Proceedings of the IASS 2024 Symposium
Redefining the Art of Structural Design
August 26-30, 2024, Zurich Switzerland
Philippe Block, Giulia Boller, Catherine DeWolf,
Jacqueline Pauli, Walter Kaufmann (eds.)

Spiral CLT-concrete composite stair clear spans 21m (70ft)

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Abstract

Using a special application of timber-concrete-composite (TCC), the KF Aerospace Spiral Stair is comprised of doubly curved and warped CLT with a structural concrete topping throughout the full spiral. Creating composite action between the concrete and the CLT significantly increases the overall stiffness and strength of the stair. This removes the requirement for any support columns along the 21m (70ft) clear span and maintains a highly aesthetic structure that serves as a welcoming showcase for the KF Aerospace museum, and a tribute to continually pushing the boundaries of what is possible with timber construction. The added mass of the concrete improves the vibration performance and ensures comfort for people ascending and descending the stairs. A Finite-Element orthotropic shell model was created to predict the structural performance of the TCC system which relies on composite action both in-plane and out-of-plane. This bi-axial composite application is highly innovative for TCC systems and required unconventional analysis and design methods.

Keywords: Timber-Concrete-Composite, Timber Engineering, Finite Element Analysis, Freeform Structures

1. Introduction

The Spiral Stairs that are covered in this report are part of a larger construction project in Kelowna, Canada. The main building that the stairs are in was built in 2022 and is a legacy project for one of Kelowna's largest employers, KF Aerospace. Kelowna Flight Craft, owner of KF Aerospace, wished to create a space which both pays tribute to the 50 years of the company's history and educates visitors on the history of flight in the Okanagan and worldwide.

The KF Aerospace Centre for Excellence is a true aerospace museum, showcasing historical planes and other industry memoirs while maintaining real aspects of aerospace design throughout the structure. Shaped as an aircraft, a central 2-storey hub "fuselage" is flanked by two wing-shaped hangars which houses historical planes. The building showcases the latest in structural innovation and mass timber construction throughout the superstructure.

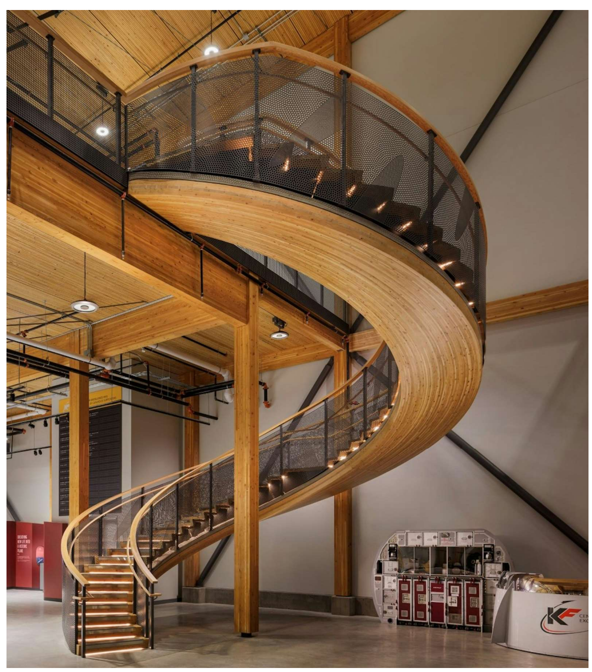


Figure 1: View of spiral stairs [1]

2. Structural system

Along the centerline of the stairs, the span is 21m and the height from bottom to top floor is 7.10m. The width of the structural components of the stairs is 1.20m. To create a structural system that can achieve these dimensions while still maintaining a light and elegant profile and meeting expectations on deflection and vibration performance, multiple different approaches were considered before arriving at the final solution.

2.1. Initial schemes and options

The initial scheme for the stairs involved a pinned-pinned connection at the base and the top of the stair to simplify the construction process. However, the pinned-pinned system did not provide adequate vibration performance to meet the clients' expectations. Three options were discussed to address this issue. The first option was to add a supporting element near mid-span that transfers some of the load to the adjacent Glulam column. The second option was a set of post-tensioned, vertical cables that attaches to the underside of the CLT and is anchored into the concrete slab to increase stiffness and dampening of the stair. The third option was to develop composite action between the timber and the concrete topping and to develop a moment fixed connections at the top and bottom of the stair.

2.2. Final scheme

For the final design, the third option explained above was selected. With the timber-concrete-composite system and the fixed connections it is possible to clear span the 21m without any intermediate support or cables, which meets the architectural intent the best.

2.3. Structural buildup

To optimize the use of the timber in this structure, several buildups were investigated with different configurations of timber and concrete thickness as well as different layups within the CLT. The final buildup utilizes a custom CLT layup of 80-35-80mm where the 80mm at top and bottom are standing laminations of 20x80mm boards and the interlayer of 35mm is a staggered layout of 17.5mm plywood strips. The concrete slab above the CLT is 100mm thick and has reinforcement in both directions. The total structural depth of this system is 295mm and thus it achieves a span-to-depth ratio of 71. The connections between concrete and timber are achieved by notches in the primary axis and 45° screws in the secondary axis.

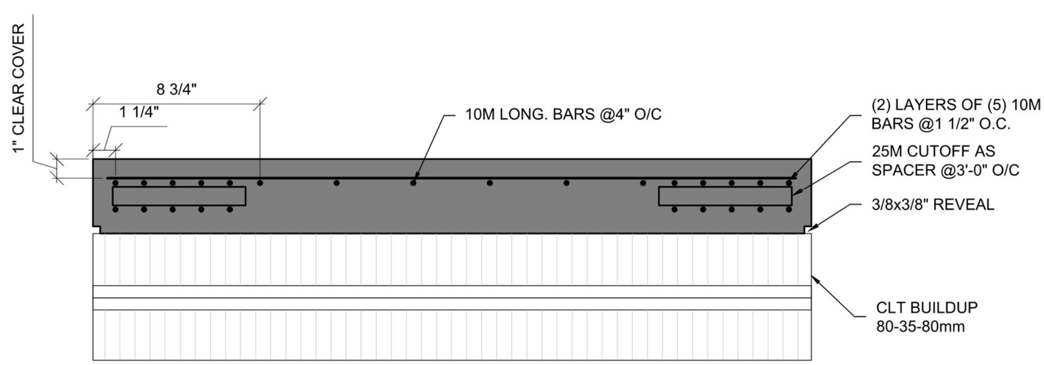


Figure 2: Section through timber-concrete-composite buildup

2.4. Base connection

To achieve the moment fixed base connection, a large free-formed concrete corbel is located below the CLT and designed to create a push/pull couple. The form finding of the corbel was intended to create a seamless transition into the concrete floor of the ground floor.

The TCC system is held down at its lower end by rebar that is developed down into the foundation and propped at the tip of the corbel. The negative moment in the TCC system that results from that applies a large compression force of 252kN on the tip of the corbel and the underside of the CLT. Because this compression can not be developed by the timber itself, reinforcement screws were inserted into the CLT at the bearing point.

The reinforcement at the tip of the corbel was designed using the strut-and-tie method to idealize the free-form of the corbel into a simple truss model and verify compression at the concrete nodes and tension at the ties as shown in Figure 3.

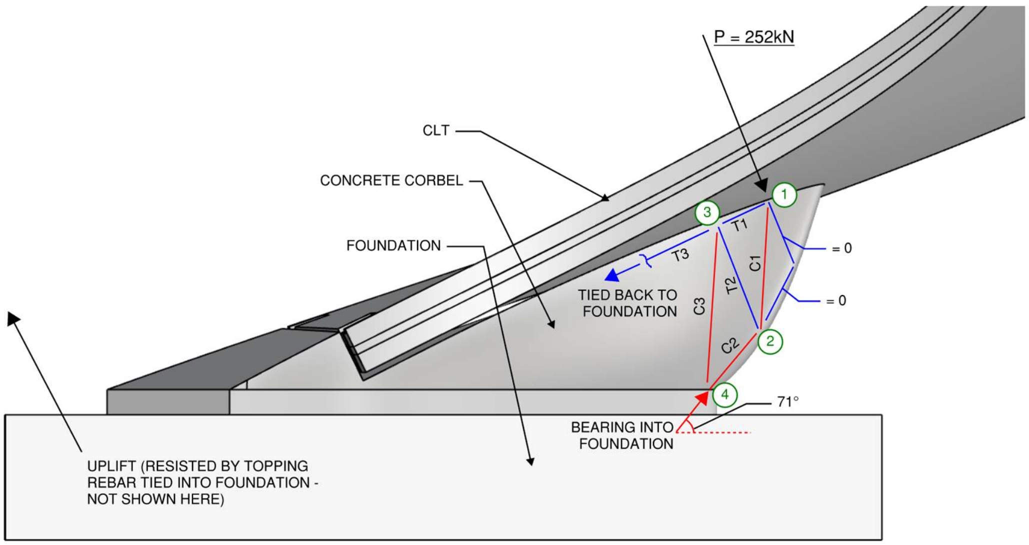


Figure 3: Excerpt from corbel reinforcement design document showing the strut-and-tie approach

2.5. Top connection

At the upper landing, a full fixity can not be achieved and therefore a semi-fixed connection was pursued by extending the rebar of the stair topping slab into the floor topping slab on the upper floor which creates a tension tie at the top of the TCC system. The compression at the bottom of the TCC system is achieved by tight shimmed gap that bears tight against the end grain of the CLT laminations.

2.6 Moment splice connection

Because the full length of the stair cannot be fabricated and shipped in one piece, the early design already incorporated a splice at mid-span that is connected on site to create a moment-continuous connection.

The shear transfer is developed by a half-lap connection between the bottom and top CLT panel, while the moment is developed by (8) perforated steel plates that are epoxied into slots at the end of the CLT panels. Both the adhesive bond of the epoxy and the mechanical connection through the perforations achieve a high moment capacity so that the (8) plates combined can transfer a moment of 45kNm.

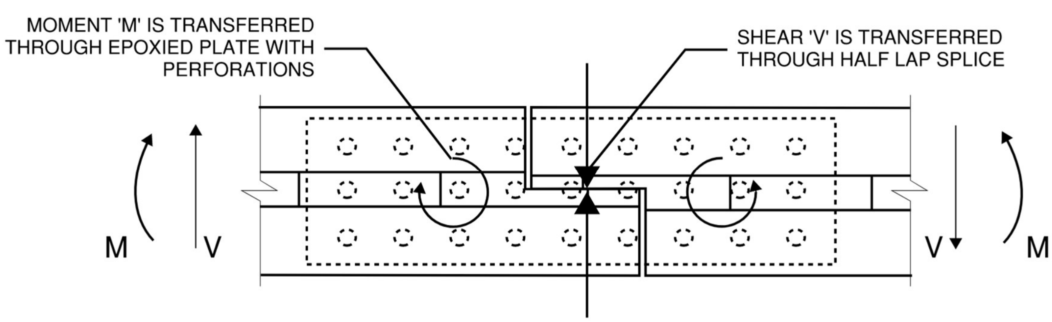


Figure 4: Simplified actions on perforated plate and half-lap splice

3. Finite-element analysis

To predict force distribution, strength and stiffness accurately, a finite-element model was created. The correct representation of the boundary conditions and connections as well as the composite behavior of the buildup both short-term and long-term (creep) were key motivations to set up a fully detailed FE-model for the structural analysis and derivation of demands.

3.1 Modelling of boundary conditions

The moment fixed base connection as described in as 2.4 was reflected in the FE-model by providing a continuous line support where the topping rebar ties down into the foundation. This support can transfer both tension and compression forces. The compression support at the tip of the corbel was modelled by a discrete support type that fails in tension.

Another key aspect that needed to be addressed in the model is the interaction of the stairs and the base structure that they are supported on. It affects the ultimate limit state (ULS) design as the flexural deflection of the supporting beam introduces a torsional moment into the stairs that must be resisted by the reinforcement of the topping slab. It also affects the serviceability (SLS) design because the compound deflection of support beam and stairs as well as the effects on the natural frequency have to be represented correctly in the model.

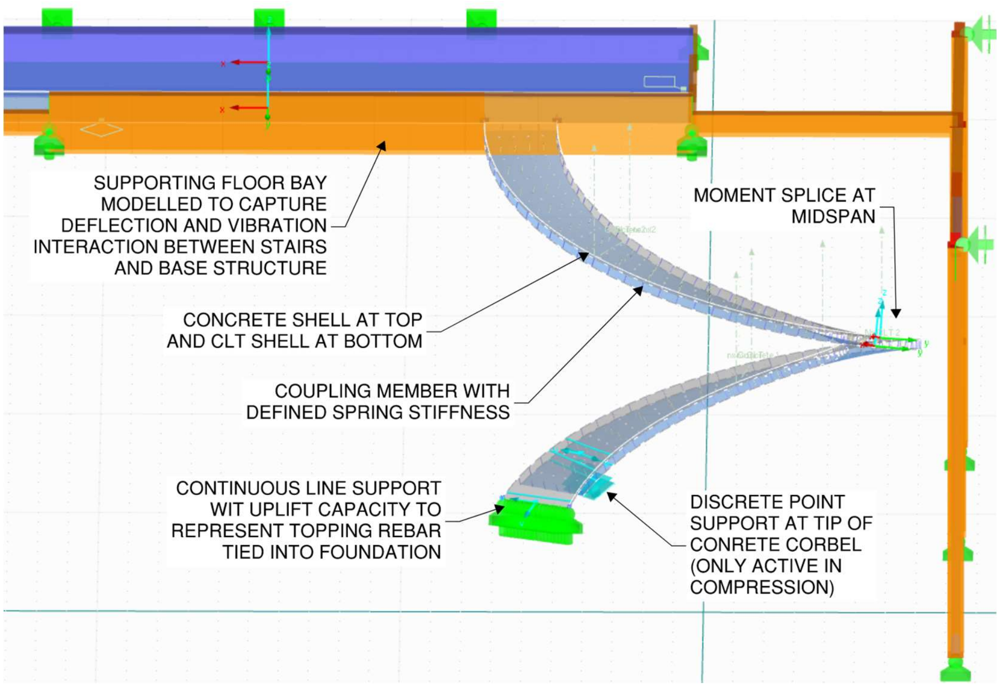


Figure 5: Excerpt from the structural analysis model

3.2 Representation of timber-concrete-composite system

To represent the composite behavior between the CLT and concrete buildup as described in section 2.3 the structure was modelled as two separate shells that are linked through coupling members with an associated spring stiffness. See also figure 5 above. The coupling members are located where the notched connections in the actual CLT buildup are located and have two different spring stiffnesses assigned to them: In the primary direction the spring stiffness of the notched connection is governed by the parallel to grain compression of the timber which is a relatively stiff load path. In the secondary direction the notched connection is governed by the much softer perpendicular to grain stiffness of the timber. The equation to derive the stiffness is based on simple spring mechanics of calculating the spring stiffness k_i for a single spring (Eq.1) first and the overall stiffness k_{tot} of two different springs in series (Eq. 2). Putting the material and geometry specific parameters of the TCC system into those equations, the overall stiffness of one notch results in equation 3.

$$\mathrm{k}_i = \frac{\mathrm{E} \times \mathrm{A}}{d} \tag{1}$$

$$\mathrm{k}_{tot} = \left(\frac{1}{k_1} + \frac{1}{k_2}\right)^{-1} \tag{2}$$

$$k_{ser} = \left(\left(\frac{d_n \times w_n \times E_c}{l_n}\right)^{-1} + \left(\frac{d_n \times w_n \times E_t}{s_n \times 0.5}\right)^{-1}\right)^{-1} \tag{3}$$

Where *k_{ser}: Stiffness of Notch*

E_c: E-Modulus of Concrete

E_t: E-Modulus of Timber (at 0° and 90°)

Remaining parameters per figure 6

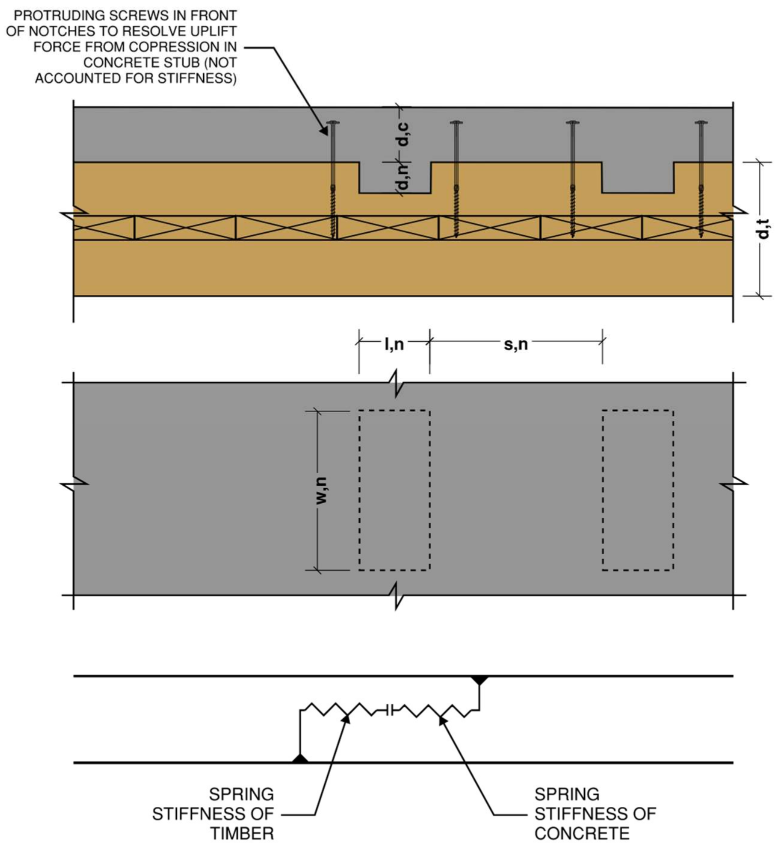


Figure 6: Model to estimate the stiffness of the TCC notches

Because the stiffness of the connection between concrete and timber is the driving factor of the effectiveness of the composite system the goal is to achieve the highest stiffness possible. Because the perpendicular to grain stiffness is very soft, the notches alone don't achieve a good composite action in the secondary direction and therefore additional inclined screws are placed next to the notch in that direction. They are protruding from the timber and tie into the concrete to transfer shear forces and increase the stiffness. Note that those are not the screws shown in figure 6.

For the strength of the notches, there are four failure modes that must be considered. The compression strength of the timber at the interface to the concrete, the shear strength of the timber in between two notches, the shear strength of the concrete along the length of one notch and the compression of the concrete at the timber interface. The latter is usually not governing when working with standard softwood species that always have a compression strength less than the concrete strength.

4. Fabrication process

The design of the stairs was always closely informed by fabrication processes and limitations. Numerous tests were conducted during the design stage to ensure that the CLT buildup that was specified was also buildable. The tests included bending tests of single laminations and a scaled mock up to test fabrication processes and the natural tendency of the CLT to spring back into its straight state after being released from the clamping jig.

4.1 Early stage bending tests

Before detailed structural analysis and design was performed, the most suitable lamination size needed to be determined. A jig was set up to represent the tightest radius at the inside of the stairs and the twist that the spiral induces into the individual boards of the CLT buildup. The sample boards were clamped against the jig to determine how much effort it takes to press the boards into the required radius and how likely breaks are at different thicknesses.

4 different thicknesses were tested: 12mm, 20mm, 25mm and 30mm and the species and grade for all was Hemlock Fir #2 with a wood moisture content between 6-10%. The radius that was tested is 3.00m and the torsional twist was 12° over the board length of 3.65m (equivalent to a torsional rate of 3.3°/m).

The testing showed that the thinnest lamination of 12mm was too susceptible to any imperfections in the wood. A single knot makes up for a large proportion of the board thickness and causes the board to break before it can be bent into the required radius.

The 30mm thick laminations could be bent into the required radius without breaking, however it required a lot of effort to do so. The tests showed that it takes three people to overcome the bending and torsional stiffness of these boards and given that more than 200 pcs must be bent like this, the 30mm laminations don't offer an efficient option for fabrication and were discarded for future considerations.

Both the 20mm and 25mm laminations offered a good compromise between the ability to be bent without breaking and the amount of effort it takes to do so. For the following design this was adopted as an acceptable range. The exact thickness of a single lamination depends also on the average glue joint thickness that was later determined in the to-scale mockup so that combined lamination and glue joint thickness sum up to be 1200mm overall width of the CLT.

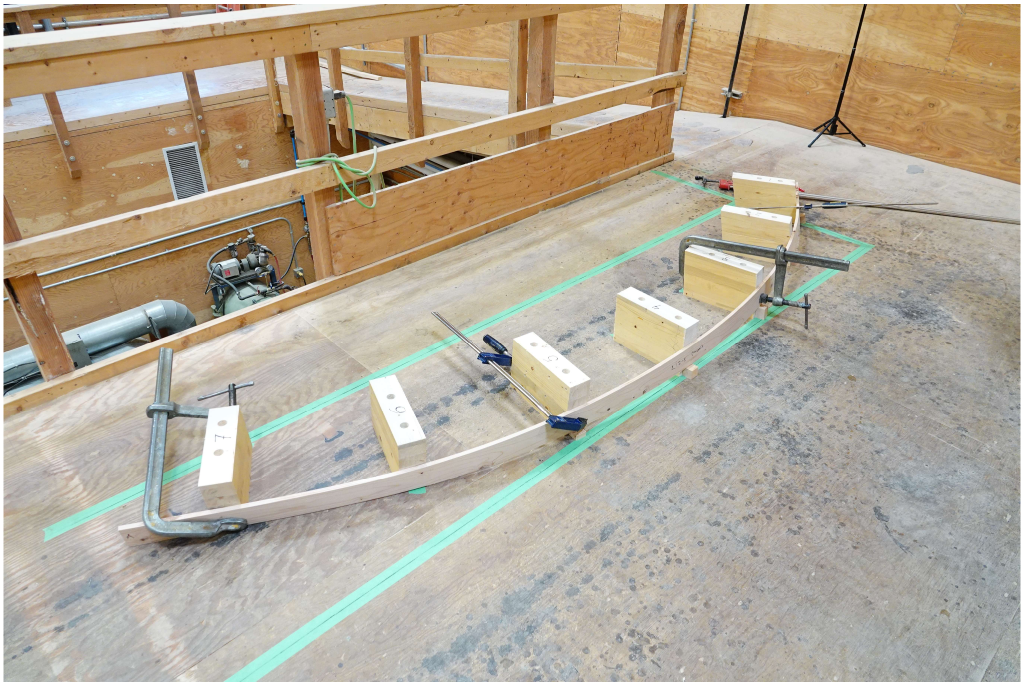


Figure 7: Setup of early stage bending tests

4.2 To-scale mockup

Before the final CLT billets were pressed, a to-scale mockup was built to further inform that design and fabrication of the final CLT. Each of the two final CLT halves were 10.40m long and 1.20m wide and for the mockup the CLT was scaled down to 2.60m length (1/4) and nominal 0.40m width (1/3). The main parameters to determine with the scaled mockup were:

1) Glue joint thickness
2) Strong axis spring back after releasing from clamps
3) Torsional spring back after releasing from clamps
4) Overall feasibility of proposed fabrication process

The fabrication process for the mockup was the same process that was proposed for the final CLT billets: An array of vertical standing plywood sheets is cut at varying angles and then arranged in a radial configuration on the shop floor to create a jig that represents the exact geometry of the spiral at the inside radius. The plywood sheets were surveyed in position with a totaling station to ensure accuracy. A fence board runs along the perimeter of the jig and was used to attach clamps that press the boards together during the layup process. For the primary layer of the CLT with the standing laminations, the boards were added one after another with a glue joint on the interface and clamped against the fence board. To release the clamps before the end of the curing time of the glue, screws were placed through the boards to sustain the clamping pressure. That way the clamps were able to be removed after the 20 minutes set time of the glue after each lamination instead of the 24h curing time. The plywood strips of the interlayer were clamped down onto the laminations below using steel angles and threaded rods to apply sufficient clamping pressure for the glue. The fabrication of the mockup showed that the process is feasible to do with three people in a reasonable amount of time. However, it was noted that the surface that faces down in the jig gets visual damage from the force that needs to be applied when clamping the boards together. While the damage is not a structural concern, it would have visual implications on the final appearance.

To determine the average glue joint thickness, the mockup was built with exactly (20) 20mm thick laminations which would result in 400mm overall width. The final width of the mockup including the (19) glue joints turned out to 404mm. The average glue joint thickness is therefore 0.21mm and well within the manufacturer's maximum glue joint limit. Furthermore, this value was later used to determine the final lamination thickness needed to achieve exactly 1200mm width of the final CLT.

The spring back effect of the CLT was determined by surveying the billet at three points in time: while the CLT was still clamped to the jog, immediately after releasing the billet from the jig and finally one week after releasing the billet to also capture potential relaxation behavior of the timber.

As shown in figure 8, the strong axis spring back was monitored by measuring the curvature of the outside perimeter of the CLT compared to the straight connection line between the two outside corners. The torsional spring effect was monitored by measuring the torsional rotation at both ends of the CLT and taking the difference between the two locations to obtain a net rotation over the length of the CLT.

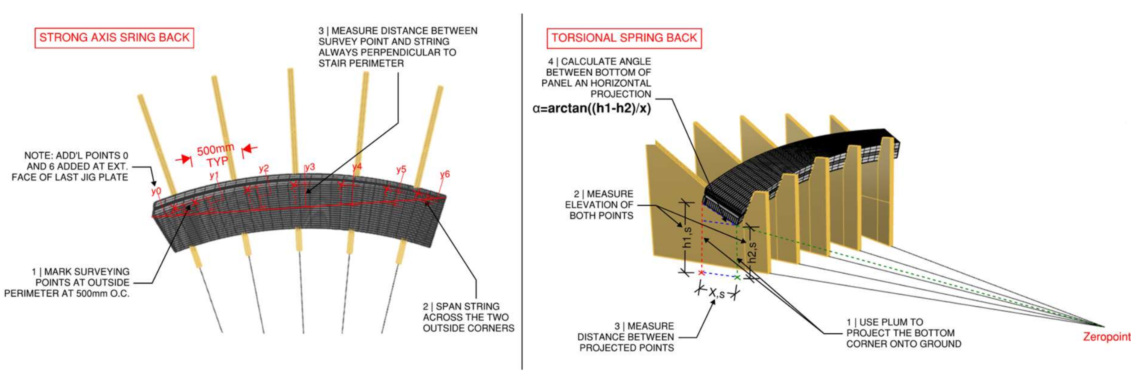


Figure 8: Illustration how the strong axis (left) and torsional (right) spring back effect are measured

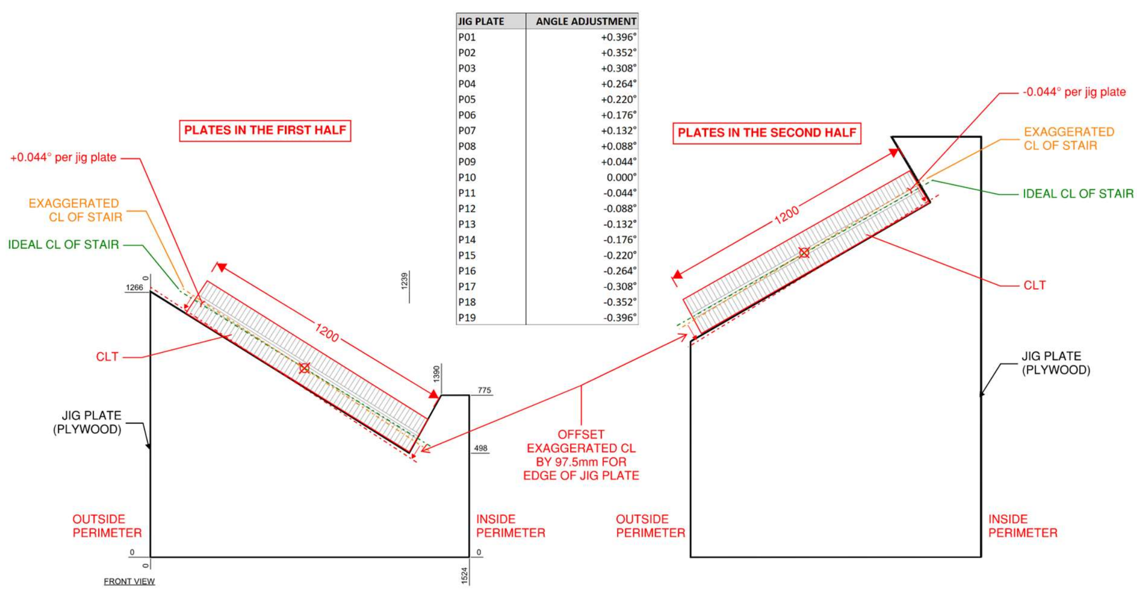
The measurements of the strong axis spring back showed that it is negligible. This can be explained by the glue joints between every single board which achieve a full composite action between boards and therefore result in a large moment of inertia to resist the tendency of the timber to spring back. However, for the torsional spring back this does not apply, and this came through in the results. Immediately after releasing the CLT from the jig, the difference of torsional rotation between start and end of the CLT decreased by 0.5° (from 8.6° to 8.1°). After one week the difference only decreased another 0.1° which shows that there is not a lot of additional relaxation happening once the timber is released from the jig.

Even though the torsional spring back of 0.6° seems small, it would cause the final stair of 1.20m width to be 13mm lower at the inside perimeter than at the outside perimeter. This type of slope is not acceptable for a stair and the spring back effect had to be addressed for the final CLT fabrication.

4.3 Final CLT fabrication

Based on the results of the mockup the final jig design and fabrication process was adjusted in four ways:

1) After the mockup showed the amount of work that is required to build and survey the jig accurately, the location of the moment splice of the stairs was adjusted to achieve two nearly identical halves. After the first half was pressed it was lifted out of the jig and the second half was able to be pressed in the same jig without any modifications.
2) The jig was arranged so that the CLT will be pressed upside down to avoid visual damage to the side of the timber that will later be exposed in the final state.
3) The lamination thickness was optimized based on the average glue joint thickness. At 1200mm target width the final layup included (55) laminations of 21.6mm thickness and (54) glue joints of 0.21mm thickness.
4) The geometry of the plywood sheets was adjusted to counteract the torsional spring back effect so that the CLT was essentially over-twisted initially and then springs back slightly to be very close to the target geometry. The spring back measurements of the mockup are adjusted for the longer and wider billet of the final CLT which results in a total of 0.8° of twist that had to be offset. Across the (19) plywood jig plates 0.4° were incrementally applied to the first (9) plates and -0.4° (in the other direction) were incrementally applied to the last (9) plates. The plate in the center remained neutral, i.e. without any deviation from the ideal angle. See figure 9 for the illustration of the over-twisted jig plates.



JIG PLATE	ANGLE ADJUSTMENT
P01	+0.396°
P02	+0.352°
P03	+0.308°
P04	+0.264°
P05	+0.220°
P06	+0.176°
P07	+0.132°
P08	+0.088°
P09	+0.044°
P10	0.000°
P11	-0.044°
P12	-0.088°
P13	-0.132°
P14	-0.176°
P15	-0.220°
P16	-0.264°
P17	-0.308°
P18	-0.352°
P19	-0.396°

Figure 9: Incremental angle adjustment of jig plates to offset the spring back effect of the timber

Besides the four adjustments outlined above, the fabrication process for the final CLT followed the same logic as described in section 4.2 for the mockup.

4.4 Installation on site

Since the moment splice between the two CLT halves relies on a tight fit and the overall structural performance was only achieved once the concrