J.W Gottstein Memorial Trust Fund

The National Educational Trust of the Australian Forest Products Industries

The Expressive Capacity of Timber in Architecture

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Joseph William Gottstein Memorial Trust Fund

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Bill Gottstein was an outstanding forest products research scientist working with the Division of Forest Products of the Commonwealth Scientific Industrial Research Organization (CSIRO) when he tragically was killed in 1971 photographing a tree-felling operation in New Guinea. He was held in such high esteem by the industry that he had assisted for many years that substantial financial support to establish an Educational Trust Fund to perpetuate his name was promptly forthcoming.

The Trust's major forms of activity are:

1. Fellowships and Awards – each year applications are invited from eligible candidates to submit a study programme in an area considered of benefit to the Australian forestry and forestry industries. Study tours undertaken by Fellows have usually been to overseas countries but several have been within Australia. Fellows are obligated to submit report on completion of their programme. These are then distributed to industry in appropriate. Skills Advancement Awards recognize the potential of persons working in the industry to improve their work skills and so advance their career prospects. It takes the form of a monetary grant.
2. Seminars – the information gained by Fellows is often best disseminated by seminars as well as through the written reports.
3. Wood Science Courses – at approximately two yearly intervals the Trust organizes a week-long intensive course in wood science for executives and consultants in the Australian forest industries.

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Abstract

This report is the result of a Gottstein Research Fellowship undertaken in August 2016, investigating the innovative use of timber in architecture in Austria, Switzerland and Japan.

Architects are attracted the use of timber being exposed in its natural state. Be it for reasons of displaying its ‘honest’ or ‘unpretentious’ materiality, or revealing its inherent richness in colour and textures, it is a material regularly favoured, and where possible, left un-painted, or if a protective coating needed, is often clear sealed. This research is interested in understanding why exposing timber is of value to architects, and how the exposure of timber in large scale buildings is achieved effectively.

A fundamental term associated with this is often referred to as the architectural ’expression’ of timber in architecture. This travel fellowship investigates contemporary international architecture that demonstrates an exemplary ‘expression’ of exposed timber structure, where the presence of exposed timber is a fundamental characteristic of the building design. The research seeks to identify exemplar projects that exhibit this ‘expression’; to understand why it is of value; and to understand how it is feasibly realized in a contemporary construction industry.

Throughout the research, the benefits of exposing timber structure in architecture were identified in three key applications. The first was the structural use of cross laminated timber (CLT) in multi story construction, particularly in medium scale residential buildings, where it has proven to be effective due being rapidly assembled on site. The second application includes more

widely reaching aspects, such as the inherent benefits for the environment, community, and personal health. The third application includes the technical and aesthetic contribution of expressed detailing in timber structures, particularly where a level of sophistication in solid timber connections has been employed. In the course of the research, a survey of buildings was undertaken in which each example demonstrated one or more of these three benefits.

It was found that a key factor underpinning the feasible realization of the exemplar projects was the employment of a sophisticated pre-fabrication process, allowing rapid and precise assembly on site. Such a prefabrication process also benefits substantially from a design and documentation methodology that assists the effective transfer of three-dimensional drawing information into the prefabrication process via digital formats. A component of the research travel therefore also included visits to manufacturing plants that design and fabricate sophisticated timber building elements. Upon return to Australia, a case study in digital modelling and fabrication was undertaken investigating the design and fabrication of an expressed solid timber connection. This was constructed from local timber and timber by-products, to test how the application of the methodology could be specifically used in an Australian timber product context.

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Introduction

Background

The research focuses on a particular approach to architecture, in which structural timber is deliberately designed as an integral exposed element, and the exposure of timber structure is a fundamental and defining element. A rich tradition of using structural timber as an expressed and integral architectural element can be identified in the architecture of the three countries of study: Austria, Switzerland and Japan. To a degree, this is due to the abundance of forest in these countries, but it is also due to the practical, climatic and seismic benefits of using solid timber. In mountainous regions, timber was easily handled and transported, in alpine climates, solid timber construction traditionally provided natural insulation as well as a robust structure under snow load conditions. In Japan, whilst a more benign climate did not always necessitate thick timber walls, timber also proved to be appropriate in earthquakes.[1]

The rapid industrialisation of building technology over the last century has seen expressed timber structure gradually removed from the construction industry. The use of expressed timber in wall construction has largely been replaced by stud framing with sheet linings, and where timber was typically expressed, it has been replaced by veneer on a substrate. Similarly, expressed solid timber connections, that utilize 3-dimensional joints have largely been replaced by mechanical fastenings, such as bolts, plates and folded steel plates. As a result of the disappearance of a genuine expressed timber structure, contemporary examples of exposed connections and solid timber in architecture, unfortunately are subject to being misinterpreted as overtly ‘sentimental’ or ‘nostalgic’, and the intricate timber connections are seen as complicated and unnecessary, rather than a genuinely pragmatic solution. Recent changes in timber fabrication technologies have started to change this however, where the use of mass timber (laminated timber products) in conjunction with modern digital machining technologies have enabled an economical and therefore increasingly widespread adoption of timber in larger scale structures and in multi-story public and private buildings.

Aim

This research seeks to review the current technologies that are being utilized in Austria, Switzerland and Japan and identify applications where exposed timber structure is evident in contemporary architecture, and why this is of relevance. It seeks to identify why the use of expressed timber structure in construction may be considered beneficial and pragmatic and therefore avoid nostalgic connotations; and how it can be implemented effectively in construction.

Methodology

This research involved travel to Austria, Switzerland and Japan looking at modern techniques of timber constructions. A series of case studies were made of notable buildings in each location, and comparisons made between traditional and modern approaches. The most pertinent selection of the visited buildings are discussed in this report. An appendix catalogues the visited projects that are not otherwise included in the report. Upon return to Australia, the research also tested modern machining techniques at the University of Queensland through the making of a prototypical connection detail that tests a local and original application of such technologies.

Outcomes

The outcome is a catalogue of exemplary international projects that demonstrate why the expression of timber structure is of value, and how it the realization of such projects is facilitated. In addition, a local demonstration prototype was developed as a tool for testing of the technology in Australia and for further dissemination of the research in a local context. This will occur through ongoing teaching and research at the University of Queensland. This research is of value and significance both due to the exemplars that offer a benchmark for the Australian timber product Industry, and through the prototype that demonstrates how such innovations and technologies can be applied in an Australian context.

Cross Laminated Timber in Mid Rise Buildings

The advent of using mass timber in buildings has increased significantly in Europe and the UK over the last two decades. With the popularity of Cross Laminated Timber (CLT) in construction, the industry has seen a resurgence of large format timber structures being used in both the interior and the exterior of buildings. In the course of the research travel, notable examples of mid rise (4-8 storeys) CLT buildings were visited, and the following is a discussion of those. The buildings visited were principally in Austria in the cities of Vienna and Graz. Several benchmark CLT housing projects were included, ranging from Europe's first large scale multi-residential project built in 2005 to seeing examples of projects recently completed in early 2016.

The city of Vienna has a tradition of providing innovative housing solutions for its residents. Since the 1920's, the city has housed over 60% of the population in high quality affordable buildings. The city itself subsidizes the construction cost of the buildings and continues to build the majority (80-90%) of new housing stock.[2] The buildings are consistently of a high quality in their design and their built execution, are socially responsible and inclusive, and also demonstrate an exemplary standard of environmentally sustainable design in terms of embodied energy used in the material and consumption of energy during the use of the building. In Austria where timber forestry represents 60% of the land area, timber is a logical choice for construction. These projects demonstrate how material such as CLT can be used ecologically, are cost effective, and provide a high quality architectural outcome. Within each project, to varying degrees, there is evidence of the timber structure being expressed as an integral element of the architecture.

Spottlgasse Housing

In a landmark policy, the city of Vienna changed its construction legislation in 2001 to allow multistorey timber buildings to be built in an urban context. The housing project in Spottlgasse designed by Graz architect Hubert Riess was a ground breaking project in Vienna at the time (completed 2005). The project was the first in the city to use timber at a scale of 4 stories, and was effectively a pilot project for the city to test the use of CLT in their subsidized housing program.

Of particular success was the rapid construction time that was proven in this project due to the extent of pre-fabrication. This ensured that the project was delivered cost effectively and also provided assurance to the city of Vienna of the quality of the final outcome, which was also received enthusiastically by the residents. It was also a pertinent case study to include in the research, as it offers an opportunity to see how a building with exposed CLT and timber cladding has aged over the last 10 years.

Figure 1 The Spottlgasse Housing project in 2005 A 4 storey building with a concrete structure on ground floor and phot 3 levels of CLT construction above. Photo Pez Hejduck

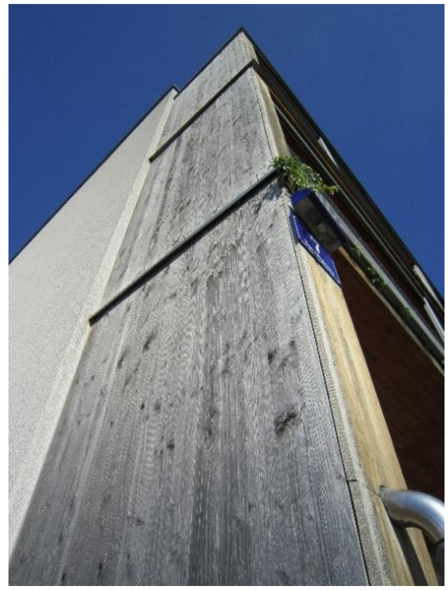

Figure 2 Exposed CLT on the flanking walls of the balcony in 2016. Photo by Author.

In this project, the regular apartment plan enabled CLT to readily be used as the primary loadbearing structure for 3 storeys above ground floor and basement carpark levels constructed in concrete. CLT was also used structurally for the principal external walls throughout, but it was only exposed on the balcony's flanking walls (as seen above). This was primarily due to the requirement for thermal insulation to be used over the external layer of the CLT. As can be seen in the photo recently taken photo from 2016, the low maintenance finish of the exposed CLT was silver-grey, but is visually consistent and its surface integrity still of a good quality.

Muhlweg Housing

The Spottlgasse project was many respects a trailblazer for subsequent Viennese housing projects to be built using CLT. Subsequently, and as a result of its success, the housing project at

Muhlweg, Vienna, was instigated by the Vienna Land Procurement and Urban Renewal fund, through running an open competition.[3] Eager to demonstrate the value of timber construction and advance the widespread understanding and acceptance of the technology after the success at Spottlgasse, the city proposed a 250 unit housing development with multiple architectural firms involved, with a brief for the buildings to utilize a complete timber or a predominantly timber hybrid structure.[4]

The apartment buildings at Muhlweg designed by Dietrich Untertrifaller consist of CLT wall and floor construction with rendered external walls with exposed CLT to the underside of slabs and to the inside of the balcony walls. The key ambition for this project was to provide an affordable, energy efficient building. Constructing the building in CLT was a key contributing factor in achieving these goals. The building meets the European Passive House standard,[5] and the building was also constructed within the budget constraints of the Austrian subsidized housing policy. This was due principally due to the use of CLT and its ability for the components to be cost effectively pre-fabricated off site with a high degree of precision, and allow for a very fast onsite construction cycle, where the building could be encapsulated from weather in just 5 days.[6]

As can be seen in comparing the original photographs from 2006 with the photographs taken on site in 2016, the exposed CLT in the underside of floors (soffits) and the internal side faces of the balcony walls have largely remained as original. The consistent weathering of the external cladding is noticeably effective, due to the flush detailing of the timber cladding enabling a consistent degree of exposure. It is possible to see some minor weathering above the sill of the opening, due to additional exposure of the wall at this point due to moisture collecting around the balustrade sill.

Figure 3 Muhlweg Passiv Houses by architects Dietrich Untertrifaller. Original condition 2006 - Photo by Dietrich Untertrifaller Architects

Figure 4: Same building in 2016. Example of weathering of the cladding compared with the CLT exposed in soffits and balcony linings. Photo by author

Figure 5 Muhlweg Passiv Houses by architects Dietrich Untertrifaller. Note the relative consistency in the weathering of the external cladding turning silver whilst the interior of balcony walls and soffits' remain clear. Note also the minor exposure above the sill on the bottom right hand side of the opening. Photo by Author.

A neighbouring apartment building designed by Herman Kaufman and Johannes Kaufman, on an adjacent site, also uses CLT for the construction of the principal structure, which again is mostly encapsulated by external layers of construction but with exposed CLT ceilings. The arrangement of these buildings on the site allows for greater variety of orientation than its neighbour and displays a more extensive use of timber cladding in the façade. The construction of the building consists of the ground floor being built of concrete construction with the first and second floor built of CLT. The construction of the floor is comprised of a 146mm CLT floor , then a 90mm layer of loose fill, 30mm of mineral wool acoustic insulation, vapor barrier, 60mm cementitious screed then a final10mm timber floorboard.[7]

Figure 6. Muhlweg Housing by Kaufman and Kaufman. Note the exposed CLT structural floor in the interior also provides the ceiling for the space, whilst the floor is visibly overlaid strip flooring as it is constructed on top of several insulating layers. Photo by Kaufman and Kaufman

Interestingly, in the largely timber clad façade that there is a series of short projecting metal caps between each floor. These were required to avoid the spread of flame between floors, a requirement under the local building code particularly when softwood species are used. The façade was originally intended to be made of a hardwood such as oak or acacia, but the cost of these species was prohibitive, thus the solution of using the metal projections was introduced and allowed Larch to be used throughout.[8] These projections do noticeably contribute to a variation in the amount of weathering, but allowed for an almost complete timber façade, with just some small quantities of painted fibre cement panel.

Figure 7. Muhlweg housing by Kaufmann and Kaufmann in 2008. Photo by Kaufmann and Kaufmann.

Figure 8. The sSame project in 2016: note the change in timber hue, and influence of the projecting fire protection upon the change in weathering of the timber. Photo by Author.

In observing these projects after a period of time, one can see that the quality of the finishes of the buildings has been sustained, and could be even be considered to be gracefully weathered, due to the well-designed detailing and the precision of the construction. The cost effectiveness of the CLT was improved as the technology became increasingly accepted and the market became competitive. After visiting the projects at Muhlweg, that were a decade old or more, the research then investigated recently completed residential projects built of CLT, and it was clearly evident to see how the confidence in the CLT industry had grown since 2006.

Hummelkaserne Housing

The 6 storey high ‘Hummelkaserne’ housing project in Graz, completed in 2016, is testament to the confidence that the Austrian authorities had gained since 2001. The increased height of the project is the result of changes to construction code of early 2016, where the maximum floor height was lifted from 4 to 6 storeys, and the minimum fire rating was lowered from 90minutes to 60 minutes.[9] A competition was run in which the architect was required to establish a team with a construction company, in this case Kaufmann Bausysteme where the designated budget was required to be met. This equated to approximately €105,000 per apartment.[10] Again the efficiency of CLT systems meant that rapid construction was enabled, with an average of one floor per 4 days, which brought site costs and costs of overheads down remarkably compared to conventional building systems.

Figure 9 Hummelkaserne Housing project by SPS Arkitekten. Photo by Author.

Figure 10. Detail of the floor to cladding. Note the perforated mesh at the base of the ventilated cavity behind the cladding enabling moisture equilibrium on either side of the cladding. Photo by Author.

