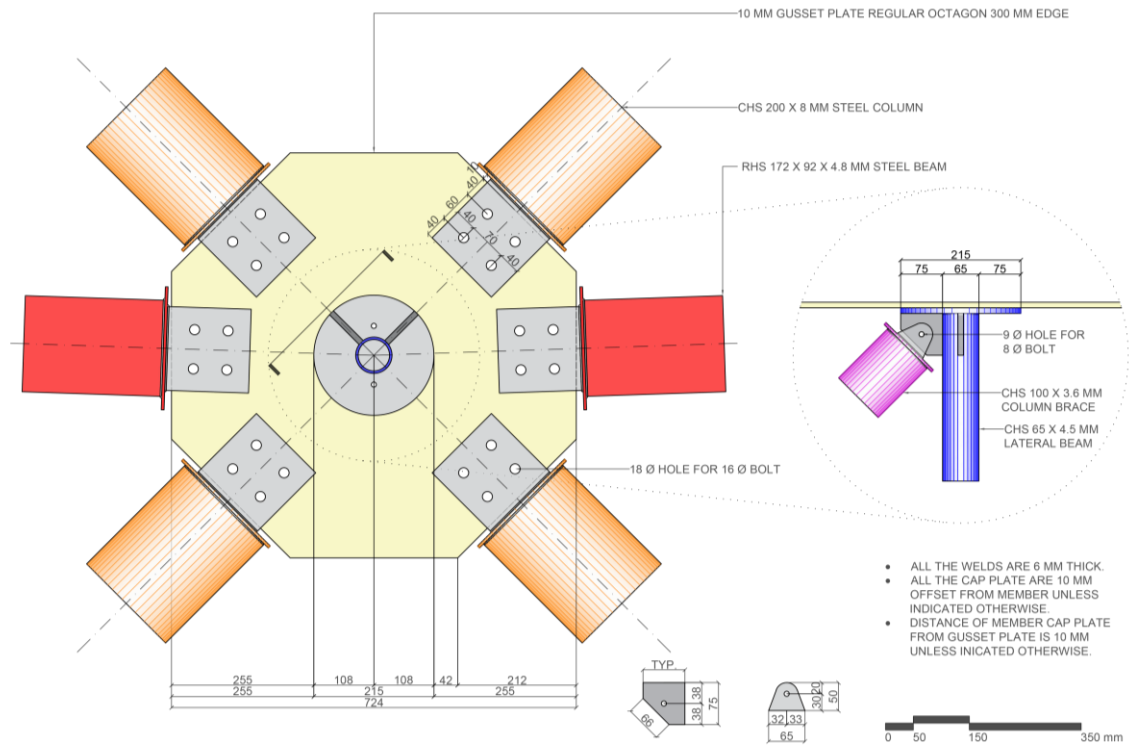


Figure 3: Central Joinery between Columns

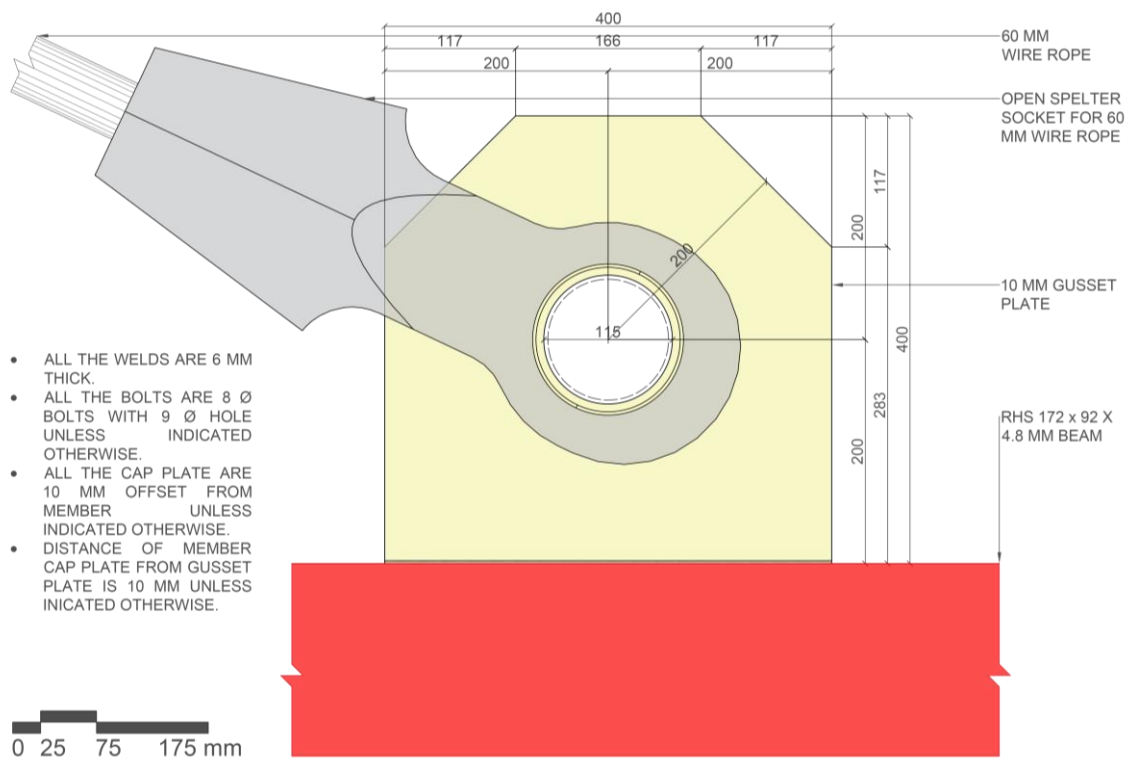


Figure 4: Tie to Beam Joinery

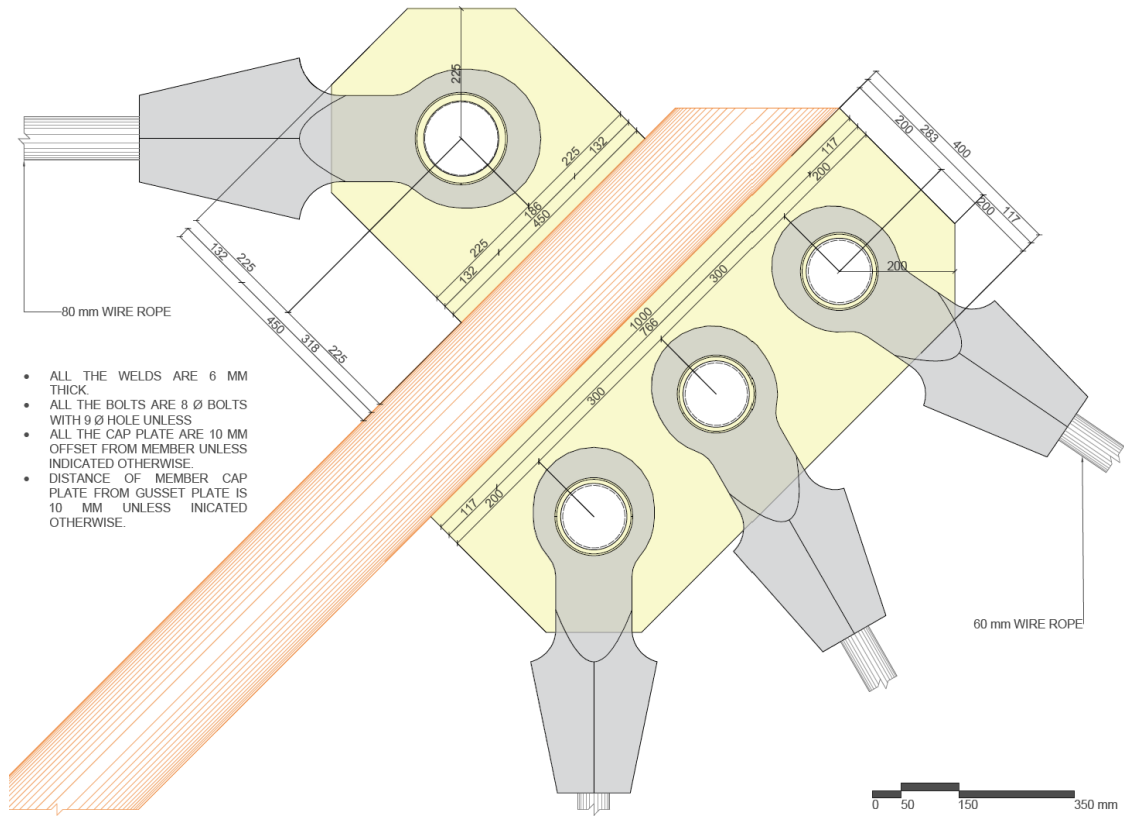


Figure 5: Joinery at Top of Column

## 2.3. Renderings

The following images depict the renders of the steel pavilion:

