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MJØSTÅRNET: THE WORLD'S TALLEST TIMBER BUILDING

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ABSTRACT: Mjøstårnet is an 18-storey mixed-use timber building in Brumunddal, Norway, built by the shore of the lake Mjøsa. The building was completed in March 2019 and has been ratified by CTBUH as the world's tallest all-timber building. Mjøstårnet consists of offices, 72 hotel rooms, 33 apartments with balconies, a restaurant on the ground floor, conference rooms and a rooftop terrace. The architectural pergola extends the building 85,4 m from the ground level.

KEYWORDS: Multi-storey buildings, high rise, assembly, glulam, fire

1 INTRODUCTION

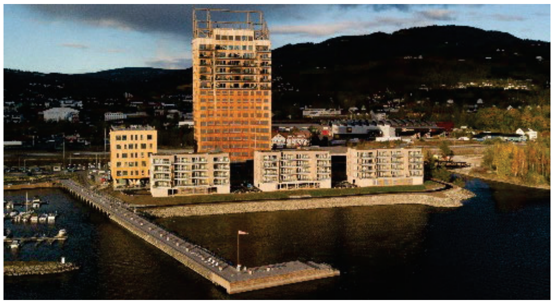

Figure 1: "Mjøstårnet". View from the lake Mjøsa

The initiative to build Mjøstårnet comes from investor Arthur Buchardt and the company AB Invest AS. He grew up in Brumunddal and wanted to build the world's tallest timber building placed in his hometown. In that way he wanted to show the world what is possible by using local resources, local suppliers, local competence and sustainable materials. He made the first sketch in February 2015 where he drew the building and its facilities.

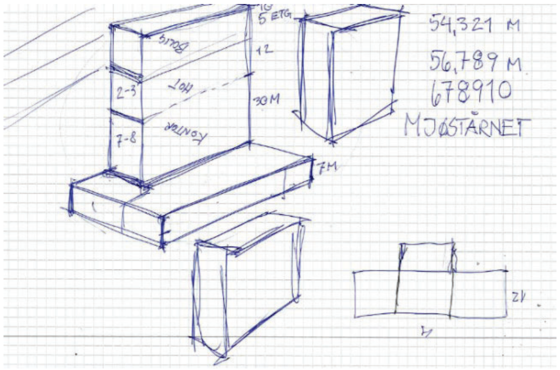

Figure 2: Sketch from February 2015 © Arthur Buchardt

Together with Moelven Limtre AS – Norway's largest glulam manufacturer - he continued to develop the project. VOLL architects were engaged as architects and HENT as main contractor. Only four years later, in March 2019, the tallest timber building was completed [6]. Brumunddal is located close to the shore of lake Mjøsa, 140 kilometres north of Norway's capital Oslo.

Figure 3: Brumunddal located in the central part of Norway

The completed building has a majority of wooden components originating from nearby sustainable forests. The wooden components comprise glulam structures in the main load bearing, CLT in the elevator and staircase shafts, as well as wooden based floor and façade elements. In total about 4000 m^3 of wooden products were used. To produce this quantity about 16.000 spruce trees were harvested.

The glulam structures as well as floor- and façade elements were produced only 15 kilometres from the site.

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2 STRUCTURAL SYSTEM

The structural and dynamic design of the tower was carried out by the Norwegian branch of the design company Sweco in collaboration with Moelven Limtre. The design was performed according to Eurocode 5 [1,2].

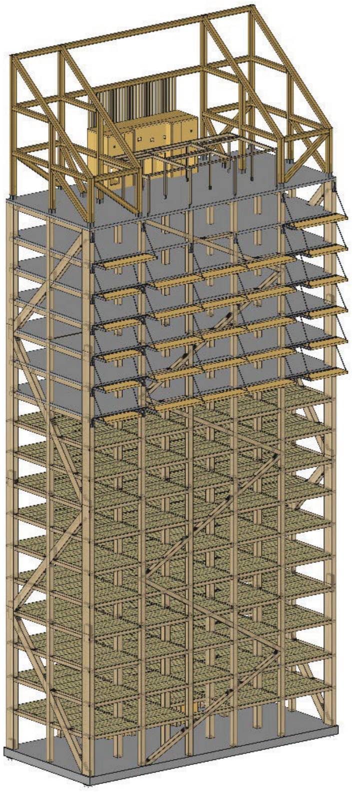

Figure 4: *Structural system*

2.1 The main load bearing

The main load bearing consists of large-scale glulam trusses along the façades as well as internal columns and beams. The footprint of the structure is 16,3 m x 36,9 m measured from the outer corners of the columns.

