The planning and construction of a double curved building in cross laminated timber (CLT) panels

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ABSTRACT: This paper examines the planning and building process of a double curved building made of CNC cut cross laminated timber (CLT) panels. The paper explains the design of the shape, the construction process, and the choice of surface material. Still, the main focus is to investigate the practical experiences collected through the construction of such a non-tolerance-building set. The paper will look at what unforeseen challenges occurred on site during the construction. The main challenge for a building system consisting of perfect shaped panels, is that there is no room for adjustments during construction. Several characteristics of the shape of the building is belied to have caused trouble in terms of accuracy compared to a convex-only building with the same construction system. Another finding was that the engineer's choice of screws had an unexpected and significant impact on the construction process in terms of accuracy and construction time. For future development of the building system, there should be paid attention to means to either be able to build more accurately or there should be developed a way to adjust the position of the elements during the building process.

1 INTRODUCTION

1.1 *The case*

The site, owned by the first author, is on a small island, Hekkholmen, close to the city Mandal, south in Norway. The purpose of the building is to accommodate guests, or a small gallery during the summer. In the winter, due to heavy storms, the building will serve as storage for outdoor furniture and water sport facilities. Nothing can be left outside without it being blown away. The new building would serve as an annex to an already existing cabin from 1972.

1.2 *History and background*

In 1917, the island only consisted of rocks, and hardly any vegetation. The island had a landmark, a huge, vertical rock, visible from distance. The island with its landmark was pictured by the Mandal born painter Adolph Tidemand (1814-1876), who later became one of the most respected landscape painters of Norway. For generations, the vertical stone represented a popular climbing challenge, as well as a nice panoramic view. In 1917, the island was bought by a shipyard owner, with the purpose of turning it into a modest summer resort. Soil was transported to the island, trees planted, and a simple cabin was built in the early 1920's. In subsequent generations, more cabins were built, and the landmark stone disappeared behind buildings. In general, the amount of "wild" terrain was highly reduced, and children's use of the island became very limiting.

Planning the new building, the following design criteria were set up: 1) The building should not reduce the area for children to play on. 2) Existing trees should be kept. 3) The building should be at least 6 to 7 meter long to be able to store kayaks during winter. 4) The construction method should be smaller CLT panels. The advantages of building in CLT were considered to be that the precut elements would save labor time on site, and the elements would be manually manageable concerning size and weight. In addition, wood has a low greenhouse gas footprint.

1.3 *The organization and the Hammerfest project*

Organizational, the project would be a cooperation between SPINN Arkitekter, The Norwegian University of Life Sciences and UK based Format Engineers. SPINN Arkitekter would be the architect company responsible for the design and the application for the building permit. Format Engineers was responsible for the transformation of the initial double curved architectural shape into a more refined and materially optimal form, penalization of the form and the static calculations. The building was to be built voluntarily by students and a person with professional contractor experience. One of the students who signed up to work voluntarily turned out to be an experienced professional cabinetmaker. Parallel to this project, SPINN Arkitekter worked on a similar project in Hammerfest. In the beginning it was not clear which project would be finished first. The original idea was to execute the Hekkholmen project prior to the Hammerfest project, as it was considered a good idea to learn from a private project, and then execute the public project in Hammerfest. However, as these sort of experimental projects are poorly paid compared to the hours of work needed to develop them, the working hours have to be spread out in time. At last, Hammerfest was both planned and built first.

The Hekkholmen project consists of 88 roof- and wall panels and is about 17 m2 in size. The total weight is 1819 kg (floor slabs exclusive). We learned from the Hammerfest project, that it would take about two days to screw the panels together (Houck et. al. 2019). There are some important differences between the Hammerfest project and the Hekkholmen project, making the Hekkholmen project more advanced:

1) The Hekkholmen project has a concave and convex shape, whereas the Hammerfest project is convex only.

2) One characteristic of the Hekkholmen project is a long, only carefully curved northern wall, whereas, the Hammerfest project has a very clear curving form all over.