The façade, like the Muhlweg predecessor, is clad in Larch with horizontal sheet metal ledges at each floor. In order to ensure the timber in the façade is kept durable and is low maintenance, it is imperative that the detailing of its fixing is properly designed with a ventilated cavity immediately behind the cladding, as can be seen above. The Larch cladding in these buildings is the same material as is used in the CLT floors and wall systems, and is grown and harvested locally. In addition to the ecological credentials of the CLT construction, the energy saving performance of the material means that it well exceeds the maximum Passive House standards, by achieving a very lean 9kwh/m2 of heating energy load per annum.

In summary, these projects demonstrate excellent examples of midrise multi-residential timber construction. They provide affordable, energy efficient buildings with high standards in architectural finish and quality but are also durable and are low maintenance. They demonstrate how effective CLT is in achieving these outcomes. It has also been demonstrated that one of the key factors, if not the *most* important factor, is the suitability of CLT construction to be pre-fabrication with a high level of precision, which allows for the buildings to be erected very quickly on site both reliably and safely.

It has been shown in this first chapter how midrise mulit-residential buildings benefit from using CLT through its ecological sustainability, cost effectiveness, and robustness. The degree by which the structural CLT panels is exposed does vary between projects, but is genuinely attempted where possible. Whilst CLT can be proven to be a pragmatic, efficient and aesthetic structural timber product, it is only part of the overall benefit that exposing timber can bring to a project. The next part of this report will identify the additional benefits that expressed timber structure can offer.

Benefits of Exposing Timber

Having discussed the benefits of CLT in terms of its cost effectiveness, this chapter will discuss some of the less apparent, but no less valuable benefits of using exposed timber in buildings. In these projects, an emphasis is placed timber being exposed in its natural state, where it is of solid constituency, ie, is not a face veneer or applied finish, but rather, is an integral internal finish or external cladding, and is often deliberately left unpainted or unsealed.

Erika Horn Residential Care Home

On a site close to the Hummelkaserne housing project, is an exemplary aged care building that was completed only two years prior. The 'Erika Horn Residential Care Home' , designed by Dietger Wissounig Architekten, makes use of a significant amount of exposed CLT in the interior environments, and has expressed the timber almost exclusively throughout the interiors. This exposed timber is visually calming and brings material warmth and a softer dampened acoustic environment to the interior. Studies have shown that exposed timber interiors do have significant positive physiological and psychological effects on the occupants, and are able to provide proven health effects by way of lowering blood pressure and heart rate.[11]

In conjunction with an outlook onto a garden or green space, these timber lined walls are materially and visually comforting, and as a result they make their residents feel at home, close to nature, and at the same time warm and protected. The plan of the building allows for several different courtyards each with its own aspect and orientation, allowing the interior spaces to have a range of shaded, sunny, garden and park views. The simple wall, floor and ceiling planes of

CLT used carefully in conjunction with frameless glass windows onto the courtyard serve to heighten the relationship between the interior and the exterior, and the precision of the exposed pre-fabricated CTL is highly successful in these situations.

Figure 11 The precise timber detailing and frameless glazing of the interiors creates a calm, yet warm space. Photo by Paul Ott.

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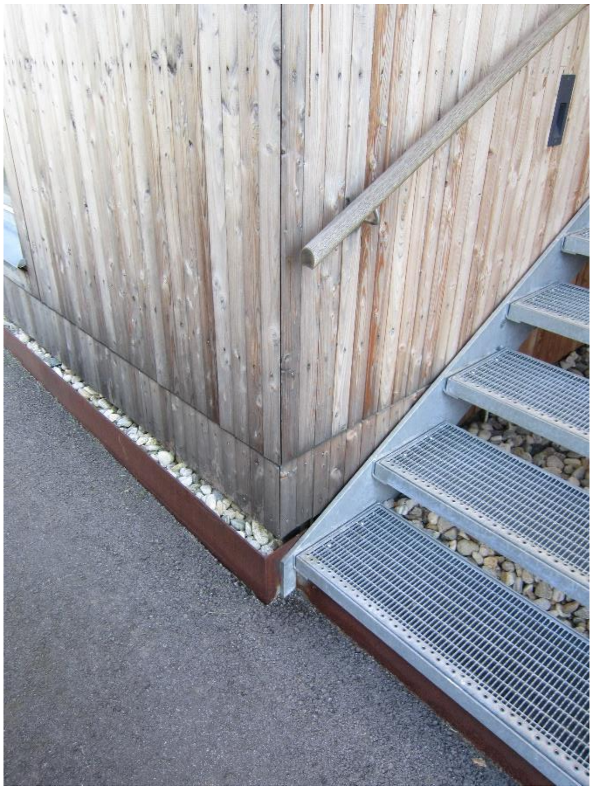
In the interiors of the bedrooms, the combination of CLT walls and ceilings, with a single large window to the garden and smaller operable window are both comforting and generous. The window sill is heated and can also double up as a window seat. If left uncoated, the timber can also act to control humidity, through some absorption and evaporation, which assists in keeping the air quality consistent and naturally moderated.[12]

Figure 12The interiors of the rooms with CLT ceilings and walls. Photo by Paul Ott.

A particular detail on this project worth pointing out is one of the strategies to provide the cladding with reliable durability. The external vertical cladding, as can be seen in these photo, does not have an eave and extends to the ground. The architect in this instance chose to provide a separate band of cladding for the lower most 300mm of wall. This lower part of the wall is subject to additional weathering from moisture splashing from the ground onto the vertical surface. This panel was therefore designed to be removable and can be replaced after several years should it be required[13]. It is possible to see in the photo below how this lower panel has been weathered in the two years since completion in 2014.



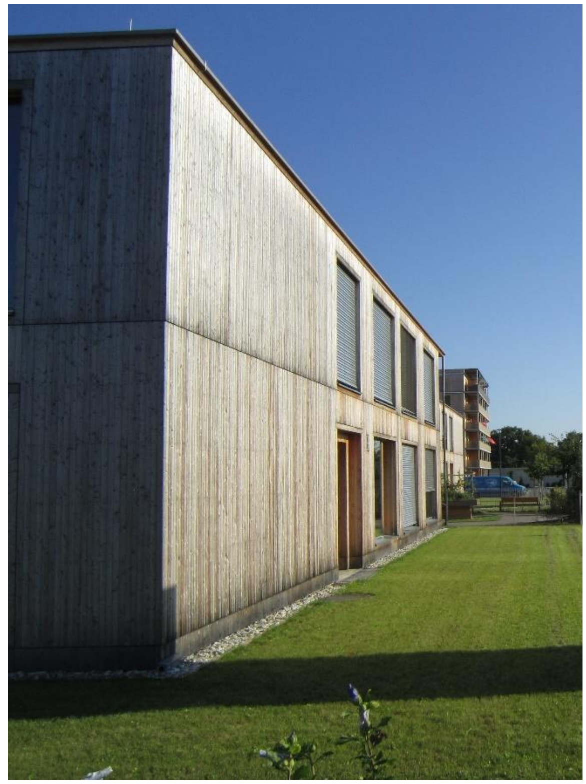


Figure 13. Note the separate replaceable panel of cladding at the bottom of the external, wall to respond to localized weathering. Photo by Author

Kranebitten Kindergarten

In the Innsbruck suburb of Kranebitten, a kindergarten project was instigated as a competition in 2014, and was won by Reitter Architekten. The kindergarten has been designed around a large external courtyard playground with a timber lined external cloister that defines two of the four sides of the courtyard. The building is located in the corner of a larger park, with adjacent playing fields, a camp ground and the mountains immediately behind. A conscious ambition for the architect has been to site the building to complement its context.

The building has been carefully organized with the gradual slope of the site, so that the main playground area is raised off the surrounding parkland by approximately 1.2 metres. This ensures that the playground has the necessary required visual and physical separation from the parkland, to keep the children safe, but allows the playground to maintain distant views across the parkland and to the mountains, making it feel part of the greater landscape. The 'cloister' edge is also very effective at providing protection from the weather.

Figure 14. The building is sited such that it complements the landscape, with the cloistered courtyard and green roof. Photo by Author.

Figure 15. The entry court, with White Fir cladding and a CLT structure. Photo by Author

Built primarily from CLT, the project was largely prefabricated off site, and erected rapidly, with only minor siteworks involved. The external walls panels are made of repeated modular panels, clad in rough sawn White Fir. The interior walls are made of CLT, with a breathable white paint finish to assist in cleaning. The flat roof has been planted out with grasses and heath, with skylights penetrating through to admit light. As a result, from the approach uphill, the building appears to integrate into the distant landscape of the playing fields. When standing below the building, the courtyard is framed by the cloister roof, where one can see through to the mountains behind. In this way, the building is highly effective at integrating with the landscape. In this example not only does the use of expressed timber structure in the CLT contribute to the interior comfort and wellbeing of the users, but as a timber building sited carefully in the landscape, promotes the values of sustainability by showcasing a building that complements its local context and has a sense of belonging. The expression of timber in the architecture contributes significantly to this.

Community centre in St Gerold

In Vorarlberg, Western Austria, a multitude of exemplary projects can be identified where, like the Kranebitten Kindergarten, timber is used to not only provide an internal air environment where air quality and environmental sustainability ambitions are met, but where timber is as an important symbolic material that is embraced by the community. In the hinterland behind Bregenz, known as *Bregenzerwald*, many community buildings are constructed wholly from timber, achieving a benchmark for low energy and finely detailed architecture.

The Community centre in St Gerold, designed by Kucrowicz Nachbaur Architekten, is an example of how a local community has fostered a unique timber project. The entire valley in which St Gerold is sited is recognized as a UNESCO world heritage site, and like most of rural Austria, the valley has significant timber forestry resources. When the village of St Gerold required a new community building to house a day care centre, a community multi-purpose space, and the local municipal offices, a strategic decision was made to ensure that the entire building was to be built from timber sourced sustainably form the valley. The 4 storey building houses the day care centre on the ground and first floor, and the community spaces and local municipal offices on the upper floors.

Figure 16. St Gerold Community Building when first completed in 2008, Photo by Kucrowicz Nachbaur Architekten

The Building utilises a very high performing wall construction in terms of energy consumption, achieving a very efficient 10.7 kwh/m2 per annum of energy consumption, which is far greater than what is required under Passiv House requirements.[14] With several constituent layers, the floors and walls (exposed to the climate) and the roof are rigorously detailed to ensure maximum insulation, minimal thermal bridging, and importantly, a correctly located and specified membrane to enable the interior surfaces to breathe whilst avoiding build-up of condensation. The is ensures that the interior exposed timber can be unsealed, and breathable, tempering the indoor air quality passively, and reducing the need for mechanical air conditioning through dehumidification.

Figure 17 The interiors are all completely unsealed, allowing them to breather and temper the indoor air quality. Photo by Author

Figure 18The precise detailing and coordination of the interior CLT panels is evident in the refined interior. Photo by Kucrowicz Nachbaur Architekten

Figure 19. The building in 2016, Photo by Author

The project was also an important exercise in the local community as it demonstrated a commitment on the part of the local municipality to ensure that a building of a very high quality could be procured through the sustainable harvest of local resources.

Fire and Mountain Rescue Station in Schoppernau

When the community in Shoppernau were instigating a new fire and mountain rescue station as part of the newly designed Community and Cultural Centre in 2001 -2003, an open competition was run and the architect Matthias Hein was successful in winning the competition. The project was completed in 2005, and was built almost exclusively from local timber felled from the Schopper Auer community forest.[15]

The building employs expressed timber wherever possible. Code restrictions on the adjacency of the fire engine garage and staff facilities area meant that the garage itself was constructed of concrete, but the remainder of the building, the staff facilities, were entirely built of timber: The exterior is clad in Spruce, and the interior is White Fir.

The building is designed to integrate strategically in the village context, with the open vehicle manoeuvring space in front the garage also adjoining the local community commercial and cultural centre. The station's training room itself is opened up to the public on occasion, transforming the adjacent space into a public 'plaza' and the training room a space for events. Such flexibility is not only a deliberate functional and resourceful decision, but also one that enables the local community to celebrate the fire fighters' highly valued and respected role in the community.

Figure 20 The Fire and Mountain rescue station has garage on the left and the training room on the right, the training room able to be used for community events. Photos by Hein Architekten.

This project is exemplary of many of the community buildings in the region built out of timber. The building itself sends a clear message: *this community values the forest in the valley*

Schopper Auer. The building is built from local timber, which supports the local forestry economy and is demonstrative of a sustainable practice. As a result, local foresters respect it, the local firefighters who are there to protect the forests and community respect it, and the building itself symbols these values.

Fire Station and Kindergarten in Thuringerberg

In 2008 the village of Thuringerberg commissioned a multi-purpose building to house its fire station, a music school, a gymnasium and the local kindergarten. The building was intended to be a local facility that could be used by a broad cross section of the community, and like the fire station in Schoppernau, become an insertion into the village that would contribute to public amenity, strengthen its community cohesion and celebrate the use of local timber resources from the valley.

The combination of the various functions has been designed carefully to utilize the inherited slope on the site. The fire station garage, excavated into the hill side, is used as a platform onto which the kindergarten playground is constructed on. The gymnasium on the ground floor is also used by the firefighters. A large entry stair from the street provides a semi enclosed space to access each floor and provide protection from the weather.

The Spruce used for construction has been sourced from the local forests and has been used throughout the project. For architect Bruno Spagolla, timber was used in a sympathetic way, his philosophy was to bring out the unique characteristic of each piece of solid timber, to express its individuality like each of the individuals in the village.[16]

Figure 21 Thuringerberg Fire station and Kindergarten. Photos by Christian Grass.

Figure 22 The Solid timber has been used throughout the semi-enclosed and interior spaces. Photos by Christian Grass

These regional projects demonstrate two key benefits of using solid timber in both the exterior cladding and the interior, where the expression is predominantly CLT. Expressing the timber in the exterior cladding is recognized as sending a clear message to the local community. It shows that the local environment is valued and that it has genuine intrinsic value, it demonstrates that a local economy is supported via the forestry, and it also demonstrates that expressed timber has the ability to integrate into the landscape sympathetically. In the interior, the health benefits of using exposed, unpainted timber draws from the comfort benefits through the absorptive surfaces as well as the psychological and physiological benefits of a timber interior, in terms of how timber has the ability to create a more calming environment. In the examples shown, both the external cladding and the interior finished surfaces in these projects have required a high level of precision in the detailing, both in the design, and in the execution.

Given that the primary method of construction is prefabricated CLT, much of this precision in manufacturing is delivered through digitally controlled fabrication processes. It is important to point out that this precision of manufacturing allows for these buildings to have in perfectly aligned surfaces and a refined architectural finish. What can be seen in the architecture are clean flush walls, ceilings, floors and rooves, and the digital coordination that has taken place in the fabrication is effectively embedded into the planes of the walls, rooves and ceilings. The structure, whilst being ever present, makes itself felt in the refinement of the flush surfaces, rather than in the display of connection details. Another type of timber expression can be found in the overt display of connection details themselves, which will now be covered in the next chapter.

Expressed Timber Structure

Seeing structural timber connections exposed in buildings is not new, but it has seen a decline in large scale buildings since steel and concrete has dominated in the construction industry. What can be seen in contemporary timber architecture, however, is a renewed vigour in the use of large scaled timber structures, driven by a host of new timber construction techniques that are now available through fabrication technologies. This chapter discusses a cross section of how these technologies have been translated into built outcomes. These projects were predominantly visited in Switzerland and Japan. Of particular focus in this discussion, is how the timber construction systems are able to benefit from new machining techniques in order to achieve a high level of sophistication in the expression of the timber joints.