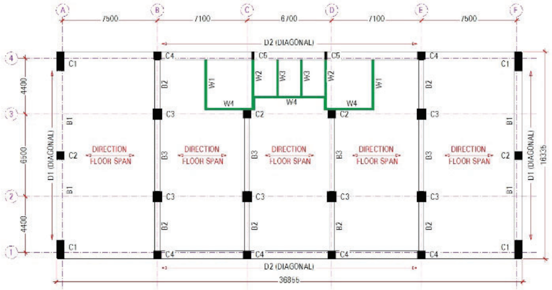

Figure 5*: The axes and main load bearing system*

The 22 columns (C) transfer the vertical load from beams and diagonals to the foundation. The cross-section of the corner columns is 625 mm x 1485 mm. These are the largest elements in the structure. Maximum span for the beams (B) is 6,5 meters and for floor elements 7,1 meters.

The lateral bracing system is quite basic. Four trusses consisting of columns and diagonals (D) are bracing the entire building. There is one truss in each façade and together they give the building the necessary rigidity to handle horizontal deformation and dynamic effects. Focus was placed on keeping the connections as simple as possible. One example is that the diagonals transferring the wind load are connected to separate columns.

Table 1*: Cross-sections of columns, beams, diagonals and walls*

Structure	Width (mm)	Height (mm)
C1	625	1485
C2	625	630
C3 at the bottom C3 at the top	725 625	810 630
C4	625	625
C5	215	625
B1 (wooden floor) B1 (concrete floor)	625 625	439 585
B2 (wooden floor) B2 (concrete floor)	395 625	585 585
B3 (wooden floor) B3 (concrete floor)	395 625	675 720
D1	625	990
D2	625	495
W1	220	-
W2	180	-
W3	160	-
W4	140	-

When designing tall timber buildings, it is important to verify that relevant comfort criteria are met. Timber buildings are light, and horizontal accelerations induced by wind must be carefully considered. For Mjøstårnet this was one of the governing aspects for the design. The structural damping obtained from the Treet building in Bergen was used for Mjøstårnet. The accelerations in the tower were monitored both during installation and after completion. The dynamic design was solved as a combination of structural stiffness and mass distribution. Tuned mass dampers (TMD's) to further reduce accelerations were not required and are not installed in Mjøstårnet. Four years after the opening there have been no reports of people feeling nauseated or uncomfortable.

2.2 Walls

CLT panels are used for secondary load bearing of three elevators and two staircases, but do not contribute to the building's lateral stability. Thicknesses of CLT walls (W) are listed in *Table 1* and the placement is shown in *figure 5*. All the CLT elements are produced by Stora Enso and installed by the local company Woodcon AS.

2.3 Floor elements

Each floor acts as a nearly rigid diaphragm which distributes the horizontal forces into the façade trusses. From levels 2 to 11 wooden floor elements are used. This is a wooden cassette deck adopted from the Swedish glulam manufacturer Moelven Töreboda, and it is called

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Trä8. The digit 8 refers to the span of this element which is up to 8 m.

Glulam joists spaced 600 mm make up the main structures in these elements. As top flange a plate of crossbanded veneers (LVL-C) is used, and as bottom flange a board of solid wood is used. By gluing the flanges to the joists, a static composite is achieved with increased bending and stiffness properties. The top flange cantilevers from the edge beam and transfers the vertical load into the supporting glulam beam. In this way the element can be mounted between the glulam beams, and only the thickness of the LVL-C plate is above the beams. This is an efficient way to minimize the structural height. The total height of the floor element is 439 mm.