3) The thickness of the CLT panels was reduced from 80 mm in the Hammerfest project to 60 mm.

1.4 *The building permit*

In general, the Norwegian building code prohibits the erection of any building or construction in a distance closer than 100 meters from the shore to secure public access. A committee consisting of civil servants and politicians decide whether at dispensation can be given. A 1:1 mock-up on site to illustrate the volume had to be made. The project was given a building permit due to its organic design and because no trees were cut down (Nerhus 2017).

1.5 *Competence and inspiration*

Bocanegra et al. (2014) identifies some main vectors contributing to increased use of timber such as cross laminated timber panels (CLT). Over the past years, computer tools like Rhino and Grasshopper and several other software have enabled the architects and engineers to both design and analyze complex shapes. But the software is complex to use. The transition from a double curved design into a buildable, rational structure in accordance to standards and regulations on construction is still a great challenge. According to Tarczewski and Święciak (2014) there is a gap between the level of development of design methods of free-form objects and methods of their construction. This is still the case.

There exist several experimental double curved building projects. However, not many are built in CLT, and even less are meant to be permanent constructions on sites with challenging weather conditions. How to calculate both an optimal shape, the elements and the connections is not at all straightforward engineering. Format Engineers had the experience of working with a double curved wooden construction, the TRADA Pavilion (Harding, 2013). However, the TRADA Pavilion was an indoor project. Calculating an outdoor project, as was the case with the HOT Cabin in Hammerfest, required innovation of the engineering tools. It had similar design challenges as the TRADA Pavilion, but in addition it would have to withstand harsh weather conditions and durability expectations. The experience of the TRADA Pavillion design process was that physical prototyping was necessary to investigate many fundamental questions concerning issues as the global structural stability and behavior of the joints (Melville, 2013). An inspiration for the HOT Cabin and the Hekkholmen project was the Landesgartenschau Exibition hall in plywood developed and designed at the University of Stuttgart, Initute of Building Structures and Structural Design (ITDK) and Institute of Engineering Geodesy (Schwimm et al. 2014, Krieg et al. 2018). This project uses finger joints. A fourth known example of a building in this category is the Diernerstein CLT shell Demonstrator from 2019 developed by the Technische Universiät Kaiserslautern. This consist of 229 CLT hexagonal plates and has a span of 12 meters (Robeller & Von Haaren 2020). However, these shells assemble a compression only structure, whereas the egg- and peanut shaped Hot Cabin and Hekkholmen projects represent more complex structures where compression and tension forces appear due to local bending. Also, the Hot Cabin and Hekkholmen are not temporary construction, but permanent buildings exposed to harsh weather condition and potentially high snow loads.

2 METHOD

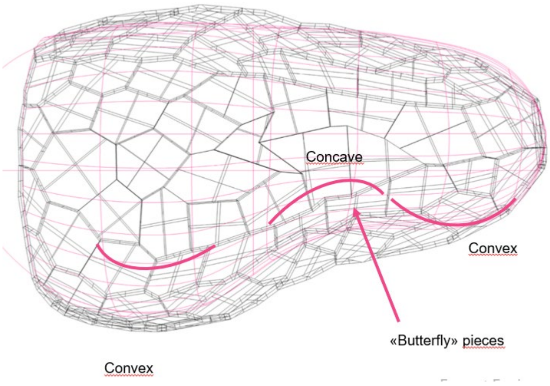
2.1 *Observation*

Designing and building a double curved CLT building is an experimental act in itself. The design method, in the sense of translating a double curved architecturally designed surface into 3D CLT panels, optimize and calculate the structure, is described in the article Houck et. Al. 2019 explaining the Hammerfest HOT cabin. The designing and building of the second building, the Hekkholmen project, gave the opportunity to improve the methods, and give the building a more complex shape and use less material. The distance between Hammerfest and Oslo did not allow an onsite observation of the building process. The observation was limited to daily updates on the project's FB site. For the Hekkholmen project, it was planned for both the architect and engineer to follow the construction on site. Unfortunately, due to Covid, it was not possible for the engineer to travel from the UK to Norway. Hourly observations of the development of the construction, reflections and conversations with the builders have been noted successively to document the building process.