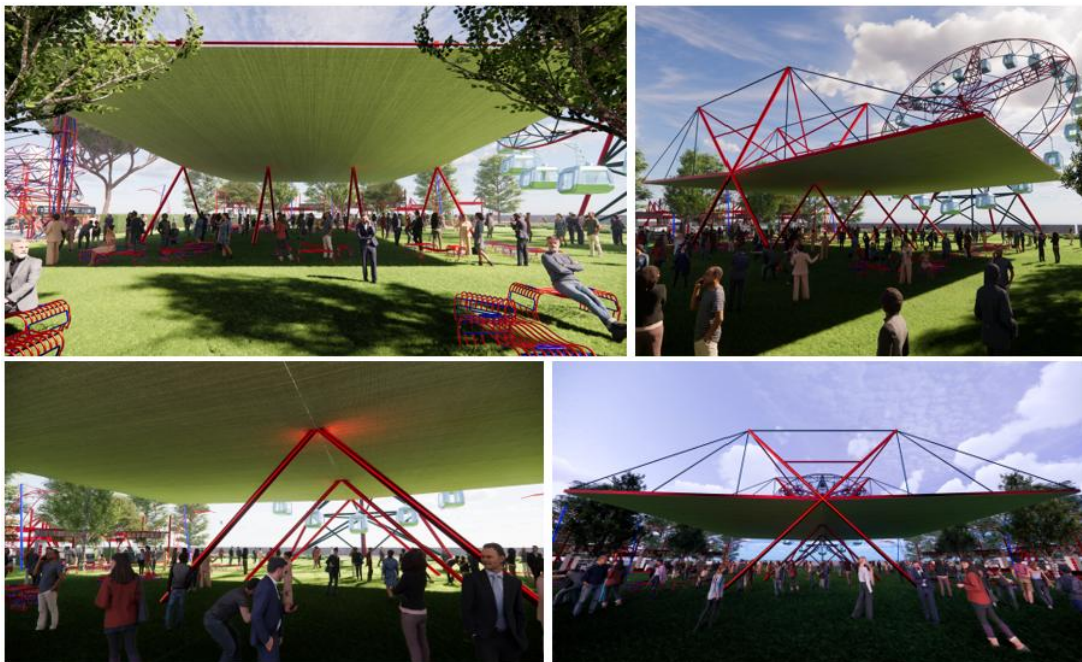


Figure 6: Representative Renders of the Steel Canopy

### 3. Reimagining the Pavilion with Timber

The following image depicts the structural system of the wooden pavilion:

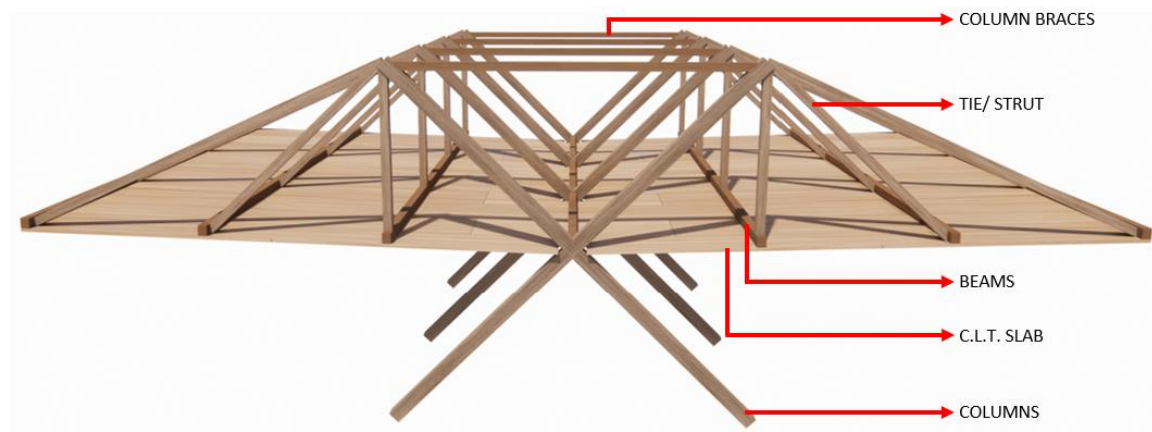


Figure 7: Structural System of Timber Pavilion

The main components in the structural system of the wooden pavilion are:

1. Column Braces
2. Tie/Struts
3. Beams
4. C.L.T Slab
5. Inclined Columns

Key differences in the structural system of the wooden pavilion are:

- Beams only in one direction (lateral direction)
- CLT slab instead of fabric
- Column Brace at the top instead of 7.5 m from the ground

Apart from this the design of the pavilion is kept the same. The benefit of using C.L.T slab instead of fabric is that the C.L.T slab can act as a diaphragm in case of horizontal loading in case of earthquake or wind loads.

All the members apart from the C.L.T slab are to be designed as Glulam members.

## 4. Analysis

The C.L.T slab was analysed using external excel 'Bemessung KLH' and its thickness was found to be 100 mm. Since the span of each roof on either side of the columns was 15 x 18 m, 8 panels of 15 x 2.25 m C.L.T slab will be required.

Following loads were considered for the analysis of the pavilion:

### 4.1. Dead Loads:

For self-weight, density of wood is assumed to be 5.5 kN/m<sup>3</sup>

### 4.2. Live Loads

The following table depicts the computation live load on the structure

Table 1: Live Loads

LIVE LOAD	
CATEGORY OF BUILDING	H
IMPOSED LOAD (LL)	1 kN/m <sup>2</sup>

### 4.3. Wind Loads

The wind loads on the roof have been calculated on according to table 7.7 of Eurocode 1 Part 4. According to that the roof is divided into different pressure zones. As per the table, the pressure zones on our roof are depicted below:

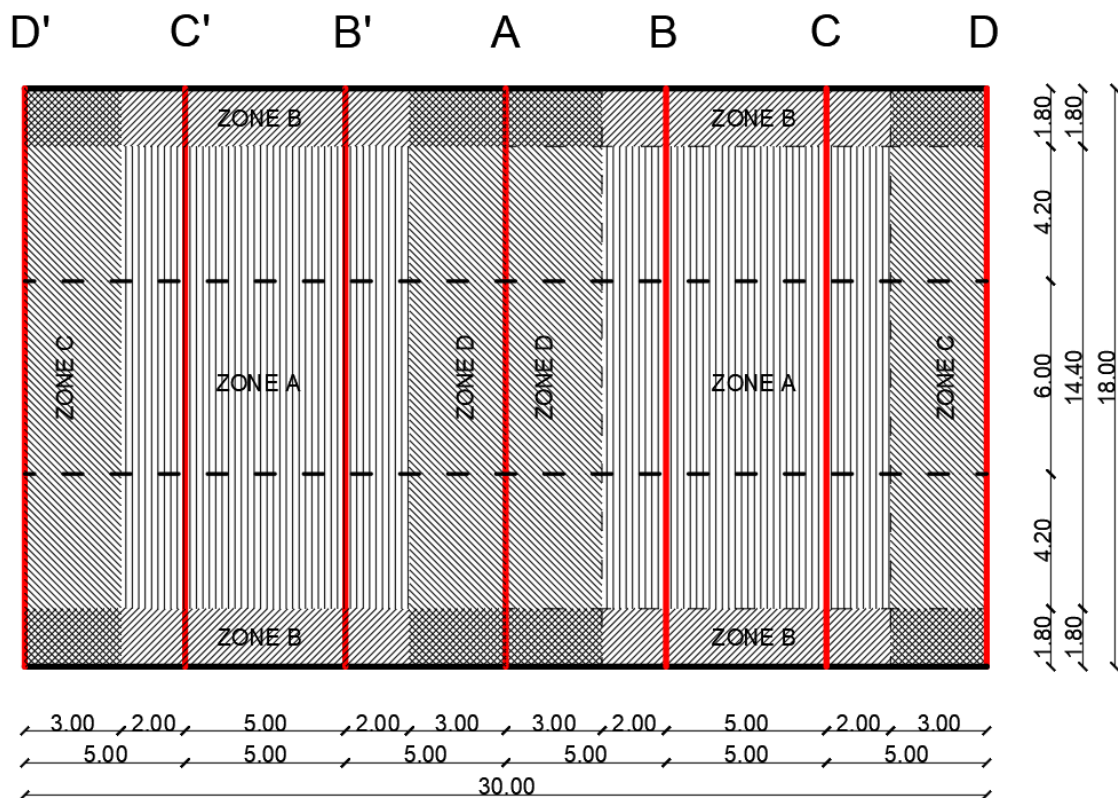


Figure 8: Pressure Zones on the Roof of the Pavilion. The red lines depict the beams on the roof.

The following table depicts the computation of wind load on the C.L.T. slab:

Table 2: Wind Loads

WIND LOAD				
ELEMENT	DESCRIPTION	VALUES	UNITS	NOTES
$V_{b,0}$	FUNDAMENTAL VALUE OF BASIC WIND VELOCITY	27	m/s	CASTELO BRANCO (ZONE-B)
<b>TERRAIN</b>	TERRAIN CATEGORY	2	-	TABLE 4.1
$C_{dir}$	DIRECTIONAL FACTOR	1	-	RECOMMENDED VALUE
$C_{season}$	SEASON FACTOR	1	-	RECOMMENDED VALUE
$V_b$	BASIC WIND VELOCITY	27	-	$V_{b,0} \cdot C_{dir} \cdot C_{season}$
$z$	HEIGHT OF ROOF	5	m	
$z_0$	ROUGHNESS LENGTH	0.05	m	TABLE 4.1
$c_r(z)$	ROUGHNESS FACTOR	0.875	-	$k_r \cdot \ln(z/z_0)$
$c_o(z)$	OROGRAPHY FACTOR	1	m/s	NO SLOPE
$v_m(z)$	MEAN WIND VELOCITY	23.625	m/s	$c_r(z) \cdot c_o(z) \cdot V_b$
$k_r$	TERRAIN FACTOR	0.19	-	$0.19 \cdot (z_0/z_0)^{0.07}$
$k_i$	TURBULENCE FACTOR	1	-	RECOMMENDED VALUE
$\sigma_v$	STANDARD DEVIATION OF TURBULANCE	5.13	-	$k_r \cdot k_i \cdot V_b$
$I_v(z)$	TURBULENCE INTENSITY	0.217	-	$\sigma_v / v_m(z)$
$c_e$	EXPOSURE FACTOR	2.52	-	$1 + 7 \cdot I_v(z)$
$\rho$	DENSITY OF AIR	1.25	kg/m <sup>3</sup>	RECOMMENDED VALUE
$q_b$	BASIC VELOCITY PRESSURE	348.824	-	$0.5 \cdot \rho \cdot v_m^2$
$q_p$	PEAK VELOCITY PRESSURE	879.05	N/m <sup>2</sup>	$c_e \cdot q_b$
<b>ROOF ANGLE</b>	ANGLE OF ROOF WRT HORIZONTAL	-1.91	DEGREES	-

ELEMENT	ZONE	FACTOR	$P_d$	UNITS		$P_d$	UNITS	NOTES
ROOF	A	0.53	466.69	N/m <sup>2</sup>	=	0.47	KN/m <sup>2</sup>	Factors applied for monoslope canopy roof (TABLE 7.7) Blockage is assumed 0
		-0.67	-588.16	N/m <sup>2</sup>	=	-0.59	KN/m <sup>2</sup>	
	B	1.59	1400.08	N/m <sup>2</sup>	=	1.40	KN/m <sup>2</sup>	
		-1.33	-	N/m <sup>2</sup>	=	-1.17	KN/m <sup>2</sup>	
	C	0.95	839.09	N/m <sup>2</sup>	=	0.84	KN/m <sup>2</sup>	
		-1.54	-	N/m <sup>2</sup>	=	-1.35	KN/m <sup>2</sup>	
	D	0.68	594.55	N/m <sup>2</sup>	=	0.59	KN/m <sup>2</sup>	
		-0.75	-663.28	N/m <sup>2</sup>	=	-0.66	KN/m <sup>2</sup>	

Now this wind loads acting as pressure loads on roof are converted to line loads on beams A, B, C and D by multiplying these pressures with the tributary area of each beam. Note that wind loads on beams B=B', C=C' & D=D' due to symmetry.

