Creating a smarter building system: Design of a prefabricated envelope system for cross laminated timber

Emma Fell
Victoria University of Wellington, Wellington, New Zealand
emma.fell@vuw.ac.nz

Guy Marriage
Victoria University of Wellington, Wellington, New Zealand
guy.marriage@vuw.ac.nz

Kevin Sweet
Victoria University of Wellington, Wellington, New Zealand
kevin.sweet@vuw.ac.nz

Dr. Paul Kremer
XLam, Melbourne, Australia
paul.kremer@xlam.com.au

Abstract: Cross-Laminated Timber (CLT) is a contemporary engineered panelised wood product and its use in construction globally is growing due to various benefits. The aim of this research is to design, develop and create a prefabricated envelope system for mass timber construction using CLT. The research capitalises on customisable building panels as they can be fabricated off-site. The design of a prefabricated envelope system is seen as the next frontier in productivity gains.

The prefabricated system is designed iteratively and developed using parametric based CAD software. CAD software facilitates the creation of a prefabricated envelope system for Mass Timber Construction (MTC) by establishing geometric relationships that respond to the unique nature of any construction site. The prefabricated envelope system is devised of proprietary joints specific to different types of cladding and unique environmental conditions. The exploration process includes fabricating the iterative schemes to test joint and hinge movement at the correct scale. The final designed envelope system can be optimised and fabricated off-site, delivered to the site, and erected quickly without need for scaffolding. The design and process results in an immense reduction of overall construction time and costs.

Keywords: Cross-Laminated Timber; prefabrication; construction; optimisation

1. INTRODUCTION

1.1 Cross-Laminated Timber

Cross-Laminated Timber (CLT) are structural building panels that are produced from wooden boards. The boards are finger-jointed to the correct size, and glued and pressed together. The wooden boards are cross laminated into billets consisting of 3, 5 or 7 layers from which the finished panels are cut using a Computer Numerical Control (CNC) machine (Kremer and Symmons, 2015).

CLT is a readily available structural timber product which offers an immense range of benefits within the construction industry including load-bearing capabilities, resistance in shear and tension, a high level of design flexibility and fast on-site construction (Fitzgerald, 2012). CLT offers sustainable aspects also, including reduction of CO2 emissions and being produced from a renewable timber resource, providing a smaller environmental footprint compared to concrete or steel (Kuilen et al., 2011).

However, the architectural uptake of CLT panels has been slow in New Zealand due to lack of technologies that take advantage of their properties. The flexibility in manufacturing different sizes of CLT has advanced significantly, however further developments are possible. A considerable opportunity for the mass timber manufacturing community is to make a CLT panel ‘smarter’ through the inclusion of a prefabricated envelope cladding system- offering advantages in timeframes of on-site construction and a reduction of health and safety issues.

The present paper explores what might be possible in designing a prefabricated envelope cladding solution to capitalise the additional benefits of CLT. The research runs from design conceptualisation through prototyping, assessing the
feasibility of potential solutions in both a manufacturing and on-site assembly context. In the following sections, research was undertaken to ascertain the current state of CLT construction, allowing for an iterative testing process to aid thinking concerning what might be possible in gaining additional prefabrication and construction efficiencies (Design Approach: Sustainable Principles & Construction Methodology, 2016).

1.2 Prefabrication

The construction industry is very established in its working methodologies and spends less time innovating when you compare it to other industries, like manufacturing. However, prefabrication techniques that have been underutilised in the past are providing significant gains in the modern era. Prefabrication consists of mainly two facets, volumetric modular and panelised variants (i.e. CLT, prefabricating framing, and cassette floors). The focus of the present study is on panelised construction, specifically using CLT. Due to its structural nature, CLT offers the potential for development of prefabricated envelope cladding systems to improve further the advantages of off-site construction (Hashemi et al., 2016).

One of the most realised benefits of using prefabrication is the decrease in time spent on-site (Hashemi et al., 2016). Off-site construction enables construction to commence in a controlled factory environment, therefore the interference of weather and the burden of site accessibility is mitigated as an issue. Off-site construction decreases time spent on site by up to 70% (Wong et al., 2003). The system/solution outlined in the present study further decreases time spent on site, and differentiates itself from other prefabrication techniques, by providing a building system that does not require scaffolding to install. Scaffolding can increase the cost of construction jobs by up to and estimated 50%, even if this is just “re-roofing or painting,” (Meadows, 2015). The elimination of time and costs of erecting and disassembling scaffolding provide significant benefits over other health and safety systems.