Chaserrugg Cable Car Station and Restaurant.

In 2011 the Swiss Architects Herzog and De Meuron were given the task to re-build an alpine building in the Toggenburg Valley in Switzerland. The project consisted of re-modelling the existing cable car station and building a new restaurant at 2262 meters high atop the Chaserrugg peak on the Churfirsten Massif. The project was initiated as part of an initiative to bring renewed economic vigour to the Toggenburg region, with the restaurant serving year-round mountain activities.

The new restaurant is a long single space overlooking the views toward the Rhine Valley and Lake Walenstadt. The restaurant was designed to incorporate the existing structure for the cable car station, and a new outdoor logia space was constructed to connect between old and the new structures. Timber was chosen as the preferred building material for two key reasons. The first reason was that it allowed a modern interpretation of the local tradition of building alpine buildings wholly of timber, the second, more pragmatic reason was that it was lightweight and could be pre-fabricated.[17]

The building references the simple and functional, robust barns of the region. They key element here being a beautiful sheltering roof that broadly encompasses both the cable car station and restaurant. The exposed structure of the roof beams and struts provide the architecture with a characteristic expression of material and structural honesty. Descending from a very tall eave over the cable car entry, the broad roof falls to become intimately proportioned on the lower restaurant side, whilst dramatically flying out at either end of the ‘wing’ via a series of strutted cantilevers, which appear incredibly light bit are in fact supported by approximately 400mm square laminated members.

Figure 23 The broad sweeping roof extends in a flying strutted eave at each end. Photos by Author.

Figure 24 The struts are robust yet appear lightweight from afar. Photos by Author

Inside the outdoor arrival hall, the tall braced columns are reminiscent of being inside a barn, with an open slatted screen to permit light into the space but shelter it from wind and snow. Inside the restaurant space, a long rectilinear dining space has a panoramic window out the view on one side, with small alcoves adjacent to the long space to provide a series of alternatively intimate settings.

Figure 25 The Interior has expressed timber structure throughout, a simple long dining space with more intimate recessed booths adjacent . Photo by Herzog and De Meuron Architects

The structural timber used throughout the project was constructed by Swiss timber fabrication specialists, Blumer Lehmann, and their fabrication arm Timbercode[18]. The timber elements were designed by Blumer Lehmann in close consultation with the architects and consultant team to ensure that the components were all able to be transported to site via the existing cable car infrastructure. This was a critical aspect to the design. The only time specialist transportation of equipment or materials was required, was when a helicopter was used to transport a small crane onto the mountain. [19] This was a requirement of the client, not only to be sensitive to the environmental setting of the mountain, but it was also a cost management imperative. Key to this transportation efficiency, was the requirement for the timber member dimensions to be coordinated precisely, without any on-site adjustment required. Blumer

Lehmann were able to provide this expertise in the design and pre-fabrication stages of the project, and were instrumental in the project's success.

This project is an excellent example of how the precise design and machining of prefabricated timber elements not only enables a functional architectural expression that references a tradition through the celebration of an open display of the strut and beam structure in the roof, but also is the fundamental basis for achieving the environmental and economic success in the project. It could be argued that this could not be achieved as effectively in any material other than timber.

Tamedia Building.

The Japanese Architect Shigeru Ban designed this extension to the Zurich offices of Swiss publishing company Tamedia, completed in 2013. The building was designed to replace an existing building in a prominent site in Zurich on the Werdstrasse and Stauffacherquai adjacent to the canal Sihl.

This seven-story building is an exemplary timber building for two key reasons: Firstly, the building type, it is a commercial office building, and as such, has distinctly different spatial requirements when compared with residential apartment buildings. Transparency and open plan spaces are critical to allow flexible functionality and transmission of light into deep floor plans. This has produced a very lightweight and also highly visible structure to be used throughout the building. The building is permeated with a substantial multi story void space and the expressed timber structure can be seen through the façade from outside.


Figure 26 The Circulation along one side of the floor plan allows for a generous void over several storeys, allowing the building to be spatially transparent and to express the timber structure throughout. Photos by Shigeru Ban Architect

Secondly, the primary timber structure relies almost entirely on timber to timber connections, there is no steel hardware in the connection between the primary members.[20] Thirdly, the insistence on the timber to timber connections has resulted in the requirement for an incredibly precise fitting together of the primary structural elements, due to the connections needing to transfer the loads of seven storeys solely through the contact of the timber bearing surfaces.

Figure 27. The Junction of the column to beam is entirely timber in construction, there is no steel hardware used. Photo by Author.

The architect, Shigeru Ban, sought to realize the building with a similar degree of rigor as a traditional Japanese buildings, using timber only connections, relying on a highly sophisticated three dimensional interlocking joint between the timber members.[21] The elegant connection system of paired beams and column uses an over-scaled 'dowel' made of beech plywood, for greater shear resistance. The system not only allows for a mechanistic assembly that is rapid and self locating on site, but also results in a remarkably clean connection visually.

The level of dimensional precision of the timber elements, combined with the visual neatness of the connections with their concealed inner shear plates, meant that the quality of the timber and the exactitude of the fabrication needed to be extremely high. To achieve the high level of quality in the timber, the Spruce trees were sourced from a single, continuous Styrian forest at a high altitude to ensure both consistency of quality with a fine grain from slower growth.[22] To achieve the high level of reliability in the fabrication, in addition to individual test fitting of individual components, the Timber fabrication specialists, Blumer Lehmann produced a full scale mock-up of the structure prior to erection on site.[23] This process whilst admittedly challenging for the construction team, allowed the structure and its system of interlocking assembly (without the need for steel connectors), to be perfected off site before the final installation.

Chapel St-Loup, Pompaples.

When the Deaconesses of the Swiss community of St Loup underwent a significant renovation to their main institutional building, a small and temporary but nonetheless extraordinary structure was designed to serve as a chapel during the interim period of renovation work. The architects, LocalArchitecture Danilo Mondada Architects, who were commissioned for the renovation work, were also responsible for the design of the temporary chapel, and they collaborated with the specialized timber research centre IBOIS run by Yves Weinand at the Ecole Polytechnic Federale de Lausanne (EPFL).

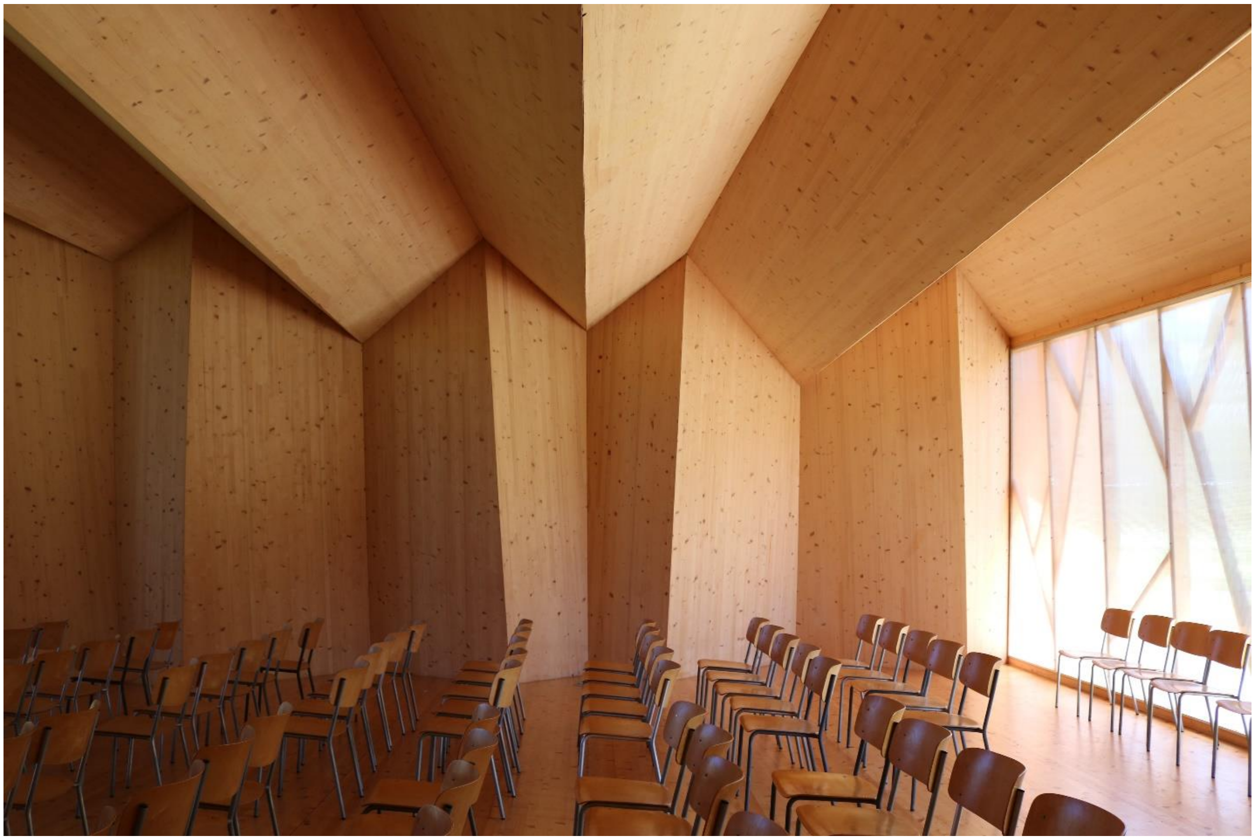


Figure 28. The folded geometry of the timber plate walls provides a unique interior volume combined with a rational, inherent stiffness to the wall and roof planes. Photo by Author.

The small chapel was intended to serve the community as a place of worship for just 2 years, and it was intended to be relatively fast to build. The proposal by the collaborative team was to employ a folded timber plate structure where the geometry of the timber plates was based on origami. The ‘pleated’ geometry of the walls and roof works very effectively serving its twin roles: to create both a sacred interior space as well as a logical structural form.

The folded geometry derives a unique interior space appropriate to a place of worship, creating a volume that evokes the essence of a church nave where both the spatial and luminescent qualities combine to provide an inspiring space for reflection. The form deliberately has a slight taper and curve in section and plan as it rises up to the altar, reinforcing the directionality of the nave terminating in a tall window and belfry. The alternating walls and roof also serve to assist in modulating the acoustics of the interior.

The geometry also underpins the structural rationality of the design due to the folded plates bringing an inherent rigidity to the overall structural form. Hani Buri and Yves Weinand describe how their research at IBOIS draws from origami:

> *.....the form finding process [...] is inspired by Origami, the Japanese art of paper folding. Based on a simple technique, Origami gives birth to an astonishing formal richness and variability. Complex geometries are generated in an economic way and this research aims at transposing these principles to construction with timber panels.*[24]

The structure uses precisely machined CLT plates fixed together along the ‘fold’ lines of the geometry via concealed folded steel plates. Although a simple paper origami pattern was a basis for the geometry, it was through the digitization of that geometry that an efficient design and fabrication of this structure was enabled, using parametric design software and CNC machining technologies.[25]

Figure 29. The external structural form also reflects the interior volume, here seen at night like a lantern. Photo by Danilo Mondada Architects.

The contiguous walls and roof are constructed of thin CLT, only 40mm thick panels in the walls and 60mm thick panels in the roof. These panels form both the interior surface finish as well as the structural wall and roof shell. These are protected from weather by a bituminous membrane, and then overlaid by a second 19mm thick ventilated plywood cladding.

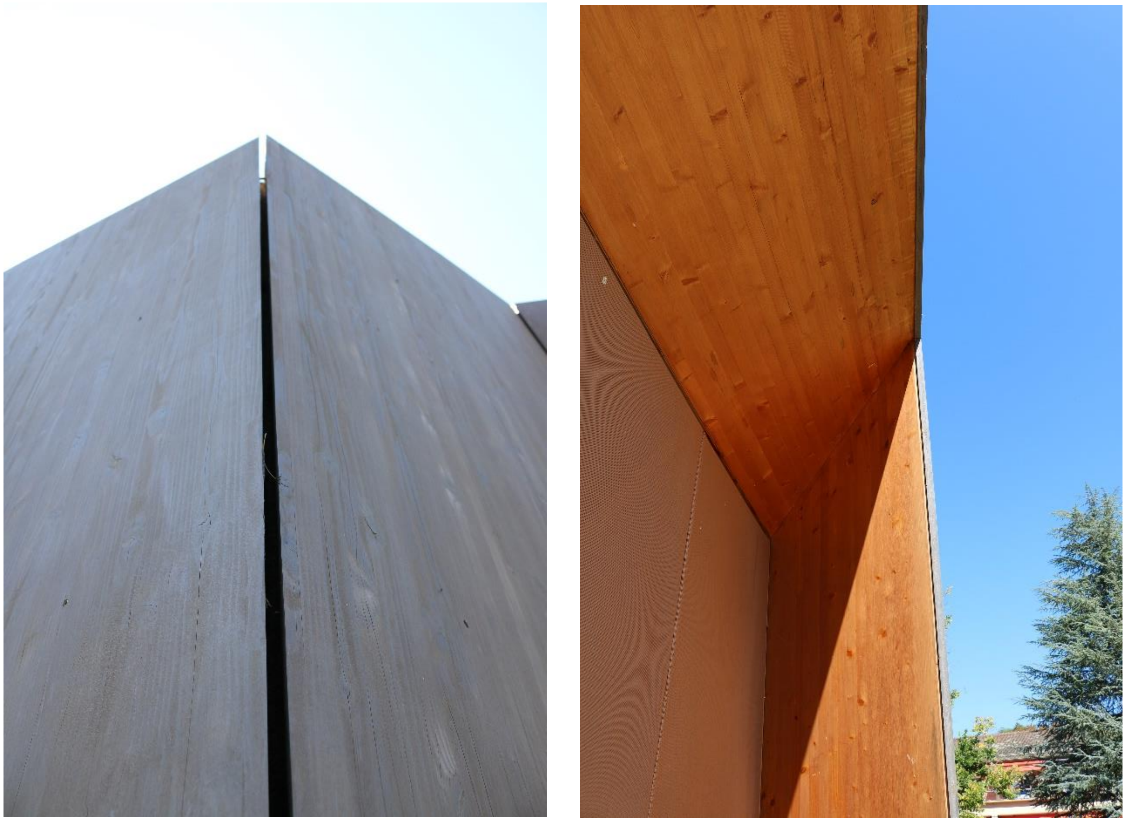


Figure 30. The CNC machining of the panels as can be seen, is very precise, with multi axis mitre joints achieved. Note the ventilation and drainage gap in the exterior ply cladding on left. Photos by Author.

Combined, the entire structure was designed and built within six months. The building period only took two months, and of that the structural panels were all installed on site screwed together in just ten days.

This project is an excellent example of how exposed structure, in this case CLT panels, can also be the most celebrated and beautiful part of the building, by shaping the interior of a sacred space. It is however, the combined contribution of the interior effect in unison with the structural and constructional rationality of the design that makes this project particularly exemplary.

Sunny Hills Cake Shop, Tokyo.

This small shop in the Tokyo suburb of Minami Aoyama is a display shop for a humble pineapple cake, and whilst at first the exterior of the building might not suggest that there are many correlations, there are nonetheless humble ambitions surrounding the philosophy of the architect, Kengo Kuma and engineer Jun Sato, when one considers the way in which the timber has been deployed.