Then these beams are analysed for individually for following load cases:

1.35 DL + 1.5 WL (+) (Max. Downforce)

0.9 DL + 1.5 WL (-) (Max. Uplift)

The following figure depicts the analysis of beam A for these loads as sample:

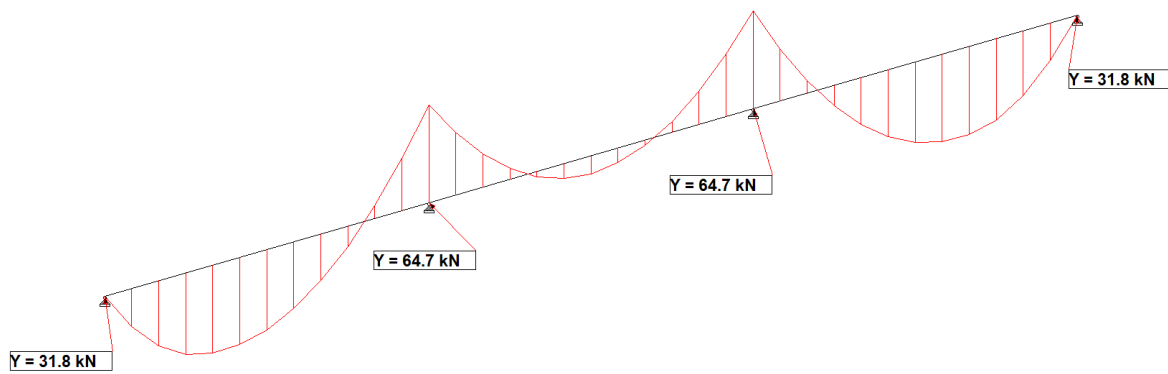


Figure 9: Analysis of beam A under Max. Downforce.

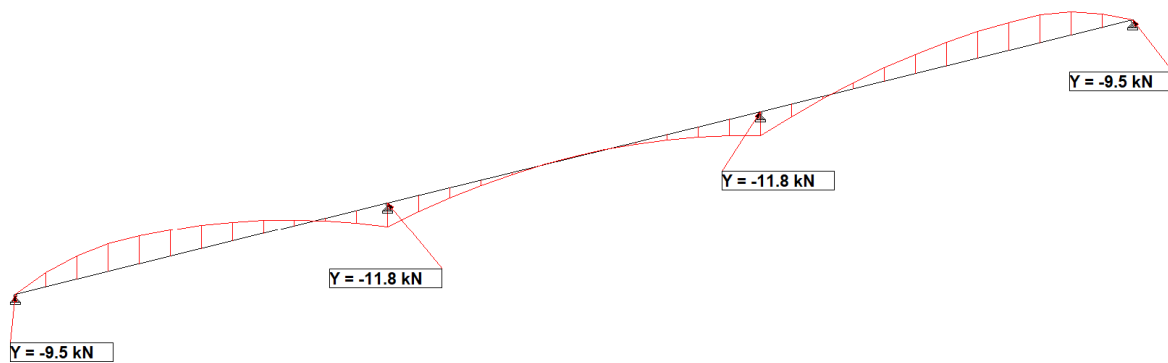


Figure 10: Analysis of beam A under max. uplift.

Similarly, all the beams were analysed in ‘Staad Pro’ and their support reactions were obtained as follows:

Table 3: Max. Positive and Negative Support Reactions for Beams.

Beam	Max. +	Max. -
A	64.7	-11.81
B	59.3	-9.02
C	60.43	-11.94
D	38.88	-21.85

These support reactions will act as point loads on the mainframe as depicted in the image below:

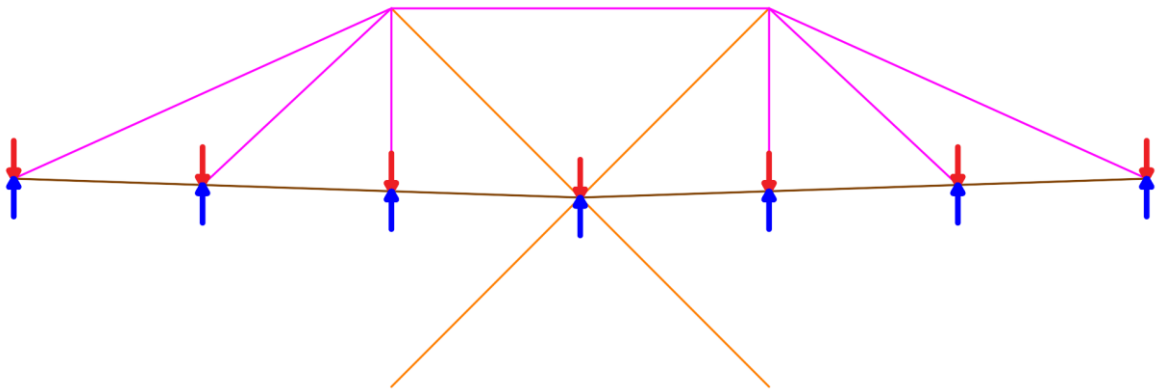


Figure 11: The red arrow depicts point loads on beams for downforce (+) and the blue arrows depict the application of point loads for uplift.

The mainframe is then analysed in 'Robot Structural Analysis' software to obtain stresses, forces and moments in the members of the mainframe- Columns, Tie/Struts, and Column Braces.

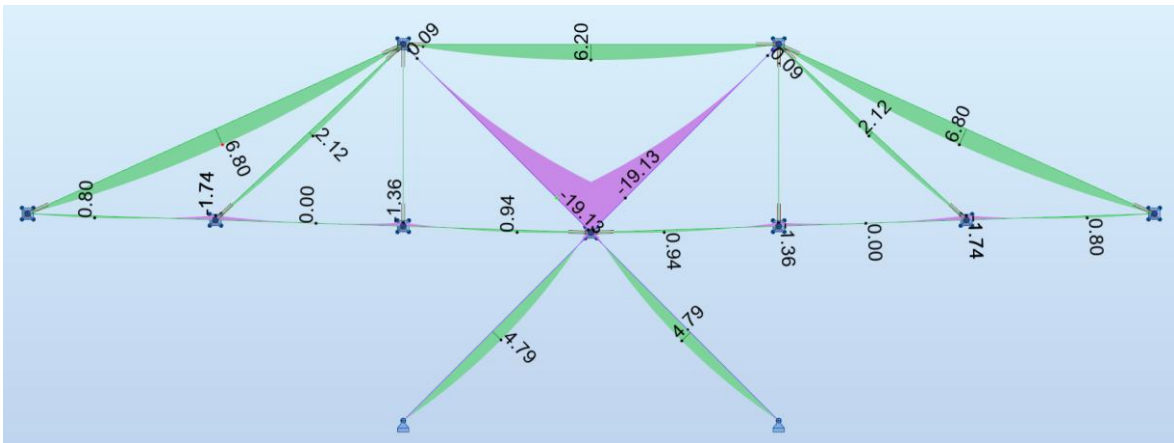


Figure 12: Analysis of Mainframe for Downforce.

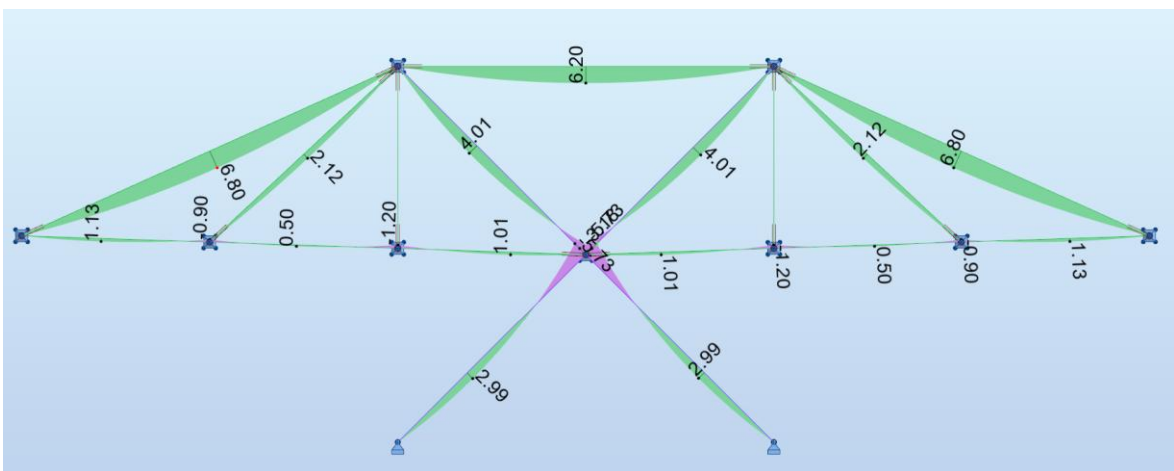


Figure 13: Analysis of Mainframe for Uplift.