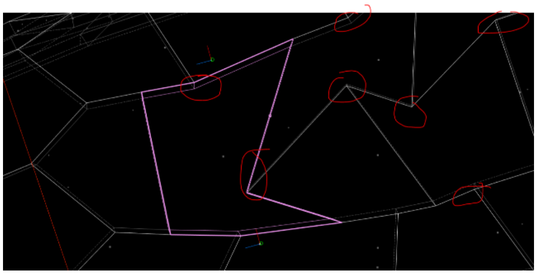
RESULTS AND DISCUSSION

2.2 *The architectural and structural design*

After working with the scale and shape of the project on site, the shape was constructed and refined in Rhino. The architect produced a double curved "skin" which was sent to the engineer who then subtly changed it to make it more efficient. i.e. to reduce the tension and compression stresses (figure 2). This was an iterative process. The double curved shape, as well as the introduction of convex and concave curves had as a result that some of the panels would have to have a more complex "butterfly" shape (figure 1). The local company delivering the elements, ordered the elements from Germany. In Germany, a 60mm thick 3,5 m x 10,0 m cross laminated panel was produced. This was cut into smaller rectangles according to the size of the different final elements. The size of the elements was too small for a normal XLAM producer to handle. The rectangular elements were therefor transported to a third company with suitable CNC machinery. Here the smaller rectangles were cut into their final more complex shapes. Digitally, the engineer's Rhino-file was transferred to CADWORK where the production files were produced. This work, including testing, was almost two weeks of work. It was the same company that produced the elements for the Hammerfest project, and due to this experience, everything went smother than by Hammerfest. The producer characterized the nature of this production as "far from normal". Also, they characterized the computer work as "very challenging, but manageable". The production of elements with inner corners to be cut, had a draw back; the CNC-circle saw cut not complete the cutting, and therefor this had to be finished manually. This may has caused minor imperfection and subsequent construction challenges. As the system is a non-tolerance system, any inaccuracy is challenging the mounting of the elements.



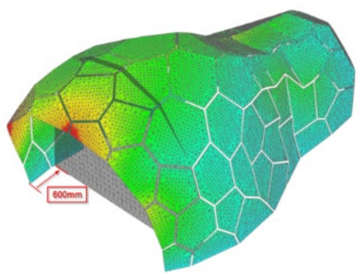
Convex and concave shape



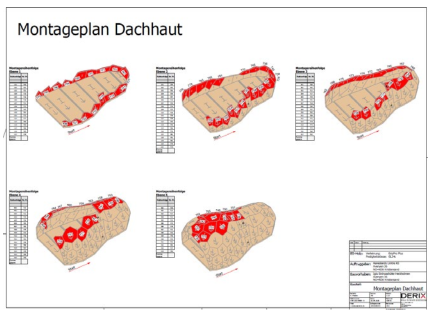
Odd shapes with inner corners to be partly hand cut (Red rings)

Figure: 1. The shape and resulting CLT panels

The calculation of the screwed connections was done through modelling the structure with a 10mm gap between the panels within the finite element model. The panels were linked with rigid links at anticipated screw locations. This was done to mimic the effect of localized screws and to more realistically model the potential rotations between adjacent panels. All of the modelling was within a generative working environment. The panelization, load application and finite element analysis was within a single script within the Grasshopper plug-in for Rhino. The finite element analysis plug-in Karamba was used for structural calculation. The results from that were then automatically exported to a spreadsheet where the screw forces and panel to panel compression stress at joints were calculated in accordance with EN 1995-1-1:2004. The design- and calculation method used in the Hammerfest project was improved in several ways. Firstly, the analysis script was refined to execute faster which enabled a more effective and speedy evaluation of different joint and screw location/numbers in order to arrive at what we considered to be the optimal location and number and secondly the screw capacity spreadsheet was refined followed feedback from a screw manufacturer (Rothblaas).



Simulation of wind forces



The mounting scheme

Figure 2. Panelization and building process

2.3 *The construction process*

The beauty of a building system like CNC cut CLT pieces, it that the parts fit perfectly, and there is no cutting or adjusting of the elements on site. However, this perfection is also a great challenge – it is a zero-tolerance system where every tiny inaccuracy will affect to what degree the coming pieces will fit. The screwing operation turned, unexpectedly, to be extremely time consuming. The operation required accuracy, holes had to be predrilled, and the 8,2 mm x 210 mm screws were hard work to screw. The contractor had developed a drill jig to secure that the screws would be parallel and in the middle of the element it was screwed into. The procedure was to put the elements into place and fix the position with 6 mm x 100 mm screws by the "mounting" team. This was fast and precise. After this, the "screwing" team added the bigger screws. The "screwing" team consisted of 3 persons with a double set of drilling tools. The "mounting" team had spent two days putting the wooden floor slabs into place. As the rest of the team came, the mounting of the wall and roof elements started. After working from 9 am to 6 pm, 72 of the 88 elements were mounted. The speed was about ten elements per hour. However, despite having three persons on the job, only about 200 of 1480 big screws were screwed. At the same time, the structure was experienced as totally stiff. The team spent almost one hour on element number 72. Due to very minor inaccuracies in the building process, and maybe even in the elements themselves, these added up, and became an increasing struggle to overcome. The structure's stiffness and inability to be bent or widened the slightest was impressive. A big sledgehammer was used, and some elements were loosened to some degree, to be able to continue. The struggle that started with element 72 continued the next day. From 9 am to 3 pm to only 11 elements were mounted, meaning 2 elements per hour. At 3:45 pm, only two elements were left were left to mount. But all inaccuracies were now accumulated, so after long, hard and patient struggle, element number 88 was in place at 5:30 pm. Figure 3 shows how the mounting process slows down significantly on day 2.

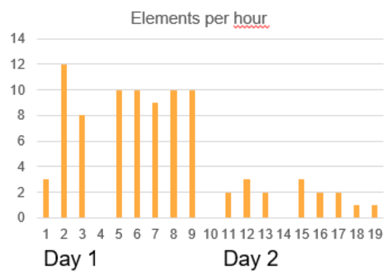


Figure 3: The mounting pace slowed down significantly after element 72

By the end of day 2, the team had 150 more screws in place, but were still less than halfway. The big screws worked well in the convex parts, but less well in the less curved parts, and the concave parts. Partly screws could be placed from above, inside the structure itself, before closing these surfaces with new elements. However, we realized, we had to supply with loads of 10 mm screws, as it would be impossible to screw sufficient big screws in the flat and concave parts. In its finished execution, the construction is held together with 700 big screws, and "countless" – approximately 1200 - 10 mm screws. All screws were screwed from the outside. Additionally, to the screws, the contractor wanted to glue the elements together with polyurethan glue. The advantage would be, a stiffer Construction (the Contractor's argument), and it would prevent tar from entering the inner surface (architect's argument). Also, it would seal the end grains of the slats in the CLT elements. In total the group spent 272 working hours in 10 days from the mounting of the wooden floor slabs started until the first layer of tar was painted on. This includes also removing waste and tidying up tools and materials.

Starting the mounting. Drilling and screwing with the invented drill jig. Every 220 mm screw took about 2 minutes.

Day two, 5:30 PM, all 88 elements are in place

Figure 4. The building process

2.4 *The surface*

In Hammerfest, the method of cladding the structure was a layer of tar paper, which took a professional about two days to finish. As there was a wish to protect the tar paper, and also have a building with a wooden appearance, it was chosen to clad the tar paper with wooden panels. It took about 1200 hours of labor to produce the wooden cladding. Fortunately, the Hammerfest project had the possibility to work in-door in a workshop, and additionally, had access to a sufficient number of volunteers with the time and motivation necessary. In Hekkholmen, this would not be the case. Firstly, because the project is private and not a public project, the access to volunteers is limited. Secondly, the project is on an island, making it more difficult with transportation. Thirdly, the volunteers would be from the Oslo area, far away from Mandal. Several cladding methods were considered, but finally it was decided to use tar. However, as the structure was built, the student experienced with wooden boats strongly recommended the joining lines of the elements to be filled with TEK7, a flexible MS Polymer. To do reduce risk this was done. A 10 mm wide and 10 mm deep trace was milled along all joint lines. The traces and also the screw holes were filled with TEK7, and then the structure was sanded. The structure was now considered ready for tarring.

