Use of tension rods in wood construction – 14 storeys – with laminated veneer lumber as shear walls: Lighthouse Joensuu

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1. Introduction

Lighthouse Joensuu is a 14-story construction that is currently being build. After completion, it will be almost 48 meters tall being by then the highest wood building in Finland. The structure is being built mainly using wood elements. It is located at city of Joensuu at eastern part of Finland. It will provide 117 apartments for local students to live in. The builder of Lighthouse Joensuu is Student housing Company Joensuun Elli. Principal designer was Samuli Sallinen from Arcadia Oy Arkkitehtitoimisto and head of structural design was A-Insinöörit, Tomi Rautiainen. The building is expected to be completed in autumn of 2019.

At case of Lighthouse Joensuu the self-weight of the building was relatively small compared to structures made of concrete or steel. At Joensuu there is a similar height and size concrete building which doesn't have any tension forces due to large self-weight. In the beginning of design process, it was also proposed to have core of the building made from concrete (elevator shaft/stairway) to add weight and stability to the building. This design option was however cut off by demand by the contractor for construction work to have the entire structure made of wood elements to have an environmentally friendlier option to concrete buildings and to see if it would be even possible to make.

After initial risk analysis with the Joensuu city building control it was determined that the building would be considered as an exceptionally demanding project and the buildings consequence class would be CC3. This would require further risk analysis procedure and the usage of external inspection during design and construction process. This procedure created demand for enhanced co-operation between project participants. In addition to regular meetings during the design and construction process it became necessary to hold also additional workshops to go through design principles, guidelines and demands which the new system of tensioned rods and high-rise wood building would bring to all participants of the project.

The structural design followed the Eurocodes and national annexes in areas where guidance was available in regards of loads and load combinations. However, the lack of available Eurocodes for tensioned wood wall structures and solid wood wall structures in general required some extra research of information at beginning of the project. Much of the needed information was however available at the ProHolz and WoodWorks guides which contained more detailed guidelines for CLT- and tie-down system structural design that the Finnish national annexes and Eurocodes lacked during that time.

The first option was to use large machine shop parts like in modular buildings. After discussions with designers and the crew at the building site it became obvious that having steel parts weighting more than 30 kilograms and being almost one meter in diameter is not going to ease the smoothness of work. The forces that were accumulated at the base levels of the building were then too big for traditional hold-down systems to be reasonable size or the amount of connections would be too large. So, it was time to move on in search of a more functional tie-down system.

The seemingly small weight of the wood building elements caused therefore large overturning moments induced by lateral loads, wind load mainly. And this in the other hand caused uplift forces to the individual LVL-X wall panels. The uplift forces needed then to be transferred directly from multiple levels to the foundation. The concrete base must also have mass and strength to resist these overturning forces. This led to usage of tension piles at the corner areas of the building and to a thicker concrete floor at first floor level. In other words, the first reinforced concrete floor acts as a stiff cube that provides the upper floor mass and stability. After some brainstorming with the structural designers, worksite crew and structure designs external inspector it became obvious that tension rod system might be our best hope to make this building work for the sake of design and construction.

Figure 1: Elevations and a floor plan picture of Lighthouse Joensuu. Courtesy of Arcadia Oy Arkkitehtitoimisto

2. Structural system and materials

The same tie-down system that is in Lighthouse Joensuu is used mainly in the United States and Canada with light-frame, multi-story wood construction. In Europe the use of rod tie-down system seems to be in a smaller scale due to several reasons: lack of knowledge, few suppliers dedicated to wood tie-down systems, no planning guidelines specified for the wood tie-down systems in Eurocodes or at national annexes. This leads the designer to a search of planning guidelines outside Europe and to a need of local authorization for used design criteria in each wood high-rise building project. (I have included in the end some useful links to ease the pain for searching these planning guidelines.). At Lighthouse Joensuu the local authorization process was used for acceptance of new design methods. Some basis of design can however be taken from Eurocodes for post-tensioned concrete and steel parts because of the almost homogenous material properties of LVL-X.

The used tie-down system in case Lighthouse Joensuu is a skipped floor system or by other name called as discontinuous rod tiedown system. The skipped floor system means that shear walls are not restrained at each level. The number for restrained levels is maximum of three floors in Lighthouse Joensuu. The rods are unbonded and can move freely inside the LVL-X wall elements. The wall elements are post-tensioned after installation and act against overturning moments.