## 5. Excels for Member Design

After the analysis the members are designed to according to the stresses it has to withstand. For this several automated & integrated excels were created according to Eurocode 5.

Following Excels were created:

1. Pure Compression Design
2. Pure Tension Design
3. Pure Bending Design
4. Pure Shear Design
5. Combined bending and Tension
6. Buckling Stability: Either compression or combined compression and bending
7. Lateral Torsional Buckling Stability: Either bending or combined bending and compression.

All these excels and their working is depicted in the sub-sections below. The cells **highlighted in yellow are input values** (dropdown menu for class and numerical value for loads and dimensions):

### 5.1. Pure Compression Design

Depicted below is the excel for compression design:

Table 4: Pure Compression Design Excel

COMPRESSION DESIGN PARALLEL TO GRAIN				
Description	Symbol	Value	Units	Notes
Material		<b>Glued laminated timber</b>	-	Dropdown Menu
Service Class		<b>2</b>	-	Dropdown Menu
Load Duration Class		<b>Long term action</b>	-	Dropdown Menu
Material Safety Factor	$Y_M$	1.25	-	acc. to material
Modification Factor	$K_{mod}$	0.7	-	acc. to load duration class
Design Compression Force	$F_{cd}$	<b>42110</b>	N	Factored
Glulam Class		<b>GL 22h</b>	-	Dropdown Menu
Width	$w$	<b>200</b>	mm	60-280 (Steps Of 20 mm)
Height	$b$	<b>200</b>	mm	Upto 1280 mm (Steps Of 40 mm)
Cross Sectional Area	$A$	40000	mm <sup>2</sup>	$wb$
Design Compressive Stress	$\sigma_{c,0,d}$	1.05275	N/mm <sup>2</sup>	$F_{cd}/A$
Characteristic Compressive Strength	$f_{c,0,k}$	22	N/mm <sup>2</sup>	acc. to glulam class
Design Compressive Strength	$f_{c,0,d}$	<b>12.32</b>	N/mm <sup>2</sup>	$f_{c,0,k} \cdot K_{mod} / Y_M$
Requirement of Stability check				
Description	Symbol	Value	Units	Notes
length of compression member	$l$	<b>1000</b>	mm	-
effective length factor	$k$	<b>1</b>	-	support condition
effective length	$l_e$	1000	mm	$k \cdot l$
Moment of inertia (about the axis of bending i.e. weaker axis)	$I$	133333333	mm <sup>4</sup>	$wb^3/12$
radius of gyration	$r$	57.74	mm	$(I/A)^{0.5}$
slenderness ratio	$\lambda$	17.32		$l_e/r$
Modulus of elasticity (5%)	$E_{0.05}$	8800	N/mm <sup>2</sup>	acc. to glulam class
relative slenderness ratio	$\lambda_{rel}$	<b>0.28</b>		$\lambda/\pi \cdot (f_{c,0,k}/E_{0.05})^{1/2}$
<b>no need to check for stability</b>				

Apart from strength check, it also checks whether stability check is required or not, based on the dimension of the compression member.

## 5.2. Tension Design

Depicted below is the excel for tension design:

Table 5: Pure Tension Design Excel

TENSION DESIGN PARALLEL TO GRAIN				
Description	Symbol	Value	Units	Notes
Material	<b>Glued laminated timber</b>	-	-	Dropdown Menu
Service Class	<b>2</b>	-	-	Dropdown Menu
Load Duration Class	<b>Long term action</b>	-	-	Dropdown Menu
Material Safety Factor	$Y_M$	1.25	-	acc. to material
Modification Factor	$K_{mod}$	0.7	-	acc. to load duration class
Design Tension Force	$F_{td}$	<b>62680</b>	N	Factored
Glulam Class	<b>GL 22h</b>	-	-	Dropdown Menu
Width	$w$	<b>200</b>	mm	60-280 (Steps Of 20 mm)
Height	$b$	<b>200</b>	mm	Upto 1280 mm (Steps Of 40 mm)
Cross Sectional Area	$wb$	40000	mm <sup>2</sup>	$wb$
Design Tensile Stress	$\sigma_{t,0,d}$	1.567	N/mm <sup>2</sup>	$F_{td}/A$
Characteristic Tensile Strength	$f_{t,0,k}$	17.6	N/mm <sup>2</sup>	acc. to glulam class
Design Tensile Strength	$f_{t,0,d}$	<b>9.856</b>	N/mm <sup>2</sup>	$f_{t,0,k} \cdot K_{mod} / Y_M$

## 5.3. Pure Bending Design

Depicted below is the excel for bending design:

Table 6: Pure Bending Design Excel

BENDING DESIGN (x)				
Description	Symbol	Value	Units	Notes
MATERIAL	<b>Glued laminated timber</b>	-	-	Dropdown Menu
SERVICE CLASS	<b>2</b>	-	-	Dropdown Menu
LOAD DURATION CLASS	<b>Long term action</b>	-	-	Dropdown Menu
Material Safety factor	$Y_M$	1.25	-	acc. to material
Modification Factor	$K_{mod}$	0.7	-	acc. to load duration class
DESIGN BENDING MOMENT	$M$	<b>10</b>	kN.m	Factored
GLULAM CLASS	<b>GL 24h</b>	-	-	Dropdown Menu
Width	$b$	<b>200</b>	mm	60-280 (Steps Of 20 mm)
Depth	$d$	<b>200</b>	mm	Upto 1280 mm (Steps Of 40 mm)
Section Modulus	$Z$	1333333.33	mm <sup>3</sup>	$bd^2/6$
Bending Stress	$\sigma_{m,0,d}$	7.5	N/mm <sup>2</sup>	$M/Z$
Characteristic Bending Strength	$f_{m,k}$	24	N/mm <sup>2</sup>	acc. to glulam class
Design Bending Strength	$f_{m,d}$	<b>13.44</b>	N/mm <sup>2</sup>	$f_{m,k} \cdot K_{mod} / Y_M$

## 5.4. Pure Shear Design

Depicted below is the excel for shear design:

Table 7: Pure shear Design Excel

SHEAR DESIGN				
Description	Symbol	Value	Units	Notes
MATERIAL	Glued laminated timber		-	Dropdown Menu
SERVICE CLASS	2		-	Dropdown Menu
LOAD DURATION CLASS	Long term action		-	Dropdown Menu
Material Safety factor	$Y_M$	1.25	-	acc. to material
Modification Factor	$K_{mod}$	0.7	-	acc. to load duration class
DESIGN SHEAR FORCE	$V_d$	1	kN	FACTORED
GLULAM CLASS	GL 22h		-	Dropdown Menu
Width	b	200	mm	Dropdown Menu
Depth	d	200	mm	60-280 (Steps Of 20 mm)
Area	A	40000		bd
Design Shear stress	$V_{c,0,d}$	0.025		$V_d/A$
Characteristic Shear Strength	$f_{v,k}$	3.5	N/mm <sup>2</sup>	acc. to glulam class
Design Shear Strength	$f_{v,d}$	1.96	N/mm <sup>2</sup>	$f_{v,k} \cdot K_{mod} / Y_M$

## 5.5. Combined Bending and Tension

Depicted below is the excel for combined bending and tension design:

Table 8: Combined Bending and Tension Excel

BENDING DESIGN (x)				TENSION DESIGN PARALLEL TO GRAIN			
Description	Symbol	Value	Units	Description	Symbol	Value	Units
Material	Glued laminated timber		-	Material	Glued laminated timber		-
Service Class	2		-	Service Class	2		-
Load Duration Class	Long term action		-	Load Duration Class	Long term action		-
Material Safety Factor	$Y_M$	1.25	-	Material Safety Factor	$Y_M$	1.25	-
Modification Factor	$K_{mod}$	0.7	-	Modification Factor	$K_{mod}$	0.7	-
Design Bending Moment	M	10	kN.m	Design Tension Force	$F_{td}$	1500 0	N
Glulam Class	GL 24h		-	Glulam Class	GL 24h		-
Width	b	200	mm	Width	w	200	mm
Depth	d	200	mm	Height	b	200	mm
Section Modulus	Z	1E+0 6	mm <sup>3</sup>	Cross Sectional Area	wb	4000 0	mm <sup>2</sup>
Bending Stress	$\sigma_{m,0,d}$	7.5	N/mm <sup>2</sup>	Design Tensile Stress	$\sigma_{t,0,d}$	0.375	N/mm <sup>2</sup>
Characteristic Bending Strength	$f_{m,k}$	24	N/mm <sup>2</sup>	Characteristic Tensile Strength	$f_{t,0,k}$	19.2	N/mm <sup>2</sup>
Design Bending Strength	$f_{m,d}$	13.44	N/mm <sup>2</sup>	Design Tensile Strength	$f_{t,0,d}$	10.75	N/mm <sup>2</sup>
<b>COMBINED STRESS CHECK</b>				<b>0.59</b>			

## 5.6. Buckling Stability: Either compression or combined compression and bending

Depicted below is the excel for buckling stability of a compression member, either under pure compression or combined compression and bending:

Table 9: Buckling Stability Excel

Buckling Stability							
BENDING DESIGN				COMPRESSION DESIGN PARALLEL TO GRAIN			
Description	Symbol	Value	Units	Description	Symbol	Value	Units
Material	Glued laminated timber		-	Material	Glued laminated timber		-
Service Class	2		-	Service Class	2		-
Load Duration Class	Long term action		-	Load Duration Class	Long term action		-
Material Safety Factor	$Y_M$	1.25	-	Material Safety Factor	$Y_M$	1.25	-
Modification Factor	$K_{mod}$	0.7	-	Modification Factor	$K_{mod}$	0.7	-
Design Compression Force	$F_{cd}$	321890	N	Design Bending Moment	M	19.13	kN.m
Glulam Class	GL 26h		-	Glulam Class	GL 26h		-
Width	w	360	mm	Width	b	360	mm
Height	b	400	mm	Depth	d	360	mm
Cross Sectional Area	wb	144000	mm <sup>2</sup>	Section Modulus	Z	7776000	mm <sup>3</sup>
Design Compressive Stress	$\sigma_{c,0,d}$	2.24	N/mm <sup>2</sup>	Bending Stress	$\sigma_{m,0,d}$	2.46	N/mm <sup>2</sup>
Characteristic Compressive Strength	$f_{c,0,k}$	26	N/mm <sup>2</sup>	Characteristic Bending Strength	$f_{m,k}$	26	N/mm <sup>2</sup>
Design Compressive Strength	$f_{c,0,d}$	14.56	N/mm <sup>2</sup>	Design Bending Strength	$f_{m,d}$	14.56	N/mm <sup>2</sup>
<b>COMBINED STRESS CHECK</b>				<b>0.19</b>			
Length Of Compression Member	l	14140	mm				
Effective Length Factor	k	1	-				
Effective Length	$l_e$	14140	mm				
Moment Of Inertia (About the Axis of Bending I.E Weaker Axis)	$I_y$	15552000	mm <sup>4</sup>				
Radius Of Gyration	$r_y$	103.92	mm				
Slenderness Ratio	$\lambda$	136.06	-				
Modulus Of Elasticity (5%)	$E_{0,05}$	10100	N/mm <sup>2</sup>				
Relative Slenderness Ratio	$\lambda_{rel}$	2.20	-				
<b>CHECK FOR STABILITY</b>							
Factors	$\beta_c$	0.1	-				
	$k_y$	3.0	-				
	$k_{c,y}$	0.2	-				
<b>STABILITY CHECK</b>		0.947					

The check for stability is only required if the relative slenderness ratio is >0.3 (refer to the red highlighted cell in the above image).

### 5.7. Lateral Torsional Buckling Stability: Either bending or combined bending and compression.

Depicted below is the excel for lateral torsional buckling stability of a bending member, either under pure bending or combined bending and compression:

Table 10: Lateral Torsional Buckling Stability Excel

COMPRESSION DESIGN PARALLEL TO GRAIN				BENDING DESIGN			
Description	Symbol	Value	Units	Description	Symbol	Value	Units
Material		<b>Glued laminated timber</b>	-	Material		<b>Glued laminated timber</b>	-
Service Class		<b>2</b>	-	Service Class		<b>2</b>	-
Load Duration Class		<b>Long term action</b>	-	Load Duration Class		<b>Long term action</b>	-
Material Safety Factor	$Y_M$	1.25	-	Material Safety Factor	$Y_M$	1.25	-
Modification Factor	$K_{mod}$	0.7	-	Modification Factor	$K_{mod}$	0.7	-
Design Compression Force	$F_{cd}$	<b>2000</b>	N	Design Bending Moment	$M$	<b>36.1</b>	kN.m
Glulam Class	<b>GL 22h</b>			Width	$b$	<b>240</b>	mm
Width	$w$	240	mm	Depth	$d$	<b>280</b>	mm
Height	$b$	280	mm	Section Modulus	$Z$	3136000	mm <sup>3</sup>
Cross Sectional Area	$A$	67200	mm <sup>2</sup>	Bending Stress	$\sigma_{m,0,d}$	11.51	N/mm <sup>2</sup>
Design Compressive Stress	$\sigma_{c,0,d}$	0.03	N/mm <sup>2</sup>	Glulam Class		<b>GL 22h</b>	
Characteristic Compressive Strength	$f_{c,0,k}$	22	N/mm <sup>2</sup>	Characteristic Bending Strength	$f_{m,k}$	22	N/mm <sup>2</sup>
Design Compressive Strength	$f_{c,0,d}$	<b>12.32</b>	N/mm <sup>2</sup>	Design Bending Strength	$f_{m,d}$	<b>12.32</b>	N/mm <sup>2</sup>
<b>COMBINED STRESS CHECK</b>				<b>0.93</b>			
<b>LATERAL TORSIONAL BUCKLING TEST</b>							
Length Of Compression Member	$l$	6000	mm	Beam & Loading Type		<b>Simply Supported- UDL</b>	
Effective Length	$l_e$	5400	mm	Span	$l$	<b>6000</b>	mm
Moment Of Inertia (About the Axis of Bending i.e. Weaker Axis)	$I_y$	322560000	mm <sup>4</sup>	Effective Length/Span	$l_e/l$	0.9	mm
Radius Of Gyration	$r$	69.28	mm	Effective Length	$l_e$	5400	mm
Slenderness Ratio	$\lambda$	77.94	-	5th Percentile Modulus of Elasticity	$E_{0.05}$	8800	N/mm <sup>2</sup>
Modulus Of Elasticity (5%)	$E_{0.05}$	8800	N/mm <sup>2</sup>	Critical Bending Stress	$\sigma_{m,crit}$	261.485714	N/mm <sup>2</sup>
Relative Slenderness Ratio	$\lambda_{rel}$	1.24	-	Relative Bending Slenderness	$\lambda_{rel,m}$	0.29	-
Factors	$\beta_c$	0.1	-	Lateral Buckling Factor	$K_{crit}$	1	-
	$k_y$	1.32	-	Stability Check		<b>0.94</b>	
	$k_{c,y}$	0.57	-				

## 5.8. Final Member Dimensions

Using these excels, the following member sizes were finalized:

Table 11: Final Member Sizes

Structural Component	b	d	Units
Columns	360	360	mm
Beams	240	280	mm
Column Bracings	240	240	mm
Tie/Strut	240	240	mm

All the components are of GL 26 h glulam class. The governing forces and moments in these components are depicted in the table below:

Table 12: Governing Forces and Moments in Members

Structural Component	Max. Compression	Max. Tension	Max Shear	Max. Moment	Required Section	Selected Section
	kN	kN	kN	kN.m	mm	mm
Columns	321.89	27.25	5.81	19.13	360 x 360	360 x 360
Beams	0	0	36.2	36.1	240 x 280	240 x 280
Column Bracings	62.68	329.38	2.48	0	240 x 220	240 x 240
Tie/Strut	42.11	-97.53	2.48	0	200 x 200	240 x 240

## 6. Timber Pavilion Overall Drawings

This section depicts the overall drawings of the pavilion with the finalized member sizes.