The use of timber in this project is based on the Japanese interlocking timber joint system of *chidori,* in which 3 or more interlocking members of timber are arranged in a specific sequence three-dimensionally so as to lock the elements together and conceal the connection. Kuma points out that the *chidori* system of interlocking timber joints is widely understood in Japanese culture through common toys called *jigoku gumi,* a three dimensional puzzle which is made of simple components that appear to be magically locked together. These games, according to Kuma are:

> '*very democratic, originated from children's toys. Anybody, even kids can participate in creating three-dimensional structures with this system called Jigoku Gumi…a superposition of two layers [of slender wooden sticks], tightly fixed together with a third layer. It is similar to weaving or knitting. Adapted Jiigoku Gumi system is structurally much stronger…..And that is an adaption and invention of Sato san. In this sense, there is an encounter between traditional system and very contemporary structural system.* '[26]

Figure 31. Whilst appearing seemingly complex, the system of interlocking timber members is based on a small number of repeated components. Photo by Daichi Ano

Chidori has traditionally been used in orthogonal x,y,z axis connections between members. A key innovation that Kuma and Sato have brought to this project is the translation of this technique to 30 degree and 60 degree connections, changing the way that the structure behaves and the space is experienced, bringing it a 'forest like' quality that is more reminiscent of Gothic Architecture[27]. What we can also see is how the very humble system of *Jiigoku Gumi* can begin to take on a vastly different architectural quality when it is deployed at a larger scale, where the structure can be walked through and inhabited.

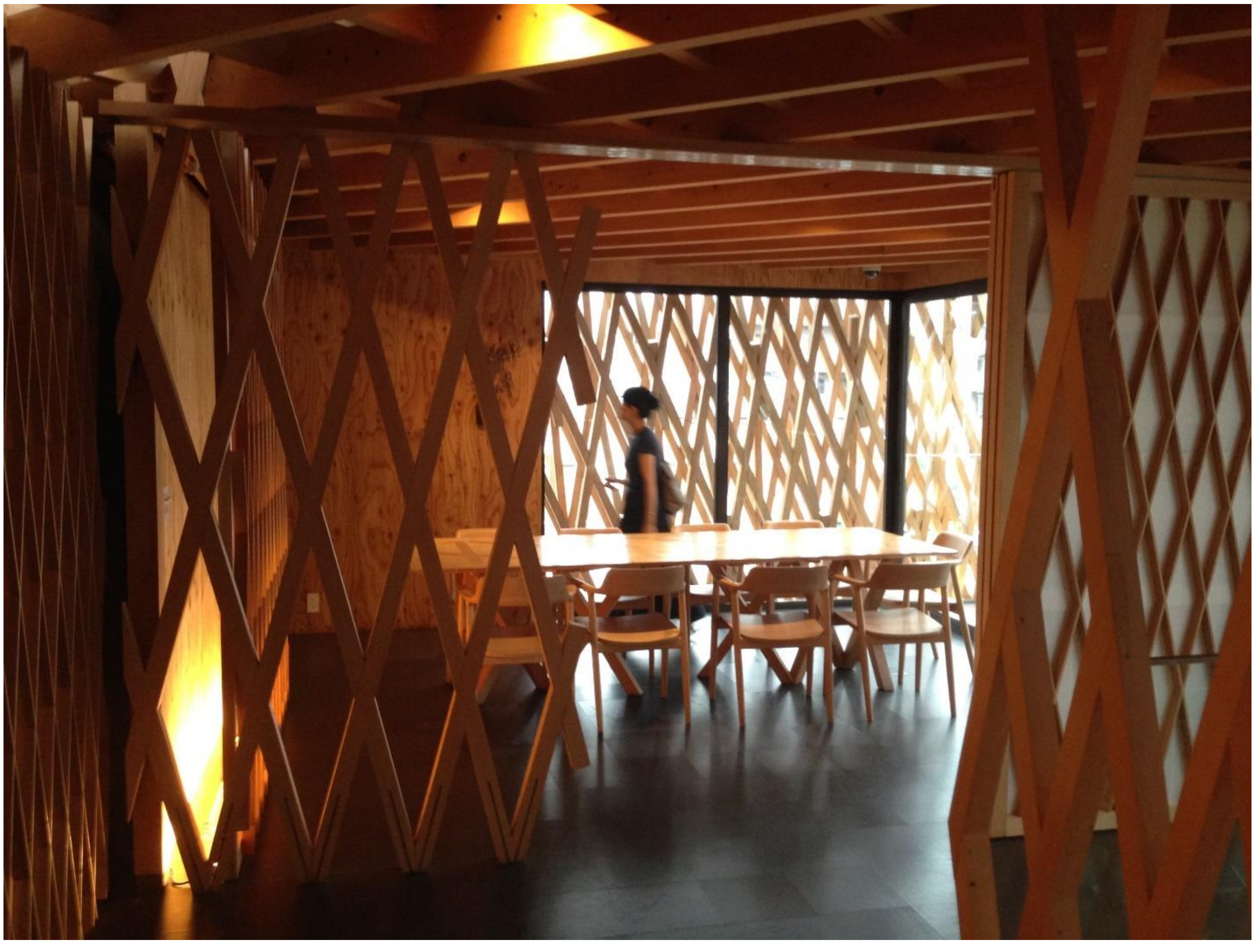


Figure 32. The interior of the building is characterized by the continuously changing dappled light of the Chidori timber structure. Photo by Author

The spatial quality of the interior is a result of the enclosing *chidori* structure, both in the walls and also in the sub floor framing, which is characterized by a soft, continuously changing dappled light being filtered through the timber. At night the structure becomes an intriguing lantern, as it is illuminated by light fixtures located in the voids between the timber members.

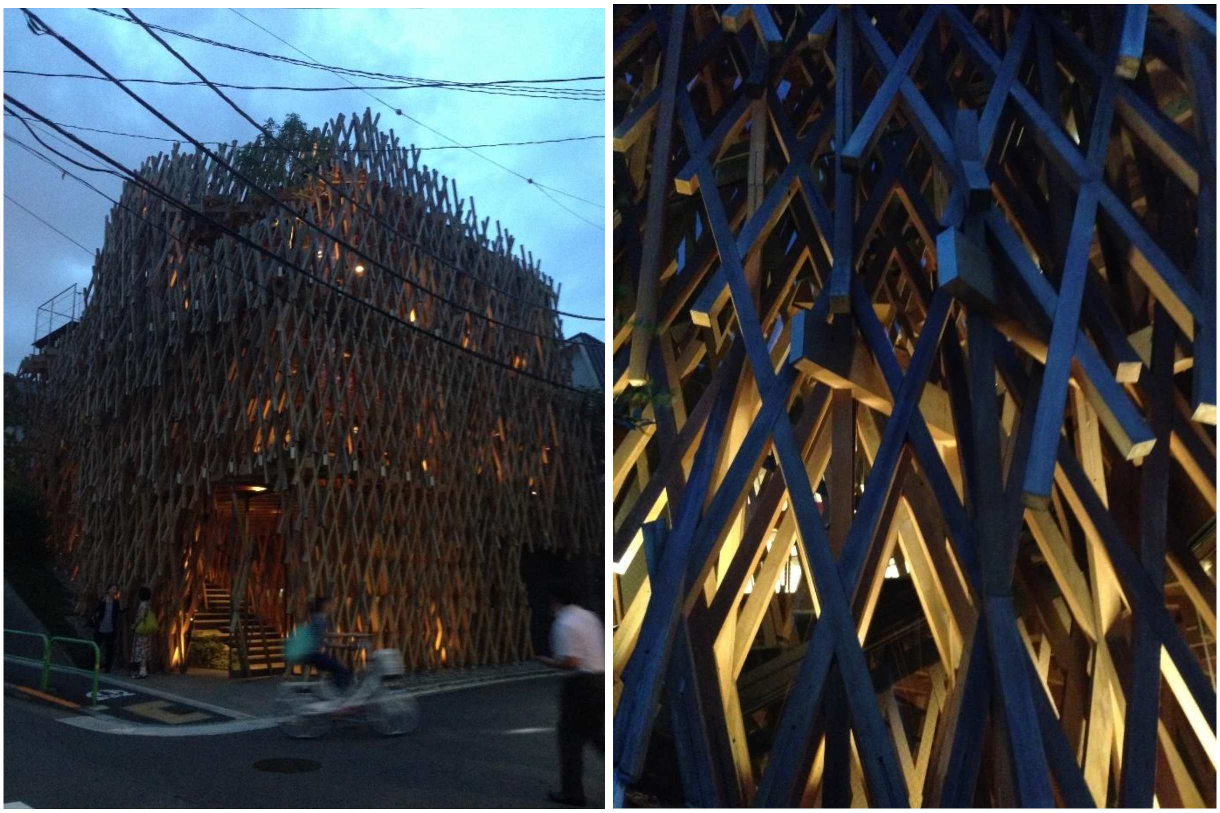


Figure 33. At night the timber Chidori is illuminated and becomes an urban lantern. Photos by author

The construction of the timber *Chidori* elements was carried out by highly skilled local artisans in conjunction with sophisticated digital design and fabrication tools. The coordination and first-pass machining of the timber members was done on CNC routers, but the subsequent finishing and assembly was done by hand. The traditional shrine builders, the *Miyadaiku,* were responsible for the final precise coordination and assembly on site.[28] The timber members were cut from traditional Japanese Cypress or Hinoki, and measure 60mm x 60mm, and almost the entire timber frame (apart from connection to footings) did not require any glue or screws in its assembly. This building is a pertinent exemplar because it demonstrates a successful modern interpretation of a traditional timber construction, as well as a sophisticated interpretation of a simple construction system, and combination of both digital CNC technologies and manual craft.

In each of the examples discussed this chapter, it is evident that when the timber connections of a structure are conspicuously exposed in buildings, they are highly effective at expressing an underlying design ambition. In the examples discussed, there has been a daring flying roof strut, seemingly floating over a precipice; the elegance of a single instrumental pin connection enlarged to the scale of a seven-story building; the synthesis of a wall and roof structure forming the dramatic interior surface of a chapel; and an intricate, modern and sophisticated interpretation of a simple timber puzzle. In each of these, the imperative to express the timber structure and celebrate the aesthetic and technical qualities of the timber connection has been at the forefront of the design and has yielded a unique and characteristic architecture. It has, without fail, relied on both an appreciation for the material, but also the means to achieve a very high level of precision in the fabrication. The next part of this paper will investigate *how* this precision is achieved.

Fabrication Technologies

A key part of the fellowship travel study involved visiting the fabrication plants that enabled the sophisticated timber construction. The two fabrication companies visited were the specialist timber fabrication Blumer Lehmann and the machine engineers Techno Wood, both in Switzerland. Both companies are responsible for developing machinery and fabrication processes that are specifically designed for to the precise machining of timber products.

Blumer Lehmann

Blumer Lehmann have in many ways led the current drive for a higher level of sophistication in the capacity for specialist timber machining of timber elements. They have been instrumental in developing both the three-dimensional programming and machining of timber elements but also have been able to develop their own machining innovations in close collaboration with timber machine manufacturers such as Techno Wood.

Blumer Lehmann have been involved in an exemplary array of projects in which the detailed design and the coordination of prefabrication processes has enabled a successful integration of both the detailed design of timber structures and the precise prefabrication of the constituent timber elements. The combined services provided by specialists such as Blumer Lehmann ensure that the prefabrication of elements is coordinated to a high level of detail. In visiting Blumer Lehmann, a tour was provided by Alexander Holl of their central mill and processing plant as well as the administration buildings in Erlenhof, followed by a tour of their state of the art new fabrication facility used by their fabrication arm Timbercode in nearby Gossau.

Figure 34. Alexander Holl (left) and Author (right) at the original plant in Erlenhof. Note the right hand side photos show the original CNC machining portal and dollies.. Photos by author.

The Timbercode facility in Gossau was opened in 2015 due to the original machining facility in Erlenhof becoming outgrown. It is a dedicated CNC machining centre capable of fabricating very large and complex timber components. It is designed to have the capacity to fabricate the components for whole buildings with precise coordination and in short periods. Due to the sensitive nature of the project for which timber components were being fabricated at the time of visiting (the new Swatch Building by Shigeru Ban[29]), photos were not permitted inside the building. The sophistication of the technology and machinery combined with the physical size of the space to work in, allows it to have virtually no limitations to the size and geometry of the components fabricated. The maximum size component is 27m long, 5.5m wide and 1.35m high. Limitations are therefore governed by means of transport, rather than means of production. The machining portal employs three 5 axis CNC milling heads, enabling all six sides of the component to be machined without having to rotate the stock.[30]

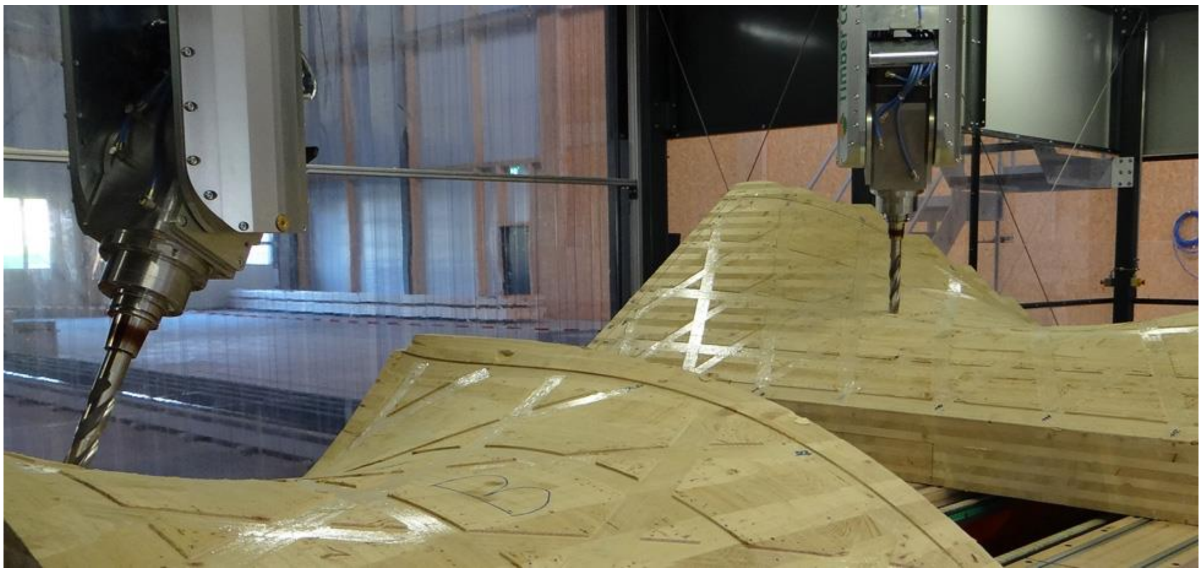


Figure 35. Timbercode facility in Gossau, note the size of the machining booth and dollies in the foreground. An overhead gantry supervision cabin has a clear acrylic floor which allows the supervisor to monitor the machining from above. Photos by Blumer Lehmann

Techno Wood

Techno Wood are designers and manufacturers of specialist machines intended specifically for the machining of timber. Their machines have been custom designed and built for fabrication companies such as Blumer Lehman who have required either specialist machines or have projects that may require a specialist process. Founded by Urs Steinmann, the company provides solutions from the writing of control software through to the final manufacture of machine components, and base their philosophy on every machine being efficient, flexible and precise.