Although the tarring of wooden churches has been common since the wikiing age, there is actually no written description of the process. Therefore, as part of a national initiative to improve the maintenance of medieval wooden churches, a scientific study was executed (Egenberg 2000). In some investigated cases, the use of tar has been as high as 10 liters per square meter. Based on the work of Egenberg, The National Heritage Authority (Riksantikvaren) produced a brochure recommending a method for tarring. People with experience from the tarring of church roofs were contacted. The method recommended was to use a first layer of "thin" tar, and then leave it for at least three weeks to harden. It is the ultraviolet light that causes the tar to harden. For the second layer, a thicker tar should be applied. This was to be achieved by boiling away 10% of the tar. For the third layer, 10% more of the tar should be boiled away. This thicker tar should be mixed with charcoal powder. The function of the charcoal is believed to protect the tar from degeneration through UV radiation. However, there was no description of the amount of coal powder to be used. The described process was followed, using boiling temperatures at about 140 -190 Celsius degrees for up to several hours. The third layer was covered with shell sand. This would make the building less dark, and therefor reduce the indoor temperature during summer. Also, the idea is that the shell sand will protect the tar, and also give the building a more "stone" like appearance. A layer of shell sand will appear less sticky on warm summer days. One problem with the Egenberg report was that it did not measure the viscosity of the tar. The viscosity of the tar used on the Hekkholmen was approximately 1500 cP in its original condition. Samples of the tar used in the different steps at Hekkholmen are saved, but the viscosity is still to be measured. About a total of 25 liters of tar was spent and 3 kg of charcoal powder. The charcoal powder was produced by crunching coal manually into the size of coffee beans, and then processed to powder in a large coffee grinder at "espresso" level. The Hekkholmen building was tarred in August 14th 2020, November 8th 2020, and April 1st 2021. After the first tarring, there were three leakage points. After finishing the second taring, very heavy rain could still cause trouble. After the third tarring, and some special effort and care at one point where the wall meets the floor slabs, the building's outer surface is considered waterproof. The expectation is that the building has to be coated with tar every third year.

Second tarring Nov. 2020	Third tarring with charcoal and shell sand April 2021. Mounting of the glass Oct. 2021

Figure 5. Surface and glass

3 DISCUSSION AND CONCLUSIONS

There is little experience in calculating and constructing double curved shapes in CLT. The Hekkholmen project, with its double curved, convex and concave shape, and a long slack curved wall turned out to be challenging to build. Despite having two experienced professionals in the team, the building process slowed down considerably as the accumulated inaccuracies in the non-tolerance building system made it difficult to fit the last 16 pieces into the structure. For a future project it may be recommendable to think of how inaccuracy could be reduced, e.g. by CNC milled physical marks. Another conclusions of the Hekkholmen project is that the number of screws may be reduced considerably. But to conclude on this more specifically, physical tests are necessary. From a builder's perspective, it is of great advantage to use more smaller screws about 100 mm length, than screws in the 220 mm range. For future projects, if the shape of the building is complex and some curves have a slack radius, it may be more important to optimize the connections prior to form or material.

When it comes to the tar-solution, it is too early to conclude to what degree this solution has been successful. It has been considerably cheaper and absolutely more time saving than the wooden cladding on the Hammerfest project. However, the tar solution is time saving in terms of working hours, but the work has to be spread out over a long period. Lastly, it has to be observed how often it is necessary to coat with tar, and whether the building stays dry over time.

4 AKNOWLEGEMENTS

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