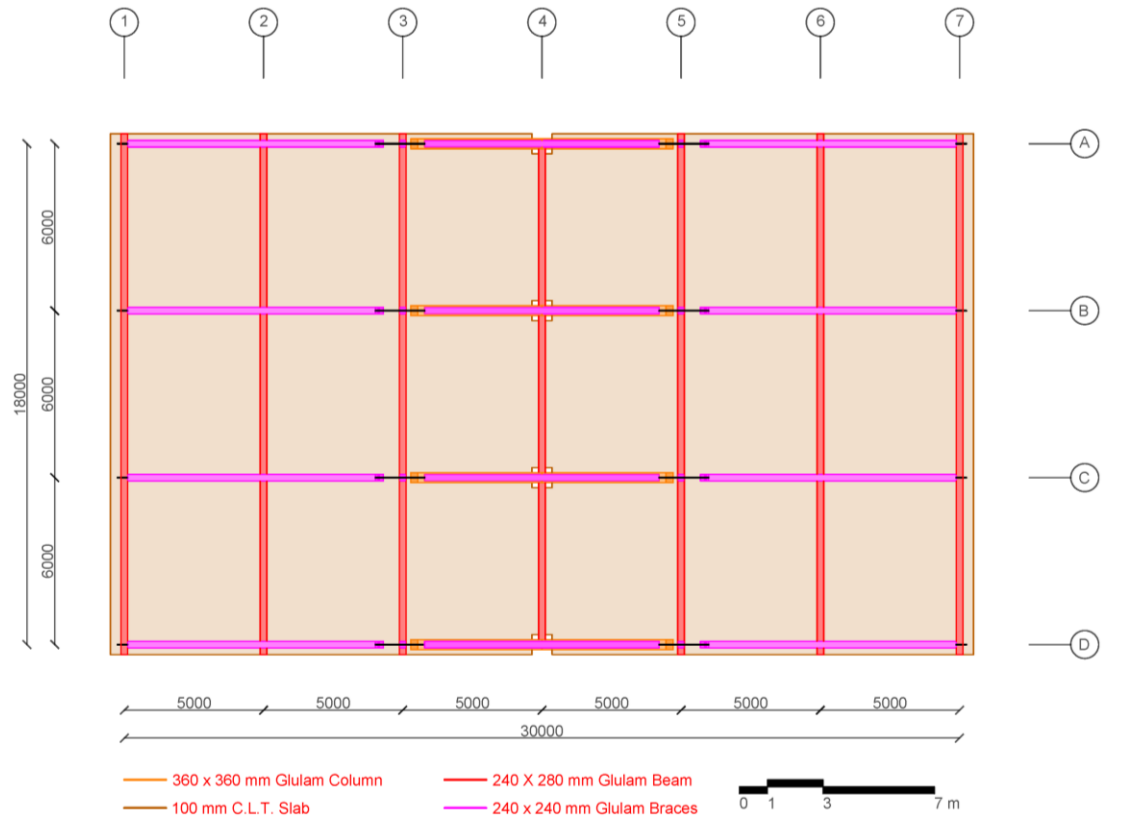


Figure 14: Plan

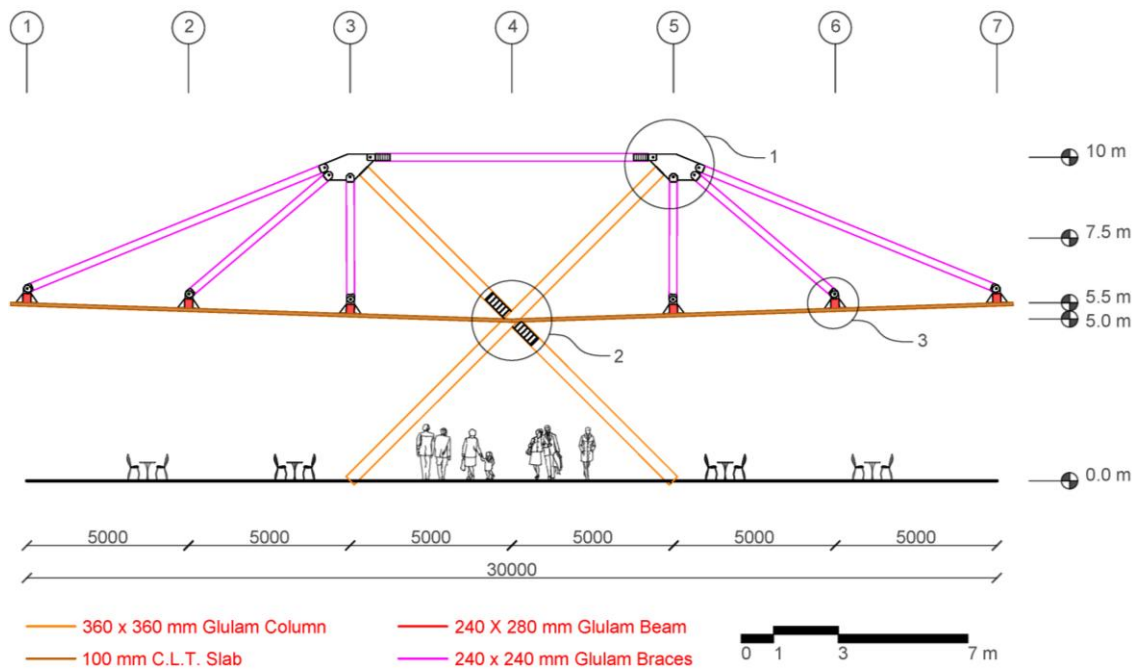


Figure 15: Front Elevation. The three joineries marked in this are explained in next section.

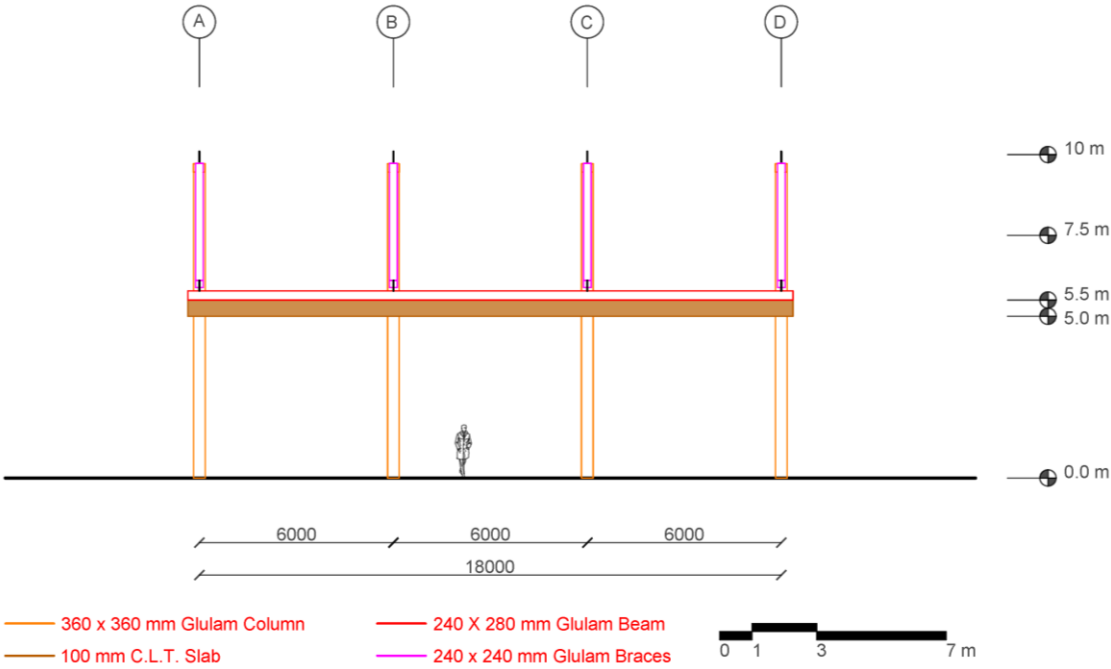


Figure 16: Side Elevation

## 7. Connection Design

Three critical joineries of the structure are designed (refer image 14) and presented in these sections. For joinery design calculations, refer annexure A, B and C.

### 7.1. Joinery 1

This is the joinery at the top of the column which connects column, column bracings and tie/struts.

Notice how the centre lines of each component meet at a single point. It is designed such that there is no additional moment generated due to eccentricity between connections.

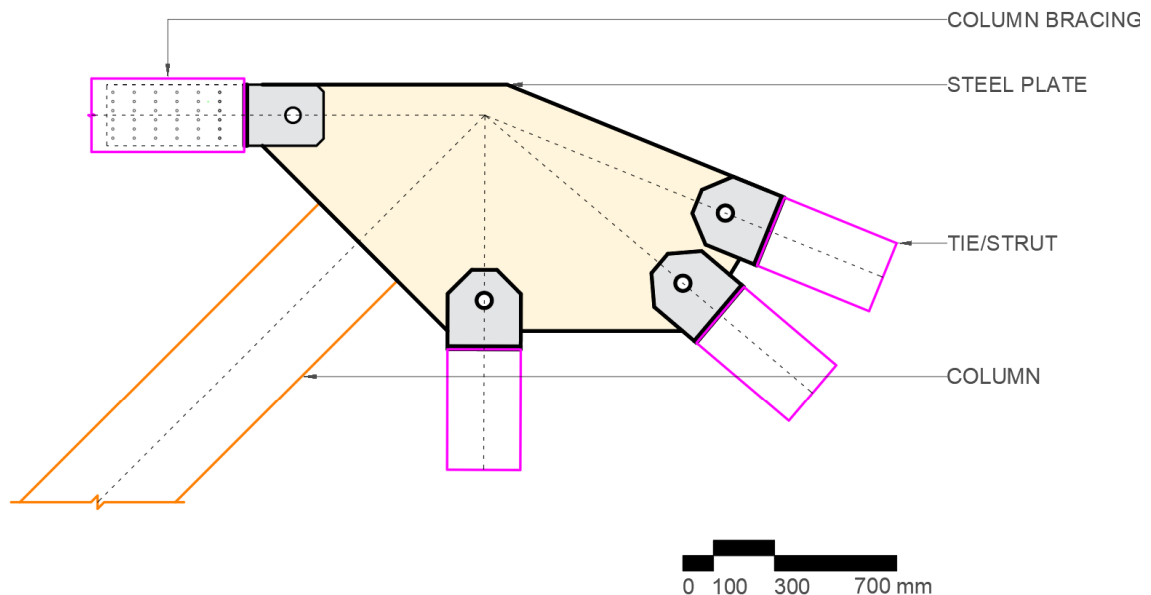


Figure 17: Joinery 1

This joinery is further divided into 3 parts:

#### 7.1.1. Tie/Strut to Plate

In this connection the screws are in tension parallel to the grain of the tie/ strut.

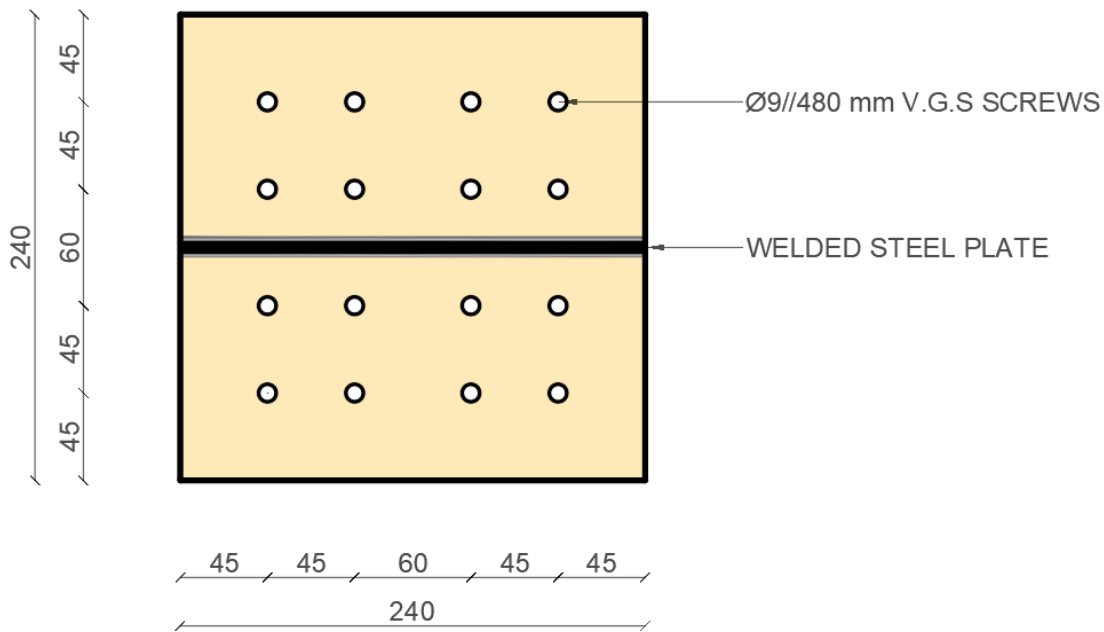


Figure 18: Joinery 1.1

### 7.1.2. Column Bracing to Plate

In this connection the dowels are in shear parallel to the grain of the column bracing.