Quality is also a factor that can be better controlled within an off-site environment, “higher quality is achieved through closer coordination of labour, materials, machinery and sub-trades in controlled conditions,” (Bell, 2012). The quality of the design is successful due to the precision of construction that can be controlled off site, in an environment that is less weather dependent, leading to better quality and healthier buildings.

1.3 Designing using parametric tools

Parametric based Computer Aided Design (CAD) software, or solid modelling design, can be paired with prefabrication for contemporary solutions in the construction industry. Parametric CAD can produce customised designs to the requirements of the client, variations to the site or with specific project context, or any other variability in the design. Designing through such software allows designers to be involved from conception through to manufacture, resulting in more flexible schemes that can be programmed to change easily through the entire process (Holzer et al., 2007).

The use of 3D printing allows for Rapid Prototyping (RP), testing and experimenting, without the initial need to consider materiality and scale, nor having to work in a controlled factory environment (Bogue, 2013). The iterative process starting from a digital model and, through to 3D printing prototypes, helps to investigate and validate the iterative design schemes. CNC manufacturing for production is now becoming common, especially as the market grows for engineered timber products (Marriage and Sutherland, 2014). The use of RP for mass timber is vitally important, as each building project will have a unique set of physical attributes, which means each CLT panel on the project may also be unique. The use of RP allows the trialling of the envelope system with varying geometric forms to determine if fixings and cladding solutions are effective.

2. METHOD

2.1 Methodology

Software

The parametric software used within the design of the prefabricated envelope system is Grasshopper, based in the programme Rhinoceros 3D. Grasshopper is a visual scripting software that links 3D geometries in Rhinoceros to parametric or changing variables. Grasshopper was created as a visual tool for designers with no previous scripting ability, to easily create parametric outputs (Stavric and Marina, 2011). The software is an essential part of the design to production workflow and provides a visual or simulated feedback loop that can constantly re-inform the digital data based on the manufacturing processes.

Procedure

The design followed an iterative design process approach where testing and research was constantly and critically analysed and developed. The research followed four main stages, the result of the second phase being reported in this paper. Firstly, the analysis and research of existing joints, structural systems, materials and construction techniques related to mass
Creating a smarter building system: Design of a prefabricated envelope system for cross laminated timber

timber construction and CLT that helped to inform the design process. Second was a research through design process, including iterative modelling of a comprehensive prefabricated envelope and panelised system developed from the research in the first phase. The third phase, which is not yet researched, will be the implementation of the designed system on two different building typologies, a small infill house and a larger scale apartment building in order to ascertain the feasibility of the system in a designed project. Finally, the design will be tested as a 1:1 scale prototype model. The detailed model will consist of CLT panels, all building elements including insulation, proprietary joint systems, and different cladding options.

3. RESULTS & DISCUSSION

3.1 Results through experiments and testing

Many factors, such as form, function, operation and assembly, were critically analysed and assessed during the iterative design of the prefabricated envelope solution. The design initially investigated an inclusive system of all elements required for a complete building envelope. CLT panels were used as the structural component upon which insulation, waterproofing membranes, cavity battens, and cladding were all integrated as additional add-on elements (Figure 1). The design was fabricated to test the system as a whole as well as the potential construction method. The design incorporates continuous insulation on the outside of the CLT panel, due to the desire for the CLT panel to be exposed from the interior in an attempt to take advantage of its aesthetic properties. The method of using continuous insulation outside of the structure is underutilised in New Zealand yet is a proven and effective method used across Europe. The proven techniques used in Europe were adopted as part of the totality of the design building system.

After considering the design in its entirety, it was realised the design needed to slowly develop at a detailed level to sufficiently analyse each building component. Developing the scheme at a detailed level ensured that each building element was designed carefully to suit the requirements of an off-site construction system. Developing a joint system between the CLT panels and cladding system was the first initial phase for designing at a detailed scale. Using CLT panels as the basis, joints were designed using parametric software. Parametric software helped to produce many iterations of the scheme that otherwise would not have been realised due to the fast and iterative nature of the software. A customised joint between two CLT panels was designed where the joint simultaneously adapted through the direct relationship with the CLT panel rotation (Figure 2).