A local company, RVT, produced the elements for Moelven Limtre.

***Table 2**: Cross-sections of components in the floor element*

Structure	Width (mm)	Height (mm)
Joist	66	360
LVL-C top flange	31	-
C3 at the bottom	148	48

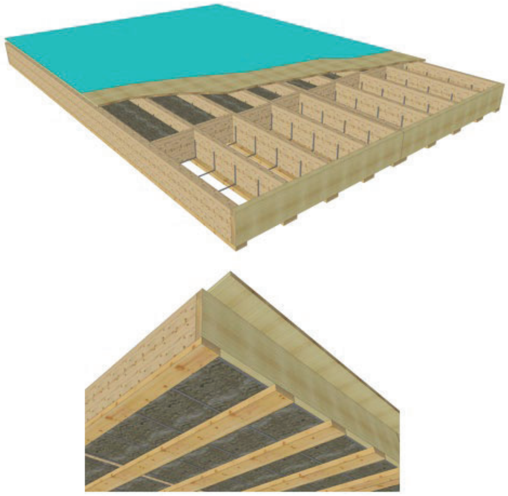

***Figure 6**: Trä8 floor element*

The seven upper floors are 300 mm thick concrete slabs supported by glulam beams. This adds extra weight to the structure which is beneficial for the dynamic behaviour.

2.4 Pergola

The glulam pergola at the very top of the building is not produced with solid rectangular cross-sections. To reduce potential shrinkage cracks on the outer surfaces these glulam parts were produced as hollow sections. The hollow section is composed of four rectangular beams with a width of 90 mm, glued together in each corner. All corners are rounded with a radius of 140 mm to improve aerodynamics.

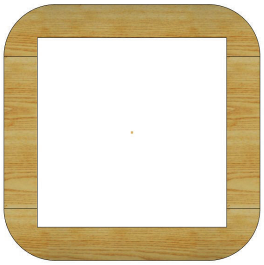

***Figure 7:** Hollow cross-section in the Pergola*

2.5 Balconies

In the six upper floors, which contain the apartments, balconies are attached to the façade and suspended from the columns with steel bars. CLT panels are used as floor elements. Polyurea coating is used to seal and protect the top of the elements from the weather.

2.6 Connections

Slotted-in steel plates with 12 mm steel dowels are used to transfer the forces between the glulam elements. The distance between the slots is 115 mm and the number of steel plates are two or four. The thickness of the plates is 8 mm or 12 mm. The number and thickness of the steel plates depend on the value of the force transmitted.

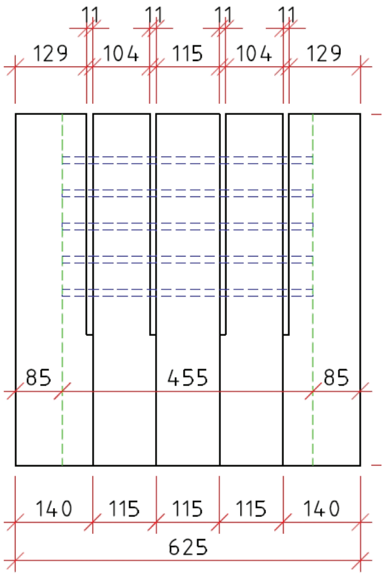

***Figure 8**: Typical cross-section build-up with slotted-in steel plates and dowels.*

Approximately 5000 kN of tension is the highest design force for a connection. It appears in the bottom of each corner when the wind load acts on the longest façade and tries to tilt the building. This requires 4 pcs of 12 mm steel plates and 100 psc of 12 mm steel dowels. All dowels are embedded 85 mm into the wood, which is the same distance as the charring after 120 minutes.

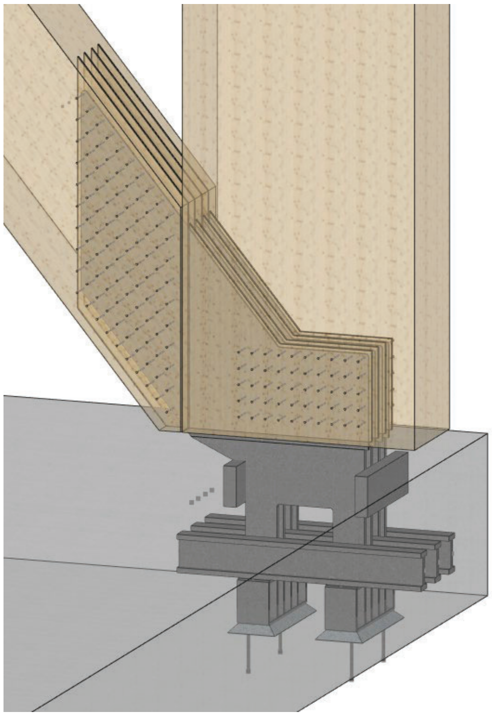

Figure 9: *Connection at the foundation in each corner.*

3 MATERIALS

A third of the volume of all materials used in the building is wood such as glulam, CLT and solid wood. The percentage of the different materials used to build Mjøstårnet is shown in *Table 3*.

Table 3: *Volume of materials*

Material	Share %
Wood	34
Insulation	33
Concrete	26
Steel	1
Other materials	6

3.1 The main load bearing

Glulam is used for trusses, beams and columns in the primary load bearing system. For the structural design, glulam strength classes according to EN 14080 [3] are used. Strength class GL30c, combined build-up, is used for all glulam structures accept from the bottom part of the corner columns which is produced as GL30h, homogeneous build-up. Lamellas with strength classes T22 and T15 are used for combined glulam, and only T22 for homogeneous glulam. Spruce is the species used for lamellas.

3.2 Walls

CLT panels is used for elevator shafts and staircases. The strength class of the lamellas is C24 according to EN 338 [4]. Spruce is the species used for these lamellas.

3.3 Floor elements

Timber floor cassettes are used in levels 2-11 and 300 mm thick concrete slabs are used in storeys 12-18. The floor joists are resawn glulam with strength class GL28cs [3]. The characteristic bending strength is 28 MPa and the modulus of elasticity parallel to grain is 12500 MPa. Kerto®-Q panels, produced by Metsä Wood, are used for the top flange and also the edge beam of the elements. Strength class for the bottom flange in solid wood is C24 according to EN 338 [4]. Spruce is the species used for all these components.

3.4 Pergola

GL30c [3] is the strength class used in the pergola structures, and the glulam is Cu-impregnated throughout. Pine is the species used for these lamellas.

3.5 Balconies

CLT is also used as floor elements for the balconies. The strength class of the lamellas used in the panels are C24 according to EN 338 [4]. Spruce is the species used for these lamellas.

3.6 Connections

S355 steel is used in connections together with acid-proof steel dowels with tensile strength f_u=700 MPa.

4 FIRE DESIGN

The fire strategy report for Mjøstårnet states that the main load bearing system must withstand 120 minutes of fire. Secondary load bearing such as floors must withstand 90 minutes. In addition, the structure must withstand a full burnout and prevent a total collapse. This means that after a burnout, the load bearing system will still be in intact and the fire in the structural elements will be put out by itself. The fire design is verified by 90 minutes burnout tests that were performed in 2016 at SP Fire Research AS in Trondheim. The tests prove the fire behaviour of large-scale glulam sections and their connections [5].

Figure 10: *Burnout test at SP Fire Research AS in Trondheim.*

4.1 Reduction of cross-section

The structural fire design was done by calculating the remaining cross-section after charring according to Eurocode 5 [2]. The charring rate is 0,7 mm/min at every exposed side of the cross-section. This means that 120

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minutes of fire gives a charring depth of 84 mm. In addition, a layer of 7 mm with loss of strength must be taken into account. The total reduction of cross-section for every exposed side will be 91 mm for 120 minutes of fire.

4.2 Protection of steel connections

Steel plates and dowels used for connections are embedded deep into the timber. In this way the timber insulates the steel and protects it from fire exposure. All gaps and slots between beams, columns and plates are fitted with an intumescent fire strip. When the heat reaches 150°C this material will start to expand up to twenty times. In this way open gaps and slots will be sealed and the steel inside will be protected. The 90 minutes fire test by SP Fire Research AS [5] proved that the temperature in the steel connections did not reach more than 250°C, which is structurally acceptable.

***Figure 11**: Sealed slots and gaps using intumescent fire strips.*

4.3 Robustness in fire

As for robustness the structure is designed to sustain the loss of the horizontal stiffness of one entire floor. It can also carry the impact load of a timber deck falling down on the floor below.

4.4 Other fire measures

The entire building is sprinklered. In escape stairs, the wall panels are covered with fire gypsum and in all open public areas the wooden surfaces are treated with a fire-retardant paint. The wooden boards used on the façade are heat treated pine, additionally pressure treated with a fire retardant. For every storey in the façade there is also a fire stop device.

5 ASSEMBLY

The assembly of the building was divided into six stages. The main body up to level 18 was built in four steps, were each step comprised four or five storeys. Thereafter came the installation of balconies and in the very end the rooftop pergola.

***Figure 12:** Assembly steps*

The first timber element was installed on the 4th of September 2017, and the final beam on the pergola's top was mounted exactly one year later.

***Figure 13:** The last beam installed.*

5.1 Preparation of elements in factory

Every single structural element is processed using Computer Numerical Control (CNC) machines. All cuttings and drillings are done in the factory. It means that the accuracy of the geometry is very high and produced practically with zero tolerances. steel plates were installed into the glulam columns in the factory before being transported to the building site.

***Figure 14**: CNC processing / Block gluing / Installation of steel plates*

5.2 Embedding of base connections

Embedding of the base connections is maybe the most crucial part of the assembly. If the placement of the bases is inaccurate the timber elements will not be possible to assemble correctly, and the geometrical tolerances of the building will be unacceptable. This is particularly important since all the elements arrive the building site precut and predrilled.

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***Figure 15**: Base connection of the corner column and diagonal.*

5.3 Assembly on ground and hoisting of frames

Before the erection started all the glulam structures for the upcoming assembly step were put together into frames on the ground. Then these frames were hoisted into the building and installed. The frame sections were four or five storeys high.

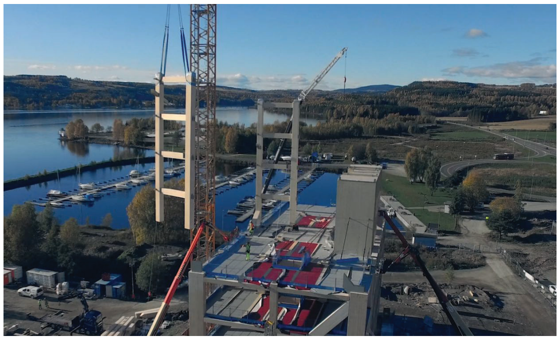

***Figure 16**: Hoisting of frames.*

5.4 Assembly of floor and balcony elements

Both the floor and balcony elements were prefabricated at the factory and hoisted directly on site. There were four lifting hooks on each floor element for lifting the floor elements. A specially designed lifting device was made for the balcony elements. This was done to avoid lifting hooks that potentially would damage the polyurea membrane coating on top of these elements.

***Figure 17**: Hoisting of balconies with tower crane.*

5.5 Assembly in height

The timber skeleton was installed using a tower crane, mobile cranes and lifts. It was not needed to use any kind of scaffolding for the installation of the load bearing structure. The tower crane was operated by the turnkey contractor HENT.

6 CONCLUSIONS

The completed building proves that an 85 meter high glulam building can be built using local competence, local suppliers and local materials. Mjøstårnet is already an iconic landmark in Norway and serves as an inspiration on how to build sustainably in the future. Using the same structural principles, it is possible to double the height.

ACKNOWLEDGEMENTS

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