At its core the company manufactures CNC mills, ranging in size and capability. The base model mill is the *TW Agil*, that can mill timber components a maximum 1.3m wide, 0.4m high and 13m long. The largest models are custom made such as the Timbercode machine in Blumer Lehman discussed earlier.

Interestingly, one of the mills they manufacture has a mobile machining portal, and travels along rails either side of the work table. The advantage of this system is that it is quite flexible, as it allows the fabricator to construct their own support table or support frame for the timber stock to be fixed to. Because the timber stock remains stationary, and the portal travels over it, the fabricator does not need to adapt clamps to connect the stock a moving dolly or carriage. Its disadvantage is that it has limited dust and waste extraction, whereas a stationary machine with conveyors or dollies to move the stock in and out of the machine, has a pit with central removal of dust and offcuts.

Figure 36. On the left, company founder and head designer Urs Steinmann standing inside the portal of a TW Agil Mill under construction, same machine on the right from outside the portal. Photos by Author

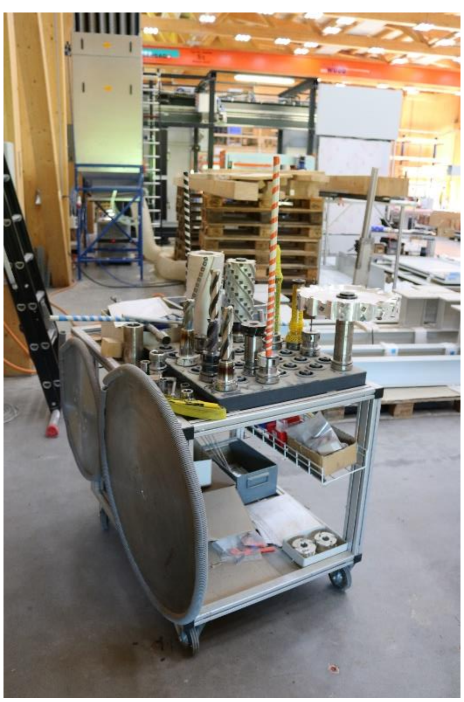


Figure 37. A selection of the tools that the mill can use, ranging from small router bits to planing heads and saw blades. The mill has an automatic tool changing station inside the portal. Photo by Author

In addition to milling machines, the other types of machines they build are machines for manufacturing timber windows, special conveying lines that can flip CLT panels, a balancing hoist that allows cranes to ensure CLT panels that are lifted horizontally, and a machine for manufacturing glueless CLT panels.

The glueless CLT technology is interesting because the panels are laminated together by diagonally driven dowels through the lamellas. A distinct advantage of no glue in the panel is that the timber is allowed to breathe throughout the whole panel assisting its ability to moderate humidity, and the material remains 100% natural and non toxic. One of the innovative aspects of the machine that Techno Wood has designed, is that it is capable of constructing the CLT panel with the openings already roughed out, ie it only puts the timber where the panel needs it, significantly reducing waste. It also coordinates the dowel location to strengthen the panel around openings.

This example of designing machines to promote a more sustainable way of using timber, is a philosophy that is carried throughout their operations. The manufacturing plant and offices are located in Toggenburg valley, a scenic rural location and the building uses advanced technologies such as a thermocouple heat exchange that circulates water deep underground to absorb heat and pump it back into the building for passive heating of the interior. As Urs reflects, he believes that it is important for the staff who are designing and building timber fabrication machines, to be reminded of the beauty of the natural environment, and to remind them constantly where the material is sourced from. Being aware of the full circle from the natural forest resource through to final product is understood and inherently valued as part of the company's ethos.

Figure 38. Urs Steinmann shown at the back of the Techno Wood plant looking up the Toggenburg valley toward the Alpstein massif. Photo by Author.

Prototyping Case Study

In returning to Australia after the international study travel period, a case study was pursued that tested the key design and construction principles learnt abroad. This prototype was made at the University of Queensland's School of Architecture workshop in 2017.

After investigating the range of projects, in the numerous examples visited, a consistent underpinning criteria of the projects visited was evidence of an expressed timber structure. Whilst timber surfaces were frequently evident in loadbearing CLT panels, of particular interest for further investigation via a prototyping process, were the examples in which the celebration or expression of the timber connection becomes a primary objective of both the construction methodology and the architecture. Several key principles have been identified that were of interest for investigating further in a local Australian case study.

A common factor that was present in all the projects visited, was the importance of a sophisticated machining process. Whilst the design of a timber connection detail may be based on techniques that could be executed by hand, the precision, speed and consistency of the CNC machining has proven to be the key factor in achieving commercial viability of timber being the principal structural material. Therefore, employing a CNC machine to fabricate the joint would constitute a key principle in the local prototyping case study.

A second principle that is consistent across the projects, is the effective use of combining multiple smaller sections of timber. In Europe this was evident in all of the projects, where laminated timber products were employed; in both glue laminated beams and columns, and cross laminated panels (CLT). Another approach to using smaller element arose from the Japanese example of using shorter and conventional selections of members of timbers joined in novel larger scale assemblies. This principle of using small sections is one that is seen to be an economical and materially efficient proposition. A second criteria for the Australian case study, therefore, was to pursue a proposed system of joining shorter members of timber.

For this purpose, the selected base material were the discarded peeler cores that are a by-product of the veneer slicing process. Plywood manufacturers peel logs in 2.7, 2.4 and 1.2m lengths, and the veneer peeling spindle machine can only slice the log to a minimum diameter. For the 2.7m and 2.4m long veneers, the cores end up being 140mm, and for the 1.2m long cores, 120mm diameter. These cores are not readily sold again in the market, and are frequently chipped and burnt to fuel the onsite kilns and conditioners. For this reason, they present a viable base product with which to investigate methods of joining. They are also dimensional very precise, as the machines consistently peel them down to the same diameter. The peeler cores used in the case study are sourced from the *Austral Plywood* plant in Brisbane and are from a local Queensland timber *Araucaria Cunninghami*, commonly known as Hoop Pine.

A third and important principle, evidnt in both the Tamedia building and the Sunny hill Cake Shop, was the design of timber to timber connections that do not need metal fastening. Here the key criteria is a self locking three dimensional timber joint that is cleverly designed and precsiely fabricated. The visibilty of this connection is also a fundamental attribute of the design. Being a well made connection, and not using any metal fastenings, it is visually appealing. The employment of the CNC machining certainly assists in achieving the precision required.

The case study prototype chosen to be pursued is the design of a self-locking timber joint that can be employed in the connection of two of the peeler cores. In this case the traditional western shipbuilding *Locked Hook Scarf Joint* or in Japanese the joint known as a *Kanawa-tsugi,* was investigated as a particular joint of interest because it allows short members to be connected end to end.

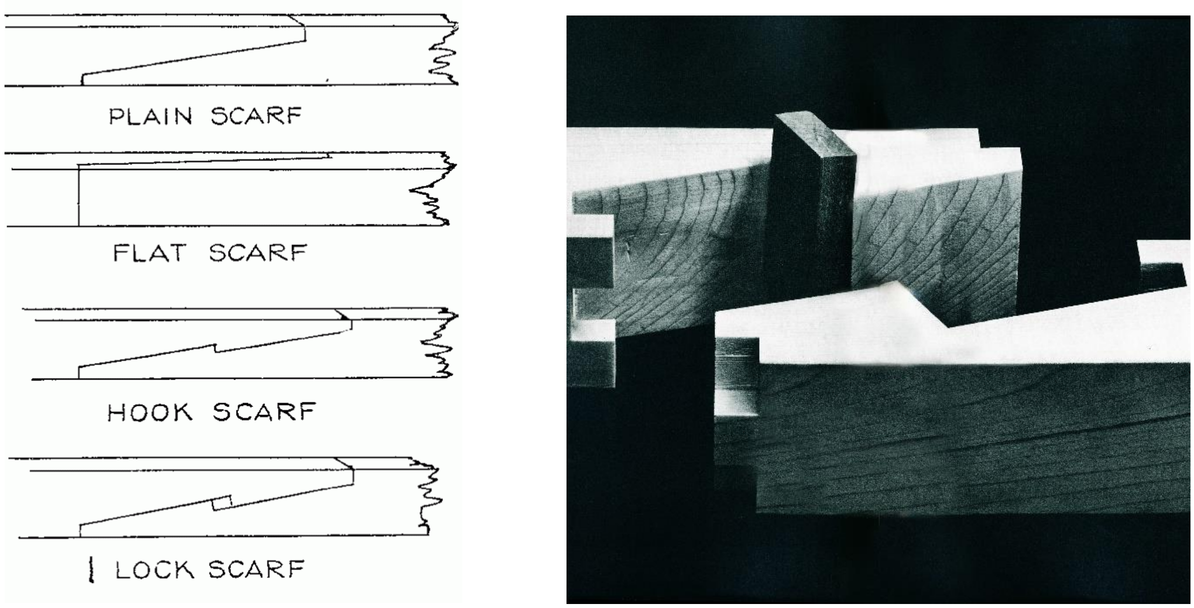


Figure 39 On left: Western ship building joints. Image from The Model Shipwright [31]. On right: the Japanese 'Kanawa tsugi' joint. Photo by Kiyoshi Seike[32]

The traditional *Locked Hook Scarf Joint* or the *Kanawa-tsugi* is a carefully made scarf joint that includes a transverse locking key that forces an interlocking of the opposing shoulders or hooks of the joint. Traditionally this joint has been prepared with saws and chisels, and so it has sharply cut internal corners. In adapting this joint to a design that could readily be machined on the CNC router, some key changes were required in the preparation of the design made in the CAD model. The CNC cutting bit is cylindrical and therefore is unable cut sharp internal corners parallel to cutting bit shank. The design of the joint was therefore adapted to be free of sharp internal corners, the corners were therefore given a radius to suit the cutting bit dimensions. In addition to this, instead of a square transverse locking key or pin, a round timber dowel was used, also suiting the shape of the cutting bit. For demonstration purposes, in order to teach students about how the joint works, a hollow aluminium tube is used for ease of removal. In constructing this prototype, several iterations were required, each time the improvements were made, particularly with regard to geometry of the joint and the tool settings on the CNC router.

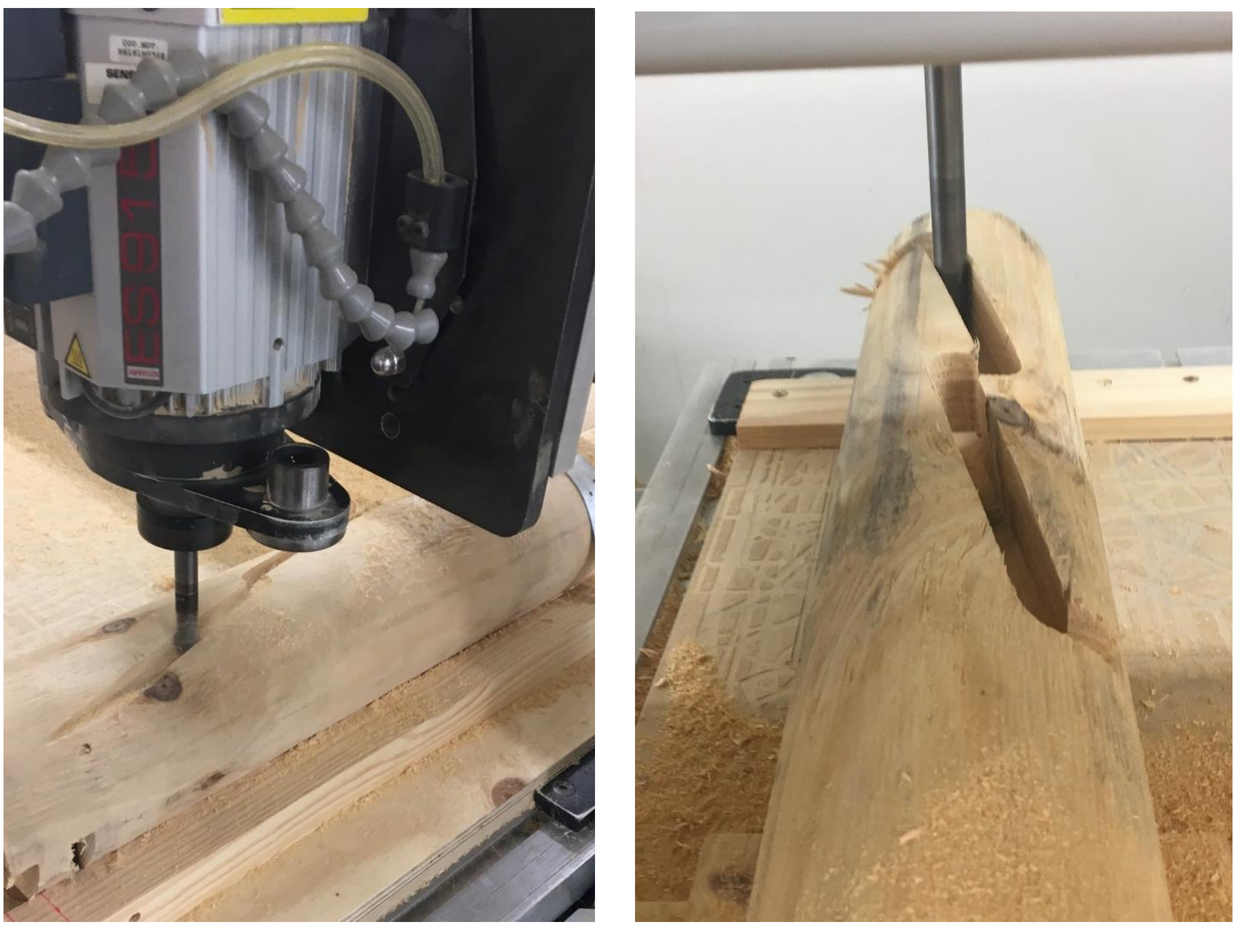


Figure 40. The geometry of the joint was coordinated with the machining constraints of the CNC router Photo by Author

Figure 41. The locked hook scarf joint shown in both the open and interlocked configuration. Photo by Author.

Once connected, the joint demonstrated significant integrity and stiffness. This connection type would typically be used to extend the length of members, and in this case, the connected peeler cores could be used in larger scale structural systems, as columns for example. If the joint was also to be glued, (which is not necessary in all applications) it would provide additional stiffness as the joint provides a large amount of surface area for glued surfaces.

Figure 42. Author with the completed prototype. With the insertion of the locking pin the joint becomes rigid. Note: in this example an aluminium tubing has been used for ease of removal for demonstration purposes. Photo by Author

The construction of this prototype has proven to be a successful demonstration of each of the key principles being investigated: It is a connection designed specifically to combine smaller members and increase their possible structural applications. In identifying a timber by-product with a relatively low existing commercial value, the connection would enable the by-product to have additional uses, thus increasing its value when the member is lengthened, and providing a sustainable re-use of the by-product; The Fabrication process has demonstrated that the joint can be successfully machined on the CNC router directly from a CAD model, and furthermore, the design of the connection is fully coordinated with the CNC own technical requirements and is based upon them; Finally, the connection is wholly timber to timber, and is completely un-reliant on metal fastenings. This makes it a visually attractive detail, is more sustainable in terms of material consumption, and most importantly in the context of the research, one that inherently expresses the structural and material properties of the connection design. In constructing this prototype and keeping the joint readily able to be dismantled, it also provides a useful teaching tool to demonstrate to students of Architecture and Engineering not only how these types of connections are designed and fabricated, but how they can also have material and aesthetic value.

Conclusions

In conclusion, through the course of the research fellowship, a catalogue of exemplar projects has been established and a series of valuable insights have been gained. In having the opportunity to visit international contemporary exemplar projects where the architecture is characterised by its expression of timber structure, the research has been able to identify why exposing timber structure is of value, and identify the critical processes required for it to be feasibly realized in a commercial construction industry.

In visiting the medium rise multi residential buildings in Vienna and Graz, an insight into the European benchmark for CLT construction could be appreciated. These projects, all government housing, necessarily had to be cost effective in order to be feasible. The cost efficiencies in these projects were proven to lie in the prefabrication of the building elements, which enabled follow on efficiencies on site by reducing the number of trades on site and shortening the overall construction program. A key insight gained from these visits was an appreciation of how the exposed timber ages over time, and how its exposed components should be properly detailed. In combination with a properly designed construction detail, it was also critical that the fabrication required a high level of precision, which was provided for in the digital modelling and the CNC prefabrication processes. A key lesson to bring to Australia is the importance of a high level of sophistication in the prefabrication technology, throughout the digital modelling stage, the fabrication stages and the effective management of the processes between.

The community buildings visited in Graz, Tyrol and Bregenzerwald, proved to be very useful exemplars because they encapsulated a broad range of benefits, both direct and indirect, that come with expressing timber in architecture. The physiological and psychological health benefits that are provided by exposing unsealed timber internally are measurable and are highly valued by the community for their oldest and youngest citizens. The environmental benefits of exposing timber are that it assists in balancing the humidity in an internal space and allows the building to perform more passively with less reliance on mechanical air conditioning. A wider reaching value in expressing timber in architecture was identified in the sense of community pride that is taken when buildings are constructed wholly from local timber resources. This has a double effect, as the building itself is valued for the added amenity and beauty that the timber brings, but perhaps more significantly, it also symbolises the community's and authorities' dedication to using local resources sustainably whilst also positively supporting the local forestry economy. These beautiful buildings offer a useful example to show to Australia as they demonstrate how even a single timber building has the capacity to bring all members of a community together.

The highly innovative timber structures visited in Switzerland and Japan demonstrate what is possible in terms of designing and fabricating expressive timber connection details. The examples in Chaserrugg and Zurich show how the translation of timber connections to large scale structures is undertaken successfully, and in doing so, create unique architectural spaces that are defined by both daring and elegant articulations of the timber connections. The inventive use of CLT in the Chapel St Loup shows how a conventional panel product can be articulated through a unique synthesis of structure and surface. The intricate use of *chidori* in Japan is a valuable reference showing how a simple system of joining small pieces of timber can create a complex and rich three-dimensional spatial structure. Each of these projects are defined by the successful deployment of a highly resolved connection detail, and each generate a highly unique architectural outcome. It is in this area of research that inventive approaches to connection detailing may be pursued further in Australia, with the case study prototype conducted in this research offering but one example in local Australian Hoop Pine.

The timber fabrication facilities visited were a valuable part of the research tour as they were representative of the current world leading technologies in large scale timber fabrication. Critical to their success was their ability to offer consultancy services in addition to digital modelling and fabrication. The fact that they have been instrumental in the realisation of many of the large scale exemplar timber projects, demonstrates their capability. A key lesson to take from visiting these facilities is the importance of involving their consultancy services from the beginning of the Architectural design stages and maintaining them through to installation and finishing of the timber in situ.

Finally, the last piece of research that was carried out, offers a test case of how these technologies could be utilised in Australia. In taking a by-product of the local plywood industry, the Hoop Pine Peeler core, the prototyping case study undertaken is a first hand demonstration of how a precise and resolved connection detail can be used to add value to cheaply available timber through a novel and attractive timber to timber connection detail.

The continuing legacy of this research will be the active dissemination of the first hand experience and the formal findings through ongoing teaching and research at the University of Queensland's Schools of Architecture and Civil Engineering. As an architect in private practice the research will also prove invaluable in its application in real projects in Australia.

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[16] Ibid., ibid.

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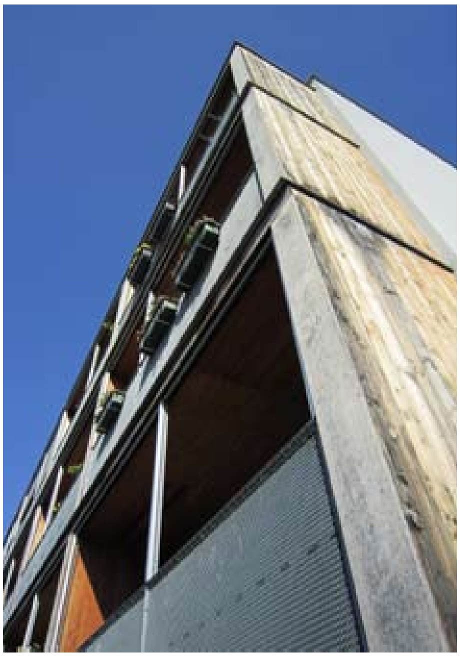
Appendix 1: Visited projects



Photos by Author.

<u>Project:</u> <u>Social Housing, Spottlgasse</u>

Location: Spotlgasse, Austria
Architect: Hubert Riess
Year: 2005
Notes: http://www.wienwood.at/05/projekte/wohnbau-spo-ettelgasse.htm

http://www.rwt.at/english/projects/national/national-2004-2007/whaspoettlgasse-wien.html

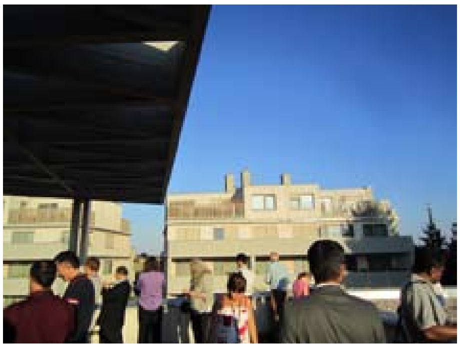




Photos by Author.

Project: Housing Estate, Muhlweg

Location: Muhlweg, Austria
Architect: Hermann Kaufmann & Johannes Kaufmann
Year: 2008
Notes: http://www.wohnbauforschung.at/index.php?id=399



Photos by Author.

<u>Project:</u> <u>Social Housing, Vienna</u>

Location: Vienna, Austria
Architect: Ulrich Huhs Architekten
Year: 2014
Notes: http://www.wienwood.at/15/projekte/Wohnanlage-Seefeld.htm

Photos by Author.

Project: Social Housing, Vienna

Location: Vienna, Austria
Architect: Anna Wickenhauser Architektur
Year: 2014
Notes: http://www.wienwood.at/15/projekte/Wohnanlage-Seefeld.htm

Photos by Author.

<u>Project:</u> <u>Waste Treatment Plant, Vienna</u>

Location: Vienna, Austria
Architect: Julius Natterer & Lukas Lang
Year: 1980
Notes: http://oe1.orf.at/artikel/330222

http://www.azw.at/event.php?event_id=1218

Photos by Author.

<u>Project:</u> <u>STRABAG Building, Hausleiten</u>

Location: Housleiten, Austria
Architect: Lukas Lang Building Technologies
Year: 2013
Notes: http://www.lukaslang.com/en.html, http://officebuild-ings.lukaslang.com/en.html

Photos by Author.

<u>Project:</u> <u>Nursing Home, Graz</u>

Location: Graz, Austria
Architect: Dietger Wissounig Architekten
Year: 2014
Notes: http://www.archdaily.com/565058/peter-rosegger-nursing-home-dietger-wissounig-architekten

Photos by Author.

Project: Communal Flats Hummellkaserne, Graz

Location: Graz, Austria
Architect: Architekt Simon Spieger & sps-architekten
Year: 2016
Notes: http://www.holzbauaustria.at/index.php?id=111&noMobile=1&tx_ttnews[tt_news]=6022&cHash=265b921c27020f5c76ce96bde6fc1f5f

Photos by Author.

<u>Project:</u> <u>Kulmer Bau Glulam Factory, Pischelsdorf</u>

Location: Pischelsdorf, Austria
Notes: http://www.kielsteg.at/referenzkunde/?lang=en

http://www.kulmerbau.at/index.php?seitenName=holzbau

Photos by Author.

Project: Kindergarten - C.I.S.E, St Johann Im Pongau

Location: St Johann Im Pongau, Austria
Architect: SPS Architekten
Const': Timber
Notes: http://www.zis-stjohann.salzburg.at/schulneubau.html

Photo by Author.

Project: Kranebitten Kindergarten

Location: Innsbruck, Austria
Architect: Reitter_Architekten ZT gesmbh
Const': Timber
Builder: Schafferer Holzbau GmbH
Year: 2015
Notes: http://www.binderholz.com/en/construction-solutions/publicmunicipal/kranebitten-kindergarten-innsbruck-austria/

Photo by Binderholz.

Photos by Author.

<u>Project:</u> <u>Kranebitten Kindergarten</u>

Photos by Author.

Project: Angelika Kaufmann Museum Schwarzenburg

Location: Schwarzenburg, Austria
Architect: Dietrich + Untertrifaller
Const': Timber
Year: 2007
GFA: 315m²
Awards: 2010 International Architecture Restoration Prize (Silver Medal)
Notes: http://www.dietrich.untertrifaller.com/projekt/angelika-kaufmann-museum

Photo by Author.

Above photos by Author.

Photo by Adolf Bereuter.

Project: Werkraum House

Location: Andelsbuch, Austria
Architect: Peter Zumthor
Const': Timber
Year: 2013
Notes: http://www.wallpaper.com/architecture/werkraum-house-by-peter-zumthor-opens-in-bregenzerwald-austria

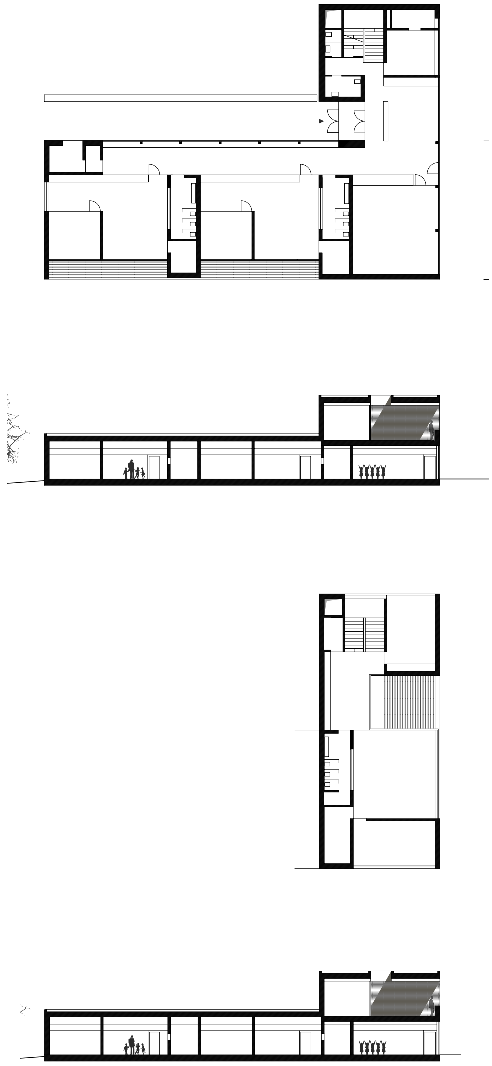
Photo by Author.

Photos by Architekturterminal.

<u>Project:</u> <u>Kindergarten Rothis</u>

Location: Rothis, Austria
Architect: Architektur Terminal
Const': Timber
Year: 2011
GFA: 789m^2
Cost: €2.0m EUR
Cost/m^2: €2540/m^2
Notes: http://www.architekturterminal.at/projekte/oeffentliches/kindergarten-roethis.html

Above photos by Architekturterminal.



Drawings by Architekturterminal.

Project: Kindergarten Rothis

Photos by Author.

Project: Horse Riding School, St Gerold

Location: St Gerold, Austria
Architect: Architekten Hermann Kaufmann ZT GmbH
Const': Timber
Year: 1997
Notes: http://www.wooddays.eu/en/wood-architecture/best-practice-architecture/detail/reithalle-st-gerold/

Photos by Bruno Klomfar.

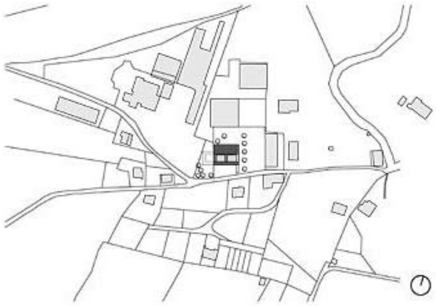
<u>Project:</u> <u>Kindergarten Egg</u>

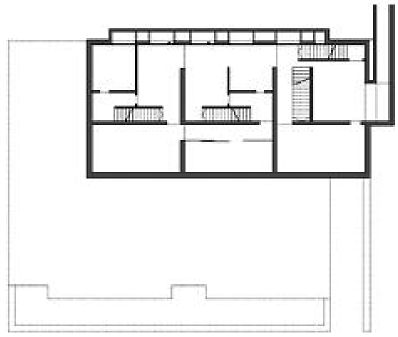
Location: Egg, Austria
Architect: Dietrich + Untertrifaller
Builder: Gemeinde Egg Entwicklungs-GmbH & Co KG
Const': Predominantly Timber with Concrete
Year: 2004
GFA: 1022m^2
Notes: http://www.nextroom.at/building.php?id=18264
http://www.detail-online.com/inspiration/kindergarten-in-egg-103563.html
http://www.dietrich.untertrifaller.com/projekt/kindergarten-egg

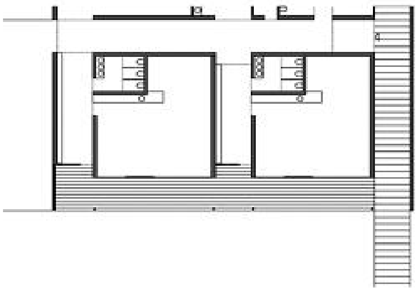
Above photos by Author.

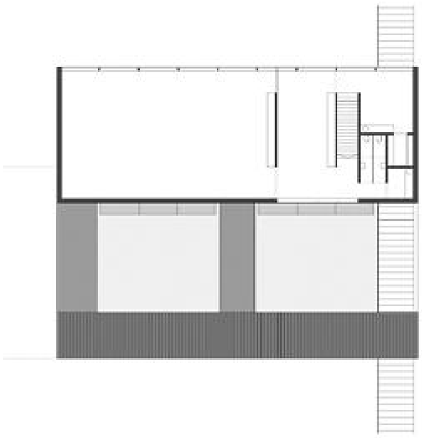
Photo by Bruno Klomfar.

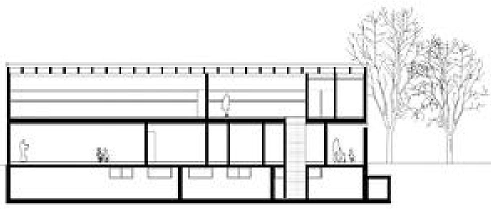
<u>Project:</u> <u>Kindergarten Egg</u>

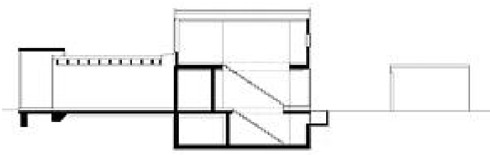












Drawings by Architect Via Next Room.

Photo by Author.

Photo by Darko Todorovic.

Photo by Robert Fessler.

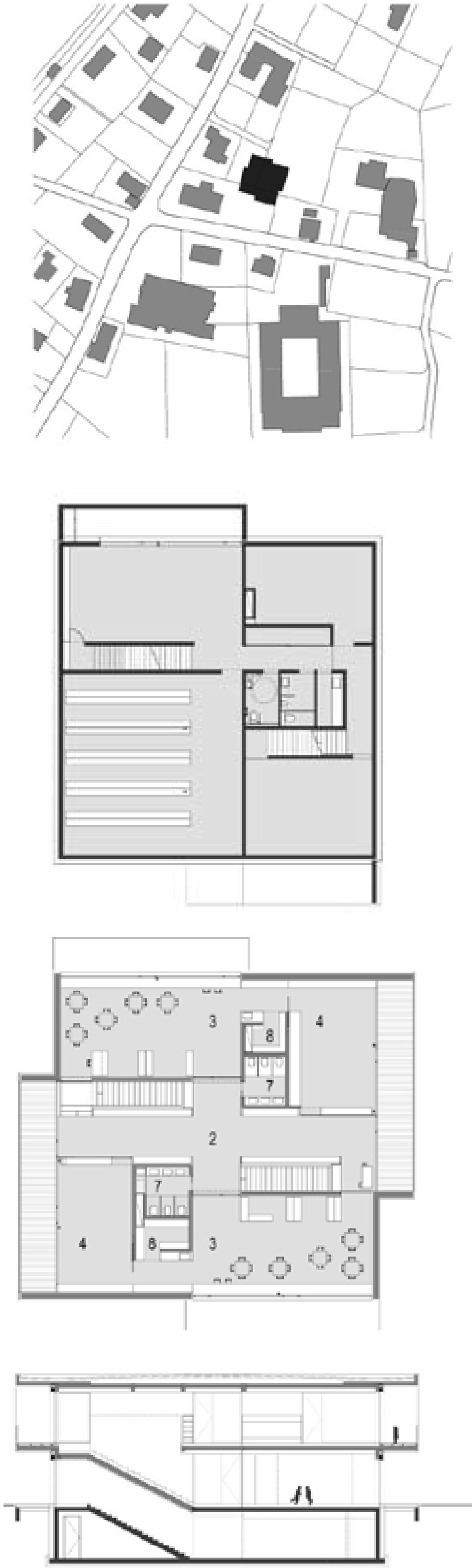
Project: Kindergarten Muntlix

Location: Muntlix, Austria
Architect: HEIN Architekten
Const': Timber
Year: 2013
GFA: 743m^2
Notes: http://www.nextroom.at/building.php?id=36362

Photo by Robert Fessler.

Photo by Kurt Horbst.

<u>Project:</u> <u>Kindergarten Muntlix</u>



Drawings by Archutect via Next Room.

Photos by Adolf Bereuter.

Project: Kindergarten Bizau

Location: Bizau, Austria
Architect: Bernardo Bader Architects
Const': Timber construction incuding cladding and lining
Year: 2010
GFA: 720m^2
Notes: http://www.bernardobader.com/projekt/kindergarten-bizau
http://www.detail.de/inspiration/kindergarten-in-bizau-106278.html

Photos by Adolf Bereuter.

<u>Project:</u> <u>Kindergarten Bizau</u>

Project: Kindergarten Bizau

Photos by Albrecht Imanuel Schnabel.

Photos by Author.

Project: Fire Station Schwarzenberg

Location: Schwarzenberg, Austria
Const': Timber

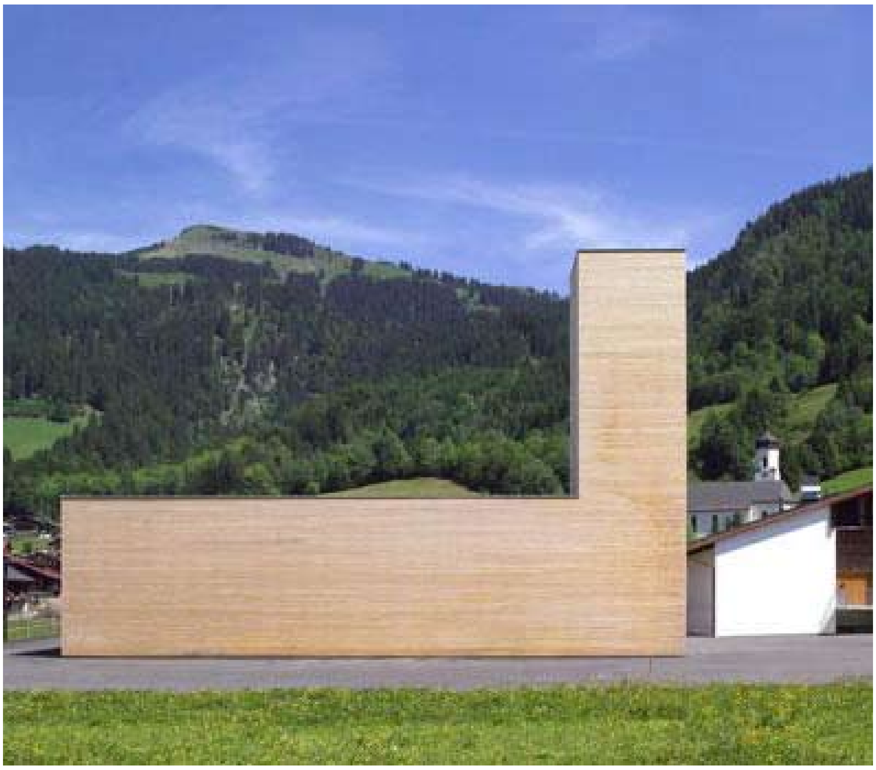


Photo by Robert Fessler.

Above photos by Feuerwehrhaus Schoppernau.

Photo by Robert Fessler.

Project: Fire Station Schoppernau

Location: Schoppernau, Austria
Architect: Matthias Hein
Builder: Gemeindeimmobolien Verwaltungs Ges, m.b.H.
Const': Timber
Year: 2005
Published: Architecturein Vorarlberg
Notes: http://www.nextroom.at/building.php?id=19109&inc=home

Photo by Feuerwehrhaus Schoppernau.

Project: Fire Station Schoppernau

Photos by Author.

Project: LifeCycle Tower - LCT ONE, Vorarlberg

Location: Vorarlberg, Austria
Architect: Hermann Kaufmann
Year: 2012

Photos by Berchtoldholz.

Project: Fire Station Andelsbuch

Location: Andelsbuch, Austria
Architect: Architekturburo Josef Schwarzler ZT
Const': Timber
Year: 2002
Site Area: 6100m^2
GFA: 1850m^2
Cost: €2.8m EUR
Cost/m^2 €1515/m^2
Notes: http://www.architekt-schwaerzler.eu/feuerwehr-und-vereinshaus-andelsbuch.html

Photos by Berchtoldholz.

Project: Fire Station Andelsbuch

Photos by Christian Grass.

Project: Multipurpose Building Thuringerberg

Location: Thuringerber, Austria
Architect: Bruno Spagolla
Builder: Verein zur Forderung der Infrastruktur der Gemeinde Thuringerberg
Const': Predominantly Timber with Concrete Engine Garage
Year: 2010
Site Area: 2017m^2
GFA: 1192m^2
Cost: €3.1m EUR
Cost/m^2: €2740 EUR
Notes: http://www.nextroom.at/building.php?id=35817

Photo by Christian Grass.

Project: Multipurpose Building Thuringerberg

Photos by Hanspeter Schiess.

Project: Community Builiding - St Gerold

Location: St Gerold, Austria
Architect: CN Architekten
Const': Timber
Year: 2009
GFA: 571m^2
Cost: €1.4m EUR
Cost/m^2 €2450/m^2
Notes: http://www.detail-online.com/inspiration/community-centre-in-st-gerold-103514.html

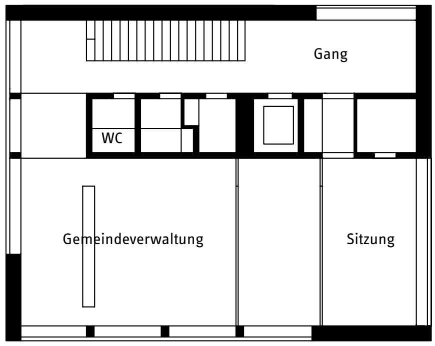
http://www.cn-architekten.at/projekte/gemeindezentrum-st-gerold/1716#

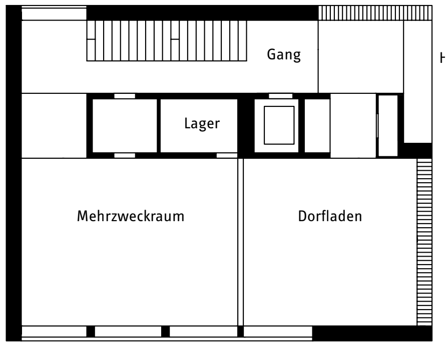

Photo by Hanspeter Schiess.

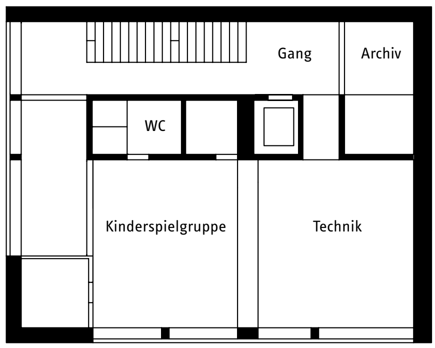
Project: Community Builiding - St Gerold

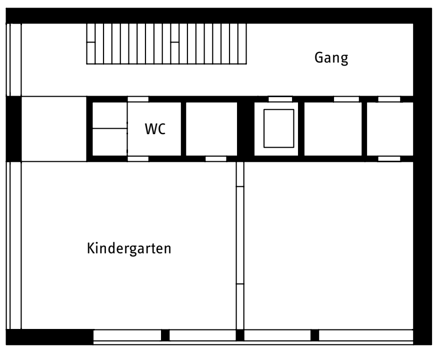
Photos by Hanspeter Schiess.

<u>Project:</u> <u>Community Builiding - St Gerold</u>









Drawings by Architect

Photo by Author.

Above photos by Juergen Pallak.

Photo by Author.

Project: Espel-Stofeli-Chaserrugg Gondola Lift

Location: Toggenburg , Switzerland
Architect: Herzog & de Meuron
Builder: E. Weber AG
Const’: Predominantly Timber with Concrete base
Year: 2015
GFA: 3000m^2 total including 3 stations
Notes: https://www.herzogdemeuron.com/index/projects/complete-works/351-375/374-2-cable-car-toggenburg/IMAGE.html

http://afasiaarchzine.com/2016/03/herzog-de-meuron-27/

Photos by Author.

Project: Espel-Stofeli-Chaserrugg Gondola Lift

Photos by Author.

Project: Manifesta 2016 ‘Pavillion of Reflections’

Location: Zurich , Switzerland
Architect: Studio Tom Emerson, ETH Zurich
Builder: Studio Tom Emerson, ETH Zurich
Const’: Timber
Year: 2016
Notes: http://manifesta.org/2015/11/pavillon-of-reflections-for-zurich-in-2016/

Photo by Author.

Photo by Tamedia.

Photo by Author.

<u>Project:</u> <u>Tamedia</u>

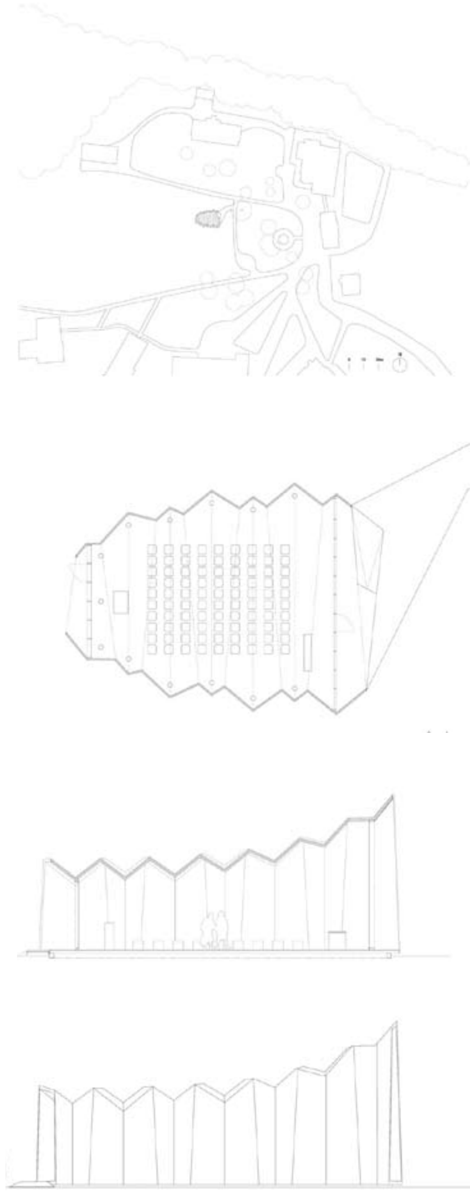
Location: Zurich, Switzerland
Architect: Shigeru Ban
Builder: HRS Real Extage AG, Frauenfeld
Const': Timber
Year: 2013
GFA: 8900m^2
Cost: $50m Swiss Francs
Notes: http://www.shigerubanarchitects.com/works/2013_tamedia-office-building/index.html

Photos by Author.

Project: Chapel St Loup

Location: Hopital de St-Loup, Switzerland
Architect: Localarchitecture + Danielo Mondada
Const': Timber
Year: 2008
Notes: http://www.archdaily.com/9201/temporary-chapel-for-the-deaconesses-of-st-loup-localarchitecture

Photo by Author.



Drawings by Architect Via Archdaily.

Project: Chapel St Loup

Photo by Katsuhisha Kida.

Photo by Katsuhisha Kida.

Photo by Author.

Project: Fuji Kindergarten

Location:	Tachikawa - Tokyo, Japan
Architect:	Tezuka Architects
Builder:	Takenaka Corporation
Const':	Concrete, Timber lined + clad
Year:	2007
GFA:	1304m^2
Notes:	http://www.tezuka-arch.com/english/index.html


Photo by Katsuhisha Kida.

Project: Fuji Kindergarten

Photo by Shigeo Ogawa.

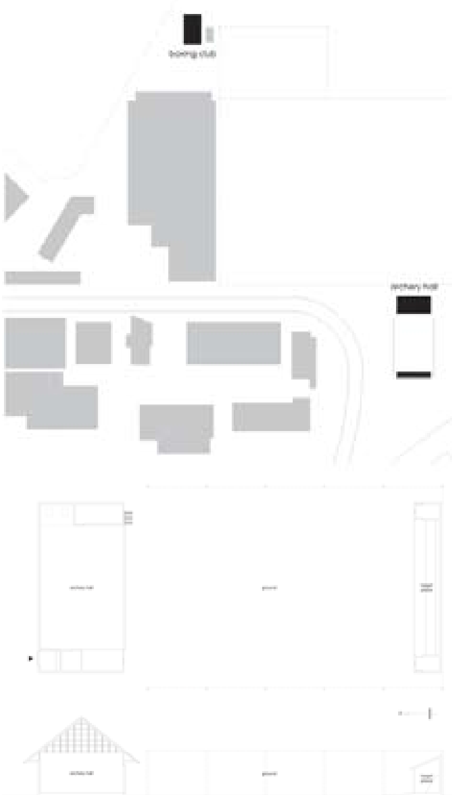
Photo by Shigeo Ogawa.

Photo by Author.

Project: Archery Hall

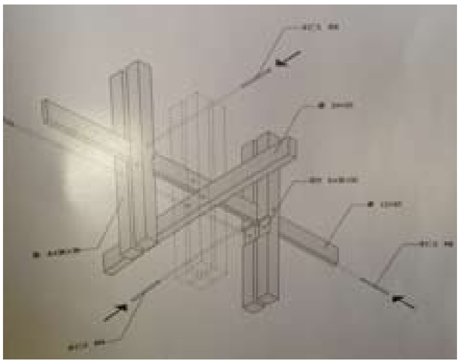
Location: Tokyo, Japan
Architect: FT Architects
Const': Timber framed, lined + clad
Year: 2013
GFA: 106m^2
Notes: http://ideasgn.com/architecture/archery-hall-boxing-club-ft-architects/

https://www.dezeen.com/2013/09/26/archery-hall-and-boxing-club-by-ft-architects/



Drawings by FT Architects via Dezeen.

Photo by Shigeo Ogawa.



Drawing by FT Architects.

Project: Archery Hall


Photo by Shigeo Ogawa.


Above photos by Shigeo Ogawa.

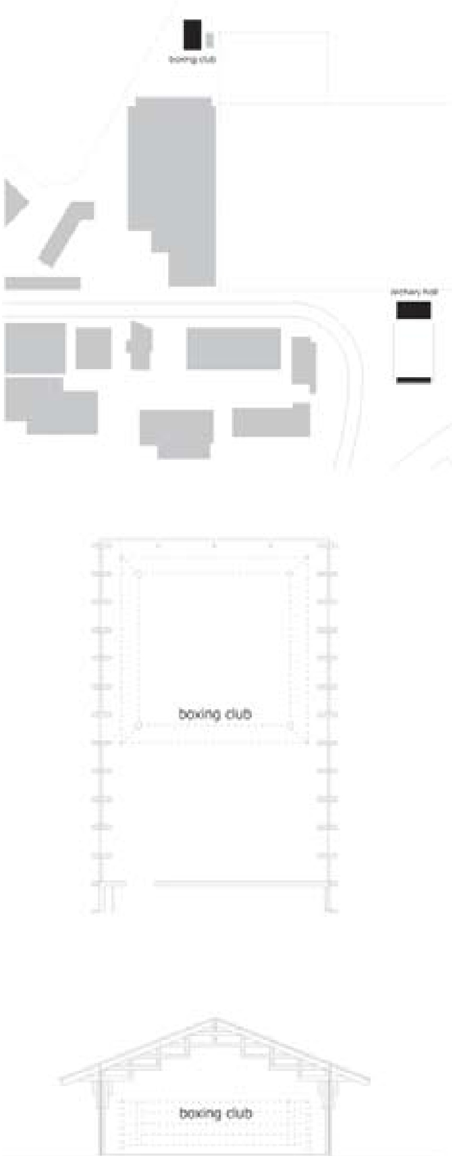

Photo by Author.

Project: Boxing Pavillion

Location: Tokyo, Japan
Architect: FT Architects
Const': Timber framed, lined + clad
Year: 2013
GFA: 93m^2
Notes: http://ideasgn.com/architecture/archery-hall-boxing-club-ft-architects/

https://www.dezeen.com/2013/09/26/archery-hall-and-boxing-club-by-ft-architects/

Photo by Shigeo Ogawa.



Drawings by FT Architects via Dezeen.

Project: Boxing Pavillion

Photos by Takeshi Yamagishi.

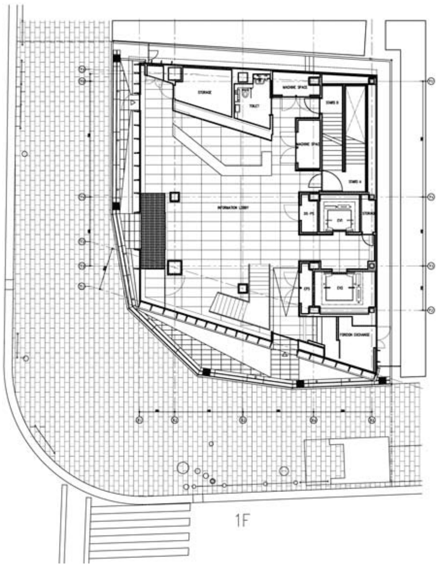
<u>Project:</u> <u>Cultural Tourist Information Centre</u>

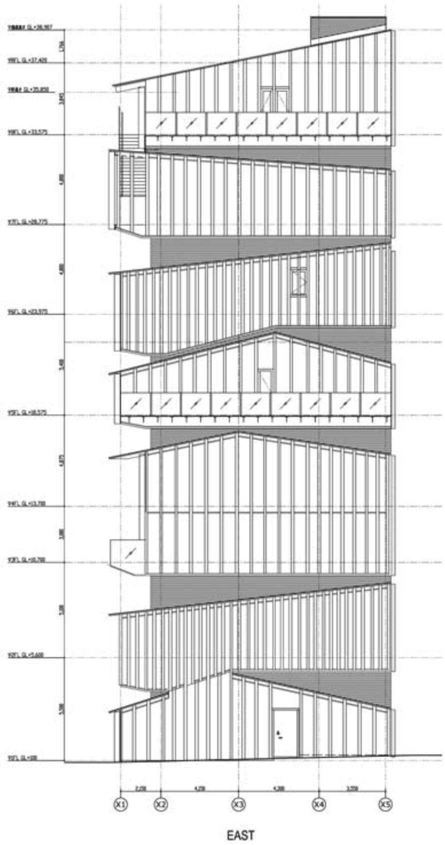
Location: Asakusa - Tokyo, Japan
Architect: Kengo Kuma and Associates
Const': Timber
Site Area: 326m^2
GFA: 2160m^2
Cost: ¥1,187,392,500
Cost/m^2: ¥5,497,187.50/m^2
Year: 2012

Notes: https://www.dezeen.com/2012/06/25/asakusa-culture-tourist-information-center-by-kengo-kuma-associates/

Photo by Author.

Project: Cultural Tourist Information Centre





Drawings by Architect - via Dezeen.

Photos by Daici Ano.

Project: SunnyHills Cake Shop

Location: Minami-Aoyama - Tokyo, Japan
Architect: Kengo Kuma and Associates
Const': Concrete + Timber
Site Area: 175m^2
GFA: 293m^2
Year: 2014
Notes: https://www.dezeen.com/2014/02/25/sunnyhills-at-minami-aoyama-by-kengo-kuma/

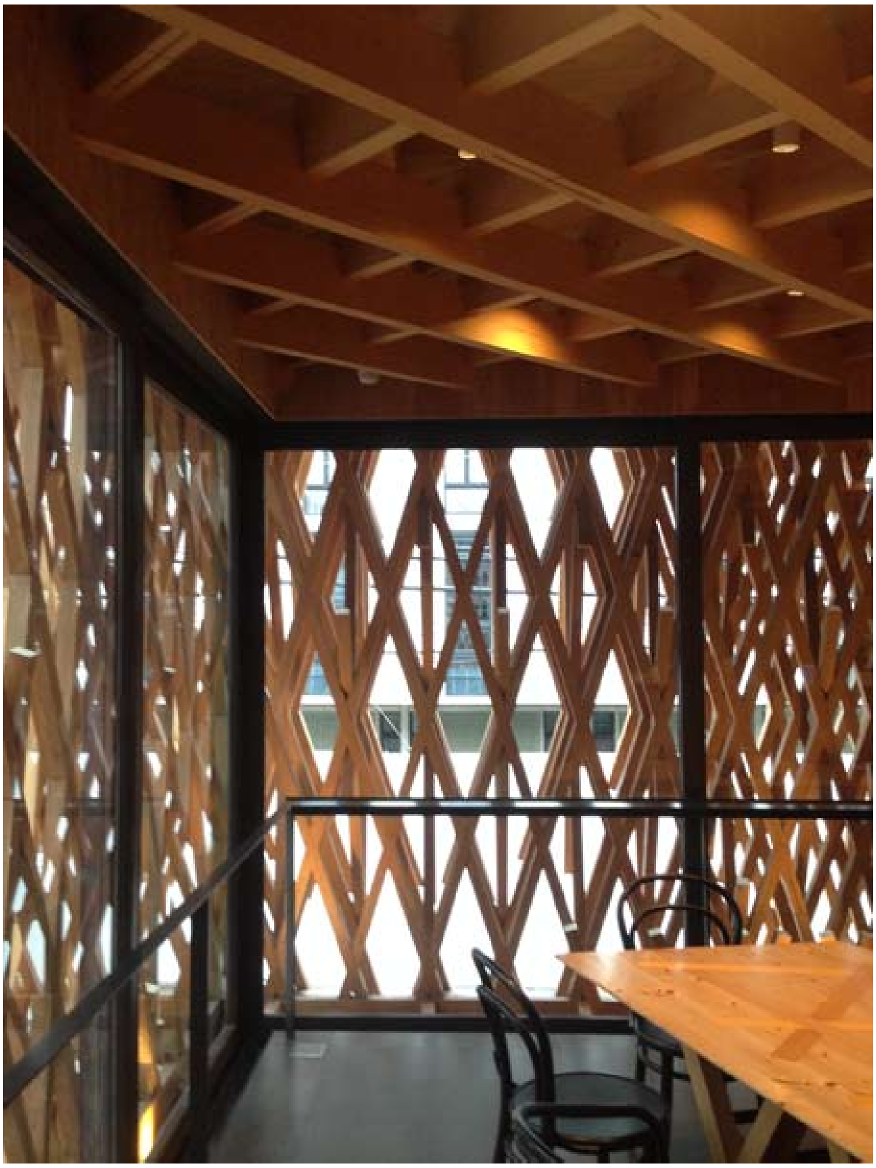


Photo by Author.

Drawings by Architect - via Dezeen.

<u>Project:</u> <u>SunnyHills Cake Shop</u>

Photo by Takumi Ota.

Above photos by Author.

Photo by Takumi Ota.

<u>Project:</u> <u>Daiwa Ubiquitous Computing Research Building</u>

Location: Tokyo, Japan
Architect: Kengo Kuma and Associates
Const': Steel + Timber Cladding
GFA: 2710m^2
Year: 2014
Notes: http://www.designboom.com/architecture/kengo-kuma-daiwa-ubiquitous-computing-research-building-tokyo-06-24-2014/

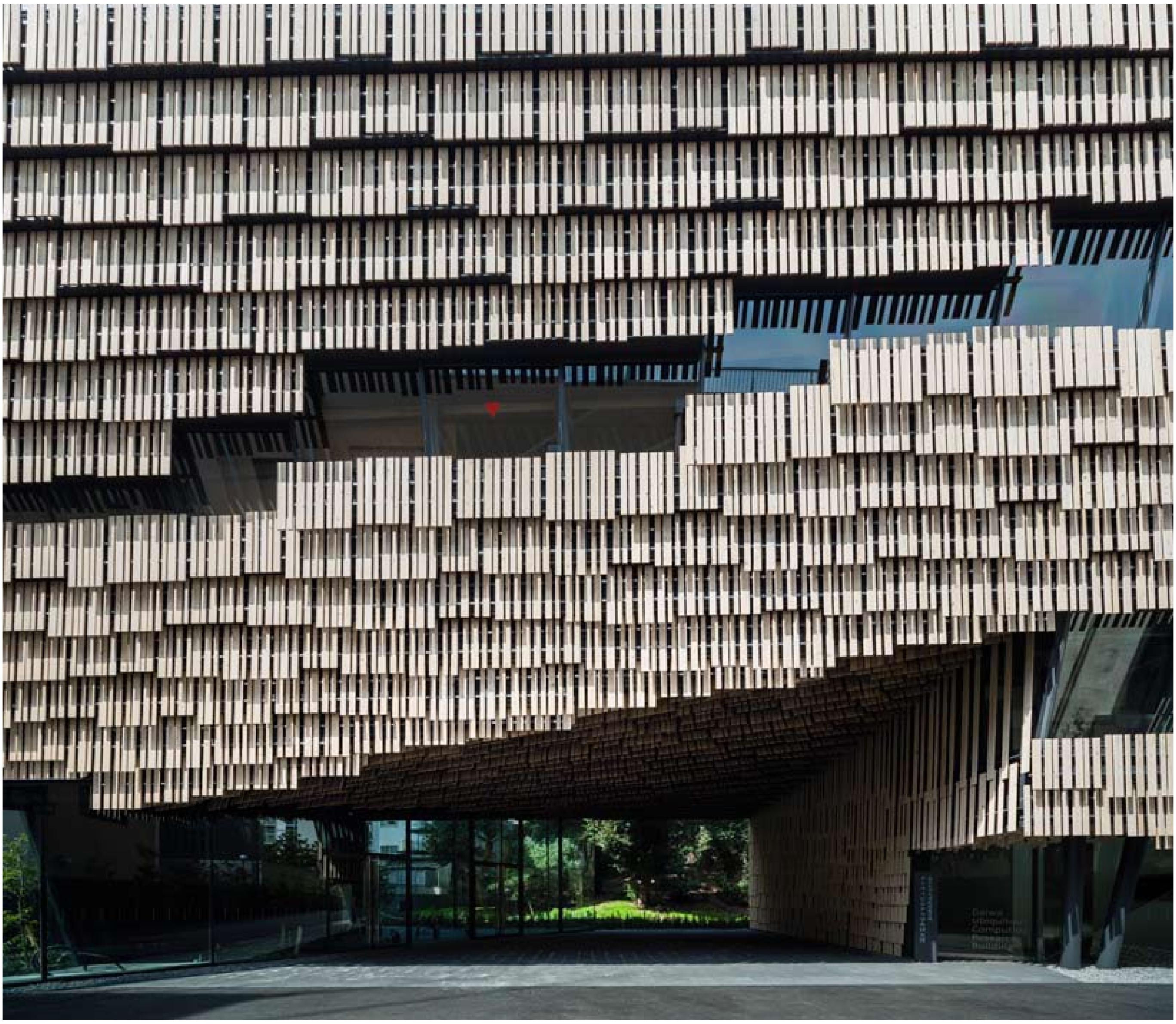


Photo by Takumi Ota.

<u>Project:</u> <u>Daiwa Ubiquitous Computing Research Building</u>

Photo by Nacasa & Partners.

Above photos by Author.

Photo by Nacasa & Partners.

Project: Mokuzai Kaikan Office

Location: Shinkiba-Tokyo, Japan
Architect: Nikken Sekkei
Const': Concrete for structural frame + Secondary Timber
GFA: 7582m^2
Year: 2009
Notes: https://www.architectural-review.com/archive/view-points/mokuzai-kaikan-office-by-tomohiko-yamanashi-and-takeyuki-katsuya-nikken-sekkei-shinkiba-tokyo-japan/5218274.article

Photo by Nacasa & Partners.

Project: Mokuzai Kaikan Office