2.1. Materials used in Lighthouse Joensuu

The first level of the building consists of reinforced concrete floor, slab and walls. The pile foundation has SSAB RR170/10 and RD170/10-piles driven to the base soil. The RR-piles

are subject to compression and head of the piles and diagonal piles withstand also shear forces. The RD-piles in the other hand are to withstand compression/tension forces at corners and intersections where overturning forces cumulate the most when the tension rod forces are transferred to foundation level.
The rest of the shear walls including the lift and stairway shaft are made from Stora Enso LVL-X (laminated veneer lumber) wall elements. The levels 2-4 are made of LVL-X with thickness of 162 mm, levels 5-11 out of LVL-X thickness of 144 mm and the top levels 12-14 are LVL-X with a thickness of 126 mm. The number of LVL-X wall elements were 29 pcs/level with a total of 381 pcs for the whole building.

The floors of each level are made from Stora Enso CLT-panels (cross laminated timber) made of spruce with a Stora Enso LVL-S support beam that is connected with self-driven screws to LVL-X wall. The larger cut of pieces from the wall elements are used as a floor panels on the narrow hallway connecting the apartments. The stairs are also made from CLT-panel and the rises are CNC-machined in the CLT-panel. The number of CLT and LVL-X floor elements were 47 pcs/level with a total of 587 pcs for the whole building.

The walls and floors are connected with Rothoblaas TTN240 steel angle bracket against shear forces. Self-tapping screws are also used at LVL-X wall to wall and CLT floor to wall connections. The panels of LVL-X/ CLT are connected among themselves with a half-lap joint and self-tapping screws. The half-lap joints direction (upper/lower flange) is governed by the installation order to provide smoother installation of elements.

The overturning forces are handled by using tensioned SAS 670/800 22TR rods (bar) as a main mean of tie-down against occurring uplift forces. The ETA-approval for GEO structures was used in case of wood stuctures (ETA-13/0840 and ETA-13/0022). The rods were connected to the concrete base with Peikko SUMO- wall shoes. The tensioned rods also connect the separate levels together and for sake of construction safety and overall stability it was chosen that the levels would be restrained as stacks of three levels. Number of SAS 670/800 22TR rods were including the ones that are connecting to upper floors: levels 2-4 total of 94 pcs, levels 5-8 total of 59 pcs, levels 9-10 total of 45 pcs, level 11 total of 45 pcs, levels 12-14 total of 34 pcs. All tie-down system parts including wall shoes are standard parts only with the expection of bearing plates which were shop made separately. So they should be available quite easily for construction.

3. Structural design

The structural design and analysis were mainly done by hand calculations to have a better understanding of the affecting forces on the building. Distribution of impact to the LVL-X elements were calculates as individual wall sections without taking in consideration the combined cross-sections when done by hand calculations. Hand calculations were counterchecked by using Dlubal RFEM calculation in independent structural peer review by A-Insinöörit, Kuopio designer Petri Rytkönen. Then these results were compared side by side to pinpoint reasons that could cause the differences in results and behaviour of structure. The calculation methods and chosen theories were also part of workshops that were held with structural main planner Tomi Rautiainen, structure designs external inspector Juha Siegberg and me. These workshops were essential to be held also with other project designers to freely discuss ideas and methods to make the structure work in every aspect of design.

As a design rule the horizontal displacement of the building was limited to H/500 (H=height of the building). The calculation was done by hand as a mast wall which would contain the tie down displacement (caused by tension losses) due to reasons listed in chapter below. The estimation was ~60 mm if the rods tension losses would be at "worst case scenario" and when comparing this to RFEM-calculation result of ~40 mm (taking account the surrounding walls) It can be assumed that the rod tie-down guidance rule of North-America region is on secure side as overall when done by hand calculations.

Figure 2: Construction crew at work unloading a truck at Lighthouse Joensuu site. Courtesy of Rakennustoimisto Reijonen

It was decided also to use portion of friction from permanent impact with a relieving effect when calculating shear anchoring for wall, formula Vd=Fd-0,9* μ*Gk (this can be found from proHolz CLT design guide). Sliding friction μ =0,2 (LVL-LVL normally μ=0,35) which is on safer side taking in account e.g. sawdust or dirt if present at bottom of LVL-wall elements. The tensioned rods were not accounted to act as a permanent impact and therefore did not have relieving effect at walls. This way the design is on safer side even if the anchor nut would not be tightly against bearing plate. If it can be shown that the anchor nut will not be loose then it could be used also as permanent impact against shear forces. It has to be noticed that in Finland friction is rarely used with wood design at structural design companies. This is because of lack of it being mentioned in national design guides for wood.

3.1. Fire resistance and requirements

The Lighthouse Joensuu's fire design was done by Insinööritoimisto Markku Kauriala Oy by Mikko Salminen with KK-Palokonsultti Oy as external inspector for fire design. In time of the design of the building, national annexes (RAKMK E1) had fire design charts for wood-buildings of 8-story height. Therefore, it was needed to use functional fire design which took in account the actual fire loads that would be present at the building during use stage. At this time happened also the fire at tower block in London which created even larger concern for fire safety in high-rise buildings. Fire design overall and prevention of fire spreading during construction came also a key concern of workshop discussions and risk analysis.

The fire requirements for surface materials therefore led to a situation where the wall faces do not have wood as visible surface. The wood structures, connections and rods are covered and encapsulated with Saint-Gobain, Gyproc gypsum board and Paroc rock wool insulation (thickness >30 kg/m3). The shafts and MEP-design installations were ensured by providing sufficient fire barriers as well. The building was also equipped with sprinkler system (OH1-class) designed by Fire Designer Tea Nieminen of Kauriala Oy. And it was shown with functional fire design that building would withstand the fire even if the sprinkler systems would fail. Therefore, it can be said that the building will withstand the fire even if the fire load would be burnt out being equal or even better compared to building build using other materials.

Class requirements for load-bearing and substructure structures	
Structure	**Class requirement**
Wood Structures, levels 2-14	R90
Staircases and landings	R30
Storage area at first floor	R120
Other areas at first floor	R120
Vertical shafts if part of load-bearing structure	R120
Integrity and insulation requirement as a rule	EI60
Integrity and insulation requirement for storage unit in first floor	EI90
Windows and doors	Half of structures class requirement
Surface material class requirements	
Interior surfaces of load-bearing structures	A2-s1 (K_230)

Figure 3: Class requirements for load-bearing and substructure structures

3.2. Acoustic design

Because of fire requirements for wood structures it became apparent that this could provide sufficient separated layer structures for impact and airborne insulation as well. A-Insinöörit Oy, Mikko Kylliäinen, also tested the structure types with acoustic simulation to provide support for structural designers. At Lighthouse Joensuu the load-bearing structures were not separated by means of vibration isolation ribbons. This was a conscious choice to reduce tension losses at rods and to decrease deformation of the structure.

4. Structural tiedown with tension rods

4.1. Design of tension rod forces and locations

To determine the location and number of tension rods for each wall the overturning moment calculation was applied. This means that the shear forces and moments caused by wind and eccentricity of walls cause overturning moments. To prevent the wall from overturning it has supporting moments caused by stabilizing forces. These stabilized forces are self-weight (0,9*Gk) and the tension force at rods (0,9*Fu,d), these forces affect by their individual torque arms. The wall has to be checked for both directions of affecting force (wind+eccentricity). It was also checked that the tension rods are placed symmetrically in respect of the centre of geometry of the undivided wall. Symmetry rule for placement is thereafter applied to whole building taking in account the centre of gravity by shear wall placement.

The tension forces and self-weight of individual walls were also transferred between elements by having steel angle brackets that had sufficient capacity to help their intersecting walls against overturning. This way at some exterior wall lines there was no need to add additional tension rods because they could share the same tension rod that had enough capacity for both intersecting walls. Alternatively, the wall that is collecting most of the dead weight loads could share its dead weight if it had excessive amount of it to be shared to other walls against overturning. The service limit states tension force against overturning is the value including all the tension losses (in Lighthouse Joensuu case ~170 kN). At ultimate limit states, the used tension force is the same that was obtained during restraining phase (in Lighthouse Joensuu case 216,4 kN). In Lighthouse Joensuu the vertical wall connections are also able to connect the walls together even at accidental situation and to prevent progressive collapse.

Discontinuous rod tiedown system load path function principle (similar to continuous tiedown system load path)

- *The end post deliver the sheathing load to the top plates and bearing plates*
- *Bearing plate transfers the load through a nut into the rod system*
- *Rod system transfer the load from the plate through tension in the rods to foundation.*

The text above is a direct reference to "Strong-Rod Systems Seismic and Wind Restraint Systems Guide". In the end after some reading and searching, the basis of design can be done therefore by following the basic guidelines of overturning moment calculation. But it must be recognised that the tie down deformation/displacement accumulates from the skipped floors to the lowest story of a set of skipped- stories.

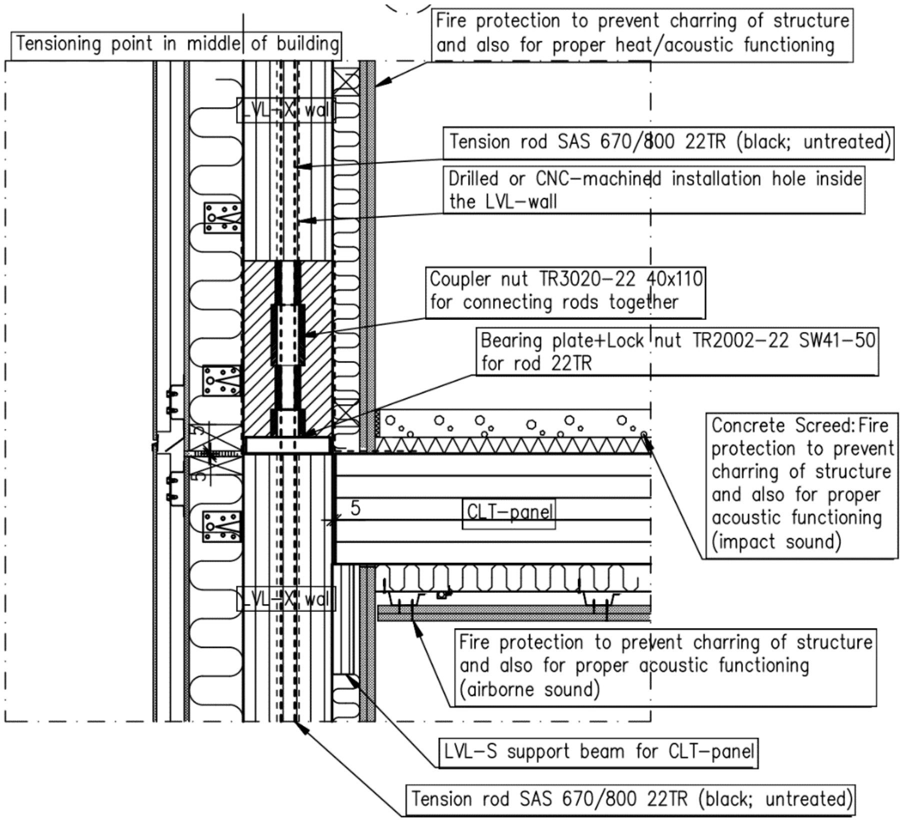

Figure 4: Detail of a tensioning point in middle of the building. Courtesy of A-Insinöörit Oy

4.2. System deflections and tension losses

There are however, some key considerations when designing the tension rod tie-down system. In case of skipped floor system, the total deflection of the system affects the total displacement of the wall as well. Tension losses can be then divided to instantaneous and mid-term or long-term losses.

The total system deflection and tension losses in rods are a sum of multiple factors:

- Tie-down rod elongation ($\Delta rod = PL/A_nE$)
- Tie-down rod heat expansion
- Tie-down rod diameter and spacing within the LVL-X element
- Positive connection in rod couplers
- Bearing plate rotation
- Bearing plate crushing
- Bearing plate bending and deflection
- Wood member shrinkage and swelling
- Wood member heat expansion (almost minimal effect)
- Long term creep of building
- Settling of wall elements
- Stiffness and deflection of wall element from lateral loads

Instantaneous losses occur during the tensioning process with hydraulic jack in the tensile length of rod: settling of wall elements, rod couplers settling, bearing plate bending and deflection, bearing plate crushing, bearing plate rotation (if friction between parts is small). At case lighthouse Joensuu the reported settling of the building was ~3 mm for stack of three floors restrained based on measurements done by Karelia University of

Applied Sciences. The installation crew of Naulankanta reported that the coupler settling was 2 mm for stack of three floors. This affected the initial value of calculated tensile length of rod and was adjusted to match these observations.

Mid-and long term losses occur mainly for: wood member heat expansion, deflection of wall element from lateral loads, wood member shrinkage and swelling and of course long-term creep. The wood members tend to swell before heating is applied indoors because of the moisture of delivered wood elements is 10-14 % for CLT and 8-10 % for LVL-X. This means that the timber moisture is in construction stage close to +2-5 % depending of exposure time to outdoor air humidity (RH-%). And after restraining the LVL-X wall element shrinks back to 10-12 RH-% after indoor heating is applied which has to be taken in account when determining total system losses of tie-down system.

At the moment the limitations and recommended values are for light-frame wood construction in the "AC391 Acceptance Criteria for Continuous Rod Tie-Down Runs and Continuous Rod Tie-Down Systems Used to Resist Wind Uplift". These values were used as a guidance when designing the Lighthouse Joensuu. The total system deflection has to be taken in account when considering the tie-down rod diameter and spacing within each LVL-X wall element.

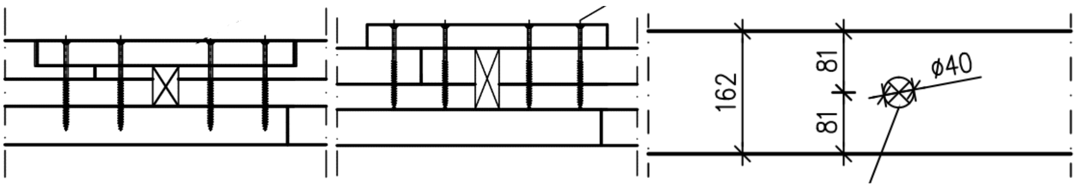

Figure 5: Installation hole options for SAS 670/800 22TR rod to be placed inside the LVL-X wall. Courtesy of A-Insinöörit, Joensuu

4.3. Installation and placement of rods

The rods are placed inside the wall element by having either a drill hole through the element or with a CNC-machined T-shape or notch CNC-machining on the face of the element with an LVL-S spline glued and screwed on the face to cover the rod. The size of the installation hole weakens the wall element itself to certain degree and reinforcement has to be considered if LVL-X manufacturing defects are present near the hole. The drill used for making the holes also tends to start drilling between LVL-X multiples of veneer or start drilling in an angle causing angular deviations. However, when using a rod installation hole that is large enough in comparison to the rod size the small deviations are acceptable.

Rod height was chosen to match with the wall element height so that installation of rods would be easier and if needed the rods could be changed within each level. This meant that rods would be connected at each level with a coupler nut. The tensioning of rods is done with a hydraulic jack so that tension is first done as 20 % of final applied tension force and length deformation is measured. Then the rod is tensioned to 100 % having the designed tension force applied to the rod (The maximum tension force used was 241,8 kN/rod and for designed tension force 216,4 kN/rod). Individual walls would be restrained in a "zig zag" fashion so that any side would not have excessively more tension force applied than the opposite side. The restraining order for building was determined so that the tensioning would start from middle of the building and the building would be equally tensioned relative to the centre of gravity. This could be easily imagined as a "water drop" causing circular wave starting from centre of gravity.

Figure 6:Restraining done from top of the wall with LVL-X wall installed afterwards.
Courtesy of Rakennu-stoimisto Reijonen

The bearing plate system consisted of standard parts listed below and the supplier and installation crew for these parts was Naulankanta Oy:

- Tension rod (bar): SAS 670/800 TR22, black (untreated)
- Bearing plate: According to structural design
- Anchor nut: TR2002-22 SW41x50
- Coupler nut with set screws: TR3020-22 40x110
- Peikko SUMO30P and Peikko SUMO39P for concrete connections

5. BIM (Building Information Model)

BIM maturity level 2 was used throughout of the project. BIM-modelling rules and guidelines were agreed at the beginning of the project between designers. BIM-modelers and designers also worked in co-operation to have equally matched coordinates and levels.

In this project we also almost got to the BIM level 3 with architect and structural engineer using the same program of Autodesk Revit. The use of single shared model was not accomplished this time due to the differences at the used Revit versions, but this could have been possible quite easily in the end by having a shared cloud service.

The main way on communication was done with IFC files between designers and by comparing the data with the help of BIM-coordinator Jesperi Vara from Arcadia Oy Arkkitehtitoimisto. Only the first floors concrete structural plans were done with traditional 2D-CAD at BIM maturity level 1. Most of details and section pictures were done with traditional ways as well.

The process itself was smooth for designers because we all were doing the design by using BIM-models. This enabled that the printed documents added up with the BIM-models and most of the geometry differences and clashes between model objects could be tracked down from the combination model as they might occur.

The biggest advantage was however, the ability to use the Autodesk Revit model directly to get the CNC-machining files and Bill of Materials out of the BIM-model. The ability to monitor changes and copy model elements between BIM-models was an eye-opening experience. The time saved by using this method was countless hours of repetitive work and leaved time for actual design of the building. In means of BIM dimensions the project was therefore at 5D-level (4D- level was achieved by noticing the installation order in modelling of e.g. half-lap joints).

However, if the manufacturer of LVL/CLT- elements is placed at different location than the CNC-machining company this creates different requirements for the BIM-element design process. There are then two main lines to follow. Firstly, the designer has to provide at early stages the data for master panels and maximum dimensions to be used. At this stage the elements are split to contain coarse detailing e.g. support beams and large openings. This way the factory can start production of needed materials for the next phase. The manufacturing of needed master panels is undergoing, and the designer continues the more detailed design of elements. In this next phase designer ads all the data from other designers including inlets, lift holes, half-lap joints etc. These BIM-objects are then tested to transfer properly from IFC/3D-DWG format to CNC-machining format with the CLTTechnik. The CNC-machining file is also tested at Timberpoint before any elements have arrived. The goal is to do minimal amount of work later on to fasten the process at the final phase.

At final phase the converted IFC-files are send by CLTTechnik to structural designer to clash with their own BIM-model. And when there is no geometry changes noticed, the file is send to Timberpoint for CNC-Machining. At this time the LVL-elements have already arrived for CNC-machining and wait time is minimized. The CNC-machined elements are then send to construction site for prefabrication.

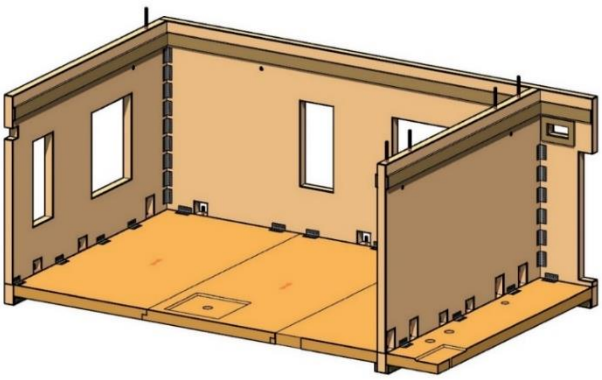
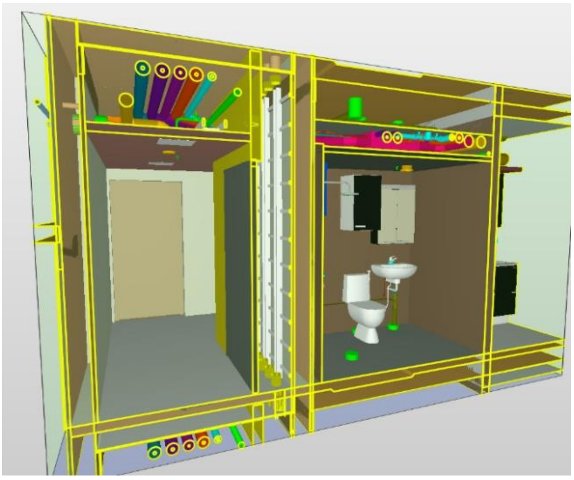

Figure 7: 3D-section of a structural model. Courtesy of A-Insinöörit. (at left).
3D-section of combined model including all BIM-models from each designer.
Courtesy of Arcadia Oy Arkkitehtitoimisto (at right)

6. Building and production tolerances

It was chosen at the beginning of the project that we would use strict tolerances to prevent movement caused by drift between the connections. This required that the gap between the elements would be smaller than that are normally used in Finnish wood building guides.

- wall to wall connection, at each end of the wall gap was 2 mm
- wall to floor connection, gap when installed on top of support beam, 5 mm at each end
- support beam to beam space for wall installation, gap would be +10 mm in respect to the wall thickness

The LVL-X and CLT-element tolerances were assured by CNC-machining all sides of the element to match with BIM-model elements. Building tolerances followed the SFS 5978 tolerance class 3 requirements.

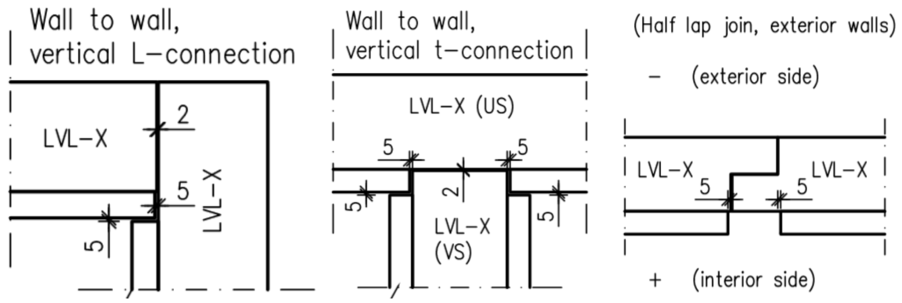

Figure 8: Tolerances used for CLT- support beams installed at prefabrication of elements. Courtesy of A-Insinöörit Oy, Joensuu

7. On-site fabrication of LVL-elements, weather protection and installation of elements

At the construction site, the Rakennustoimisto Reijonen Oy responsible site manager Jukka Timonen and site manager Jouni Räsänen direct the completion of prefabrication and building of Lighthouse Joensuu.
Unloading and lifting of elements is done by using mobile auto crane that is present at worksite for whole duration of the building. The lifting of elements is done by only one set of lifting slings that have capacity for all phases of prefabrication and construction process. The construction crew has also a separate elevator for their usage during the construction.
Rakennustoimisto Reijonen crew prefabricated the exterior LVL-X wall elements by installing the exteriors rock wool heat-insulation+ wood framing, façade panels, windows and doors at the tent located next to the main construction site. This way it was secured that the LVL-X elements are covered from excessive moisture, especially from rain. The LVL-X element grains are also sealed on edges so that moisture may transfer only through the surface of the element.
The walls are installed after the previous levels CLT-elements are in their place. This way the installation crew can move freely on the top level having almost no hindrance in their way and improving work safety as well. The weather sheltering rafter segments are lifted off only when the need to install LVL-X or CLT elements arises. The gybsum boards are lifted on top of the CLT-floor prior to installation of next floors CLT-installation. The installation time of one wood level is one to two week and the pace has improved as the installation crew gains more experience and work methods become more familiar.

8. Conclusion

In future of wood building projects in general it would be wise to have to structural designers that are really doing the dimensioning and calculations involved at early stages of draft design. It will be too late to have the structural designer involved when the shape and materials of the building are already decided. This leaves little to no room for optimization or good structural design choices at the stage where decisions are already made. Solutions are thereafter only acceptable or compromises to reach the given goal. In the design process designers should be given enough design time and not to be rushed to make hastily decisions that would later require redesign in worst case.
The tie-down system of tensioned rods seems like a working system for wood building and further research should be done especially to determine how the system affects the peak accelerations of a high-rise building. This tie-down system seems to be best suited especially for seismic areas. On the other hand, attitude of right materials to the right places must also become a reality and the sole goal to build out of this world structures build solely from wood is farfetched. To really build environmentally friendly sustainable housing it requires that the wood building has to be industrialized and standard parts to be used, then it can truly be cost effective with concrete and steel structures. The Industry 4.0 is coming faster than expected with BIM, smart systems and CNC-machining becoming the key factors and necessity to make wood building the way of the future.

Figure 9:Picture taken from inside of the prefabrication tent located next to building site.
Cour-tesy of Rakennustoimisto Reijonen

8.1. References and useful information

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Design and behaviour of a mid-rise cross laminated timber building. Conor Lenon

Seismic design of post-tensioned timber frame and wall buildings. Michael P. Newcompe

Strong-Rod Systems Seismic and Wind Restraint Systems Guide

Coming Up with Tie-Downs Part II. Bryan Wert, M.S, P.E.

Evaluation of wind-induced vibrations of modular buildings. Asko Talja, Ludovic Fülop

9. Participants of project

9.1. The main attendees (in no particular order)

Joensuun Elli: Jarmo Ojalainen, Vesa Vapanen

Arcadia Oy Arkkitehtitoimisto: Principal designer Samuli Sallinen, Heikki Toivanen, Jesperi Vara

Granlund Joensuu Oy: Anssi Pesonen, Johanna Lankinen, Jani Määttä, Niko Hellberg, Mikko Sallinen

A-Insinöörit Oy, Joensuu: Head of structural design Tomi Rautiainen, Anne Muuri, Jukka Kettunen, Mika Keskisalo

Rakennustoimisto Eero Reijonen Oy: Jarmo Hämäläinen, Jukka Timonen, Jouni Räsänen and the construction crew

Stora Enso: Antti Koukkunen, Sami Typpö, Jukka Silvennoinen, Sanna Kinnunen, Juha Kirjalainen

Stora Enso CLT-Technik Team: Wilhelm Polster, Lukas Hasler, Herbert Reutner

Palotekninen Insinööritoimisto Markku Kauriala Oy: Mikko Salminen, Päivi Myllylä, Tea Nieminen

Timberpoint Oy: Marko Suonpää and the Timberpoint employees

Lämpökarelia Oy:Jari Könönen and the employees

Sähkö-Saarelainen Oy:Jorma Tykkyläinen and the employees

Scneider Electric: Jukka Romppanen and the employees

A-Real Oy:Pekka Tuunanen

LVI Ekonsult Oy: Esko Jalkanen

FCG: Eino Mönkkönen

Juha Siegberg, structure designs external inspector

Insinööritoimisto SRT Oy: Pauli Oksman, post-tension external inspector

A-Insinöörit Oy, Joensuu: Petteri Peltomaa construction works external inspector

Naulankanta Oy: Henri Huoso, Juha-Matti Paloniemi

Joensuu Building control: Jukka Hyttinen, Petteri Elonen

Rothoblaas: Giovanni Vitale, Andrés Reyes

Saint-Gobain Finland Oy/Gyproc Arto Hyttinen

A-Insinöörit Oy, Kuopio:Petri Rytkönen (FEM-model verification)

Karelia University of Applied Sciences: Mikko Matveinen, Timo Pakarinen, Ville Mertanen

I would like to thank the participants of this project for making it possible. Especially the people at construction and manufacturing crews for making the designs come to reality.

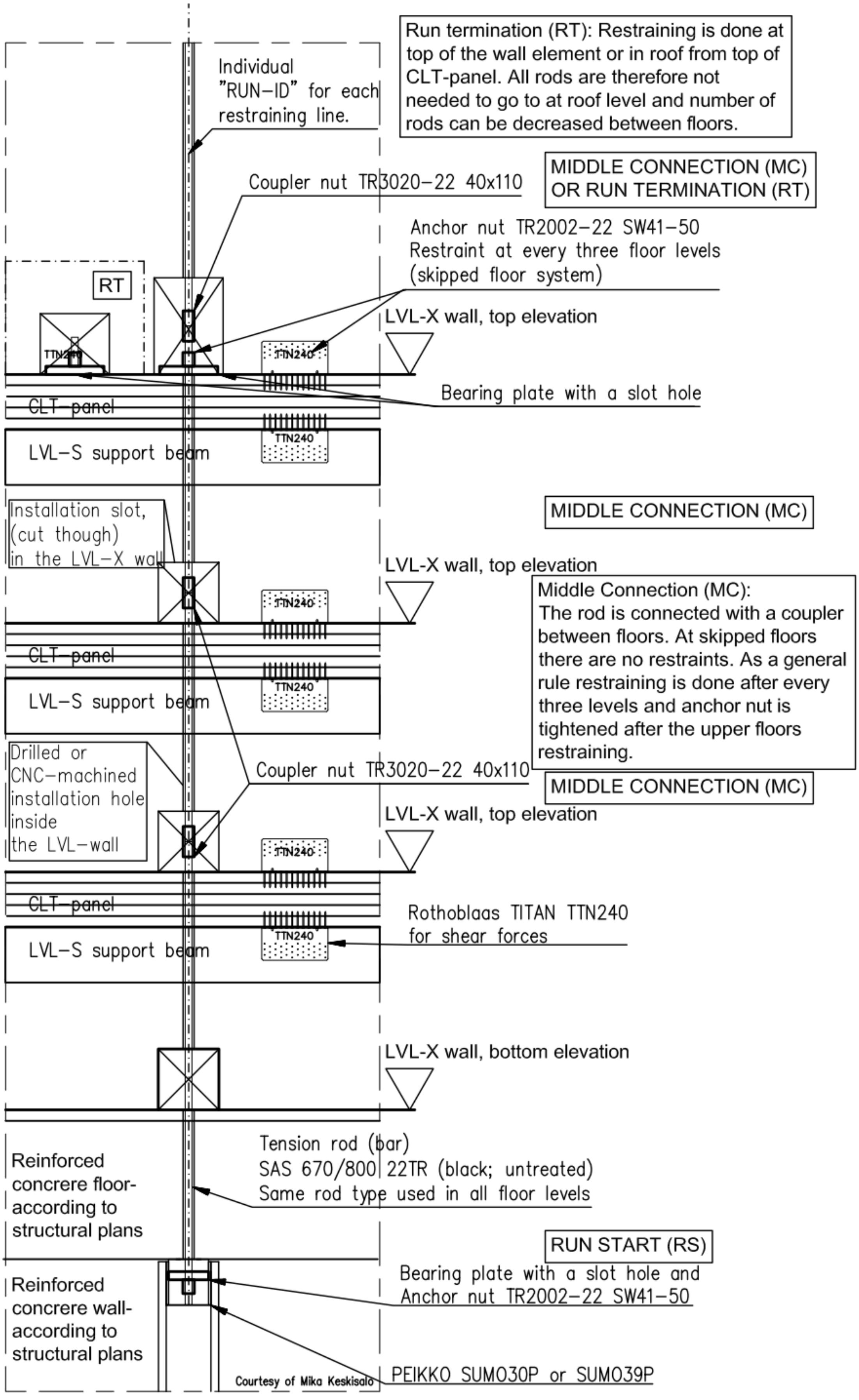

Figure 10: The principle of skipped floor system for LVL-X walls with post-tensioned tie-down rods. Courtesy of Mika Keskisalo (A-Insinöörit Oy)