![Figure 1. Testing of initial design scheme physical model](image1)

![Figure 2. Plan views of parametrically designed joint in-between two CLT panels adapting due to parametric input](image2)
The design process also included the development of the CLT panel edge details, creating customised notches that would be intended to CNC in the construction process to receive the jointing system. The proposal was tested physically through 3D printing at a 1:10 scale to show the slight changes and variances (Figure 3).

Analysis of the physical prototype revealed that the joint should be standard to fit with any panelised design, rather than a customised joint for each rotation. Hinges were then re-considered and modelled on door and furniture joints. The newly designed hinges were attached to notches within the CLT panels, allowing for the connection between each CLT panel to rotate sufficiently (Figure 4).

Figure 3. Photo of fabricated parametric joint with adaptive joint in-between CLT panels

Figure 4. Designed and fabricated hinge testing between two developed CLT panels
The new approach was to focus on the joint and iterative development considering the movement of hinges. The act of designing digitally prohibited the understanding of hinge movement and connections, as there is no physical properties in the digital simulation. Therefore, each iteration was 3D printed at a 1:1 scale to test and fully understand the correct movement of the hinges. Physically exploring the movements provided an empirical understanding of how the joints worked (or did not) and were vital for decision making in the next iteration (Figure 5).

With a working and acceptable resolution of the hinge and panel joint, the system then incorporated how external cladding could interlock with the joint and how this would connect with the CLT panels (Figure 6). It was noted that customised cladding systems needed to be addressed within future iterations based on the cladding being only speculative at this point in the research.

In further iterations of the design, the system incorporates a cladding system- interlocking with the joint attached to the CLT panels. The design was developed to ensure the joint simultaneously rotated and adapted to the rotation of the CLT panels, resulting in customised and flexible design outputs (Figure 7).
Additionally, CLT panels were added both horizontally and vertically, testing how the system reacts to a stacked CLT panel design and how the CLT panel can remain exposed from the interior. The system can easily change through re-informing the data, resulting in customised outputs (Figure 8).

The results lead to two different cladding orientations – vertical cladding and horizontal cladding. In further considerations, the design led to the development of rigid wood fibre insulation, which integrates a ribbed cavity system (Figure 9).

The ribbed rigid insulation enables flexibility within the design cladding options. The development of the joint system relative to the cladding type and insulation is still underway; therefore, future exploration involves rectifying and completing the design. Developing the scheme to incorporate a viable construction and transportation process is highly important and relevant for this system.

3.2 Future Research

The design of two prototypes will also occur once the system has been finalised. The prototypes will be implemented on two building typologies including a smaller infill building; and a high-density apartment block. In future research, careful consideration will be given to developing the design to suit transportation requirements and issues impacting upon site assembly/erection of the system without the use of scaffolding. Lastly, a 1:1 prototype model depicting the system using CLT panels, different cladding options, and the proprietary metal joints, will be constructed to test the viability of the solution in a real-world application.
4. CONCLUSIONS

4.1 Conclusions, observations and future research

The aim of this research is to design and develop a prefabricated envelope system for a disruptive new construction technology, CLT. Results of the present study include the reduction of time spent on site, efficiencies (time, quality and cost); safety risk lowers due to no scaffolding, and ease of construction on sites hard to access. The proposed design is a universal system that uses many cladding options, which takes the guesswork out of testing as it is conducted here for the market to use as a resource. The system complements and builds on previous work – therefore adding to the body of knowledge that will increase the likelihood of greater adoption of CLT and the cladding system. The constant integration of parametric software increases the precision.

Future intentions with the design and development of this research includes testing using a 5-axis CNC machine to reduce limitations and tolerances, with potential to creates forms with the CLT that currently has not been explored. Testing the system through 3D printing does not prove the viability of the scheme due to the incorrect materials and machine processes. CNC testing will be used at a 1:1 scale with CLT panels to prove the viability of the materials and accuracy of the machine, rather than testing only through 3D printing. The design and construction of a scaled prototype relating to two different building typologies- an infill build and a high-density apartment block, will test the viability of the solution.

Overall, the prefabricated envelope system creates many efficiencies due to being designed and developed at a very detailed and precise scale. The design and development of the prefabricated envelope system aids in the uptake of engineered timber; specifically, CLT. Using the latest CAD software, the system begins to revolutionise the construction industry; shedding light on new opportunities for prefabrication within architecture.

References


Figures / Images

All images are authors own