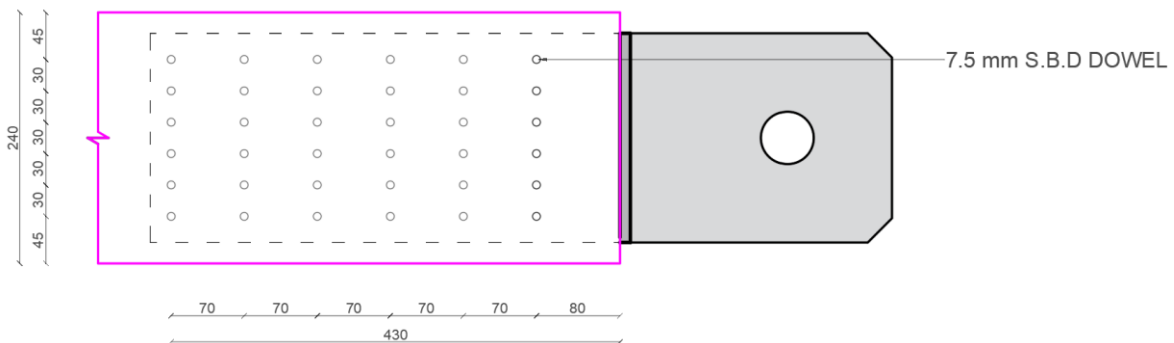


Figure 19: Joinery 1.2

### 7.1.3. Column to Plate

In this the connection is designed to such that the screws are in tension parallel to the grain. This was decided to be **designed as an axial connection rather than shear one** so that the **compression forces would be directly transferred to the column via bearing pressure** of the plate on column cross section instead of being transferred via shear strength of screws. Thus, in this way, the connection had to be designed **only for tension** on the top of the column.

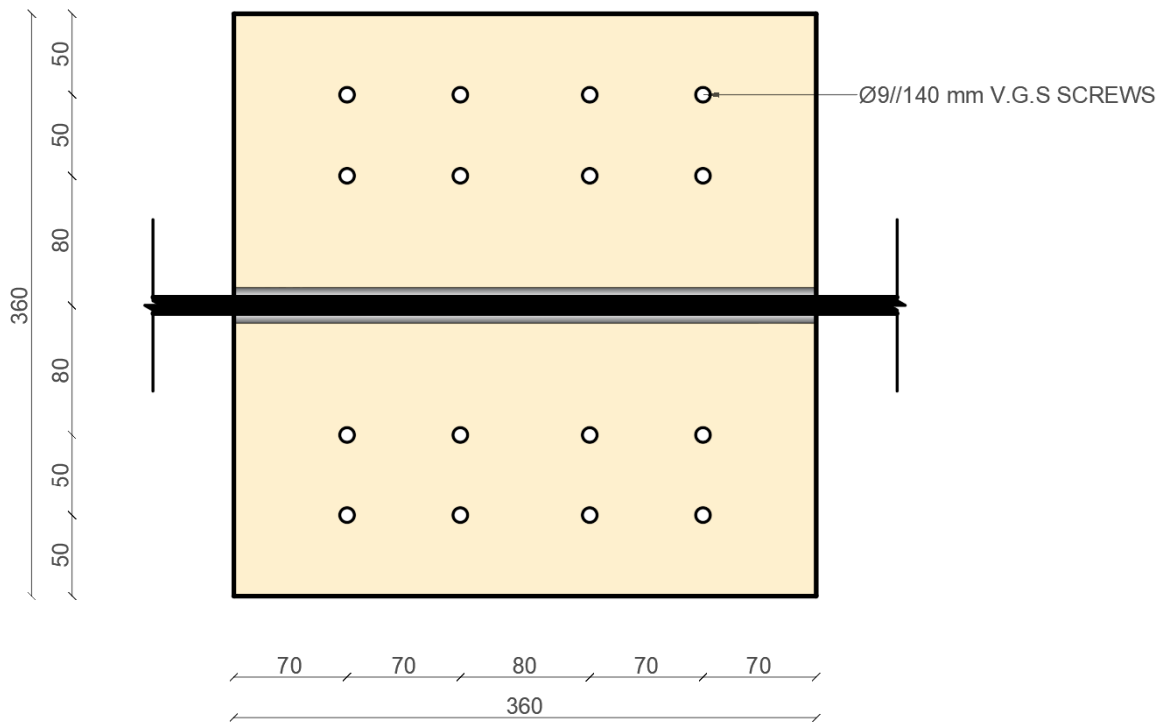


Figure 20: Joinery 1.3

## 7.2. Joinery 2

This is the central joinery between the column. It is a moment connection and designed as a shear-type connection with dowels.

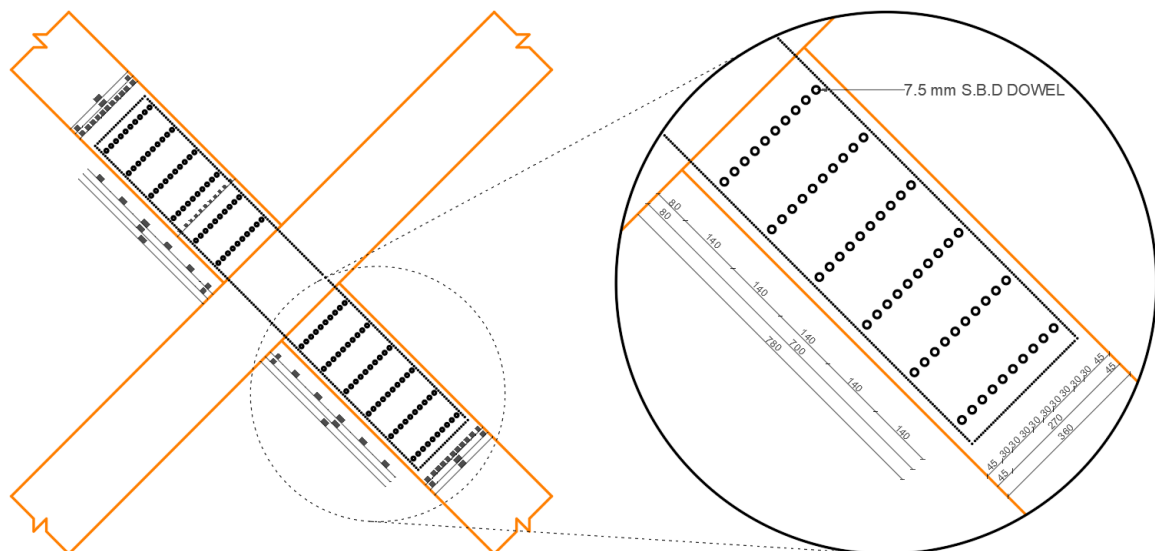


Figure 21: Joinery 2

### 7.3. Joinery 3

This is the joinery between tie/struts, beams and C.L.T slabs. Due to the eccentricity between the components in the connection, the connection is designed to withstand the corresponding moment.

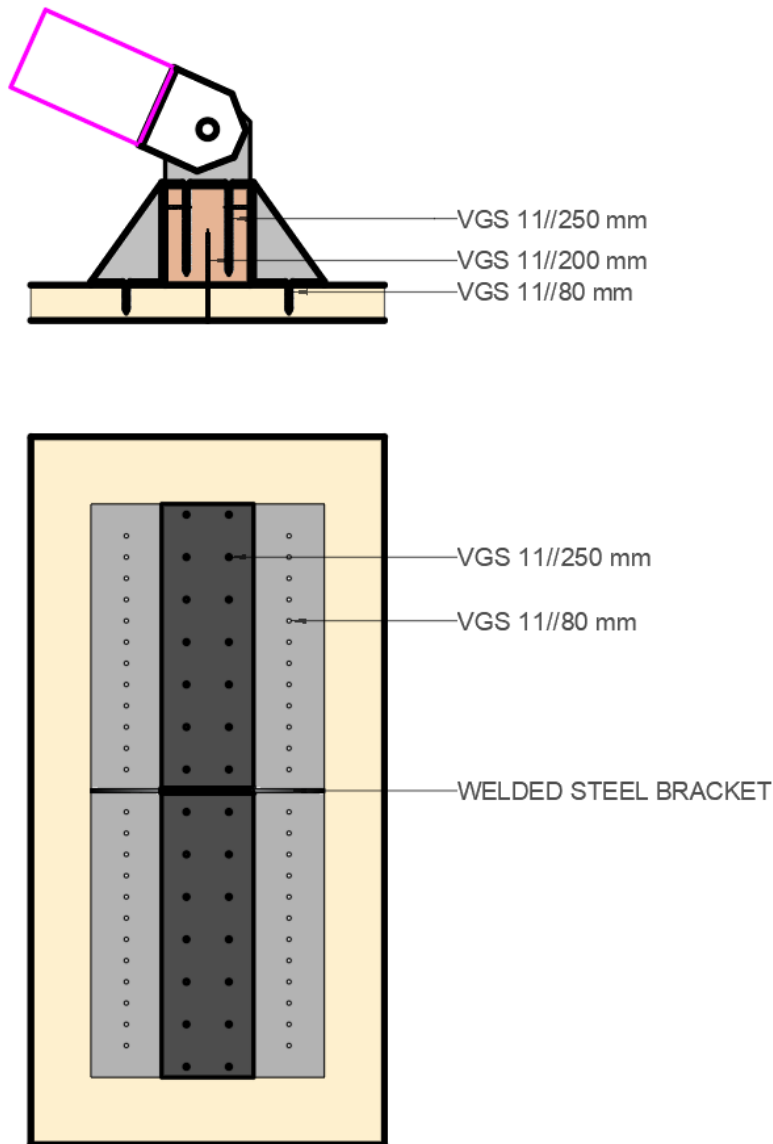


Figure 22: Sectional and top view of Joinery 3

All the three screws depicted in the top part of the image serve different purpose. VGS 11//250 mm screw transfers axial force and moment to the beam and its covering plate. The beam then transfers the axial force to the C.L.T. via VGS 11//200 mm and moment via VGS 11//80 mm screws.

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## 8. Conclusion:

Along this design journey, several analysis and design concepts were learnt, as presented below:

1. Understanding failure modes are essential to calculate the strength of any material or component.
2. Timber is an orthotropic material meaning that its properties are different parallel and perpendicular to the direction of grain. This makes it crucial to check the strength of wooden members and joineries in both directions.
3. Many times, connections govern member sizes rather than the loads and moments.
4. While designing shear-type connections in joineries (dowels), it is beneficial to keep metal plate inside the wooden member rather than on the top of the wooden member. This is because wood performs better than steel in fire, since wood reduces its cross section slowly during fire, unlike steel which melts entirely across the whole cross section.
5. Ventilation is an important aspect to consider while designing wood steel connections to ensure durability.
6. Wooden joineries have to be more detailed since welding is not possible.
7. Unlike steel members which are slender due to its higher strength, wooden members are bulkier.

## 9. Annexure A: Joinery 1 Calculations

### 9.1. Joinery 1.1

The following table depicts calculations for joinery 1.1:

Table 13: Joinery 1.1 Calculations

TIE/STRUT TO PLATE				
Description	Symbol	Value	Unit	Notes
TENSION	$T_D$	97.52	kN	-
COMPRESSION	$C_D$	42.11	kN	-
Material Safety Factor	$Y_m$	1.3	kN	for connections
Load Duration Factor	$k_{mod}$	0.5	kN	service class 3
Characteristic Tension	$T_k$	253.55	kN	$T_D \cdot Y_m/k_{mod}$
no of screws	$n$	16	kN	-
Characteristic Tension per screw	$F_{sk}$	15.85	kN	-
Dimeter of Screw	$\phi$	9	mm	-
Length of Screw	$L_{req}$	480	mm	-
Finalized Screw		VGS 9 X 480		

### 9.2. Joinery 1.2

The following table depicts calculations for joinery 1.2:

Table 14: Joinery 1.2 Calculations

COLUMN BRACING TO PLATE				
Description	Symbol	Value	Unit	Notes
TENSION	$T_D$	329.38	kN	-
COMPRESSION	$C_D$	62.68	kN	-
SHEAR	$V_D$	2.48	kN	-
Material Safety Factor	$Y_m$	1.3	kN	for connections
Load Duration Factor	$k_{mod}$	0.5	kN	service class 3
Characteristic Force	$F_k$	856.388	kN	$T_D \cdot Y_m/k_{mod}$
No of lines of dowels	$n_l$	6	kN	-
Characteristic shear per line	$F_{sk}$	142.73	kN	-
Characteristic Shear Capacity of Dowel	$F_{sk,d}$	31.8	kN	two steel plates
Effective number of dowels	$n_{eff}$	4.49	nos	-
6 Dowels with $a_1 = 70$ mm				

### 9.3. Joinery 3

The following table depicts calculations for joinery 1.3:

Table 15: Joinery 1.3 Calculations

TIE/STRUT TO PLATE				
Description	Symbol	Value	Unit	Notes
TENSION	$T_D$	<b>27.25</b>	kN	-
Material Safety Factor	$Y_m$	1.3	kN	for connections
Load Duration Factor	$k_{mod}$	0.5	kN	service class 3
Characteristic Tension	$T_k$	70.85	kN	$T_D \cdot Y_m / k_{mod}$
no of screws	$n$	<b>16</b>	kN	-
Characteristic Tension per screw	$F_{sk}$	4.43	kN	-
Dimeter of Screw	$\phi$	9	mm	-
Length of Screw	$L_{req}$	140	mm	-
Finalized Screw			<b>VGS 9 X 140</b>	

## 10. Annexure B: Joinery 2 Calculations

Since moment can create components of forces in both directions, the strength is checked in both- principle and transverse direction. For converting moment to forces, the distance between outermost bolts is used, since strain due to moment will start to propagate from outwards to inwards.

Table 16: Joinery 2 Calculations

Column to Column Joinery				
Description	Symbol	Value	Unit	Notes
TENSION	$T_D$	321.89	kN	-
COMPRESSION	$C_D$	27.25	kN	-
Moment	$M_D$	-19.13	kN.m	-
Material Safety Factor	$Y_m$	1.3	kN	for connections
Load Duration Factor	$k_{mod}$	0.5	kN	service class 3
Characteristic Shear due to Axial Force	$V_{ka}$	836.91	kN	$T_D \cdot Y_m / k_{mod}$
No of lines	$n_l$	10	kN	along the grain
Distance between lines	$a_2$	30	mm	perpendicular to the grain
Distance Between outermost dowels	$d_0$	270		$(n_l - 1) \times a_2$
Characteristic Shear due to Moment	$V_{km}$	184.21	kN	$M_D / d_0$
Total Characteristic Shear in Dowels	$F_{sk}$	1021.13	kN	$V_{ka} + V_{km}$
Characteristic Shear per line	$F_{sk,l,0}$	102.11	kN	$F_{sk} / n_l$
Characteristic Shear Capacity of Dowel	$F_{sk,d,0}$	18.64	kN	one steel plate
Effective number of dowels	$n_{eff}$	5.48	nos	$F_{sk,l} / F_{sk,d,0}$
<b>Spacing between dowels in a line</b>	<b><math>a_1</math></b>	<b>140</b>	<b>mm</b>	parallel to the grain
No of dowels required	$n$	6.0	nos	-
Checking for Strength in transverse direction				
No of lines	$n_l$	6.0	nos	-
Distance between lines	$a_1$	140		parallel to the grain
Distance Between outermost dowels	$d_{90}$	700		$(n_l - 1) \times a_1$
Characteristic Shear due to Moment	$V_{km,90}$	71.05	kN	$M_D / d_{90}$
Characteristic Shear per line	$F_{sk,l,90}$	11.84	kN	-
Characteristic Shear Capacity of Dowel	$F_{sk,d,90}$	14.79		-
Effective number of dowels	$n_{eff}$	0.80		-
<b>Spacing between dowels in a line</b>	<b><math>a_2</math></b>	<b>30</b>	<b>mm</b>	perpendicular to the grain
No of dowels required	$n$	2.00	nos	-

Since no. of bolts provided in transverse direction= number of lines in principle direction=11 > 2, the joinery is okay.

## 11. Annexure C: Joinery 3 Calculations

The following table depicts the calculations for **axial force transfer between Beam and C.L.T. slab**:

Table 17: Joinery 3 Axial Force Transfer: Beam & C.L.T.

Axial Load Transfer between beam and C.L.T. slab				
Description	Symbol	Value	Unit	Notes
Force	F	97.58	kN	Max Tension
Angle	$\Theta$	90	degrees	conservative approach
Axial Load	$T_D$	97.58	kN	Vertical Component
Material Safety Factor	$Y_m$	1.3	kN	for connections
Load Duration Factor	$k_{mod}$	0.5	kN	service class 3
Characteristic Tension	$T_k$	253.71	kN.m	$T_D \cdot Y_m / k_{mod}$
no of screws	n	10	kN	-
Characteristic Tension per screw	$F_{sk}$	25.37	kN	-
Dimeter of Screw	$\phi$	11	mm	-
Length of Screw	$L_{req}$	200	mm	-
<b>Finalized Screw</b>			<b>VGS 11 X 200</b>	

The following table depicts the calculations for moment transfer between Beam and C.L.T. slab:

Table 18: Joinery 3 Moment Transfer: Beam & C.L.T.

Moment Transfer between beam and C.L.T				
Description	Symbol	Value	Unit	Notes
Force	F	97.58	kN	Max Tension
Angle	$\Theta$	24	degrees	wrt horizontal
Eccentric Load	$F_e$	89.14	kN	Horizontal Component
Eccentricity	e	490	mm	-
Moment Generated	M	43.68	kN.m	$F_e \cdot e$
Material Safety Factor	$Y_m$	1.3	kN	for connections
Load Duration Factor	$k_{mod}$	0.5	kN	service class 3
Characteristic Moment	$M_k$	113.57	kN.m	$M_D \cdot Y_m / k_{mod}$
Distance between screws	d	530	mm	Outermost (lever arm)
Total Force due to moment	$F_M$	214.2814	kN	$T_k / d$
No of pairs of screws	n	24		-
Force per screw		8.9		-
Diameter of Screw	$\phi$	11		-
Length of Screw	$L_{req}$	80	mm	-
<b>Finalized Screw</b>			<b>VGS 11 X 80</b>	

The following table depicts the calculations for axial and moment transfer between tie/strut and beam:

Table 19: Axial Load and Moment Transfer: Tie/Strut &amp; Beam

Axial Load & Moment Transfer between Tie/strut & Beam				
Description	Symbol	Value	Unit	Notes
Force	F	97.58	kN	Max Tension
Angle	$\Theta$	24	degrees	worst case: outermost
Eccentric Load	$F_e$	89.14	kN	Horizontal Component
e	e	160	mm	
Moment Generated	$M_d$	14.26	kN.m	$F_e \cdot e$
Material Safety Factor	$\gamma_m$	1.3	kN	for connections
Load Duration Factor	$k_{mod}$	0.5	kN	service class 3
Characteristic Moment	$M_k$	37.08	kN.m	$M_D \cdot \gamma_m / k_{mod}$
Distance between screws	d	120	mm	outermost
Characteristic Force Due to moment	$F_{mk}$	309.03	kN	$M_k / d$
Characteristic Axial Force	$F_{ak}$	253.71	kN	worst case: 90 degree (100%)
Total Force per screw in pair	$F_t$	435.89	kN	$F_{mk} + F_{ak}$
No of pairs of screws	n	14	nos	-
Force per screw	-	31.13	kN	-
Diameter of Screw	$\phi$	11	nos	-
Length of Screw	$L_{req}$	250	mm	-
<b>Finalized Screw</b>		<b>VGS 11 X 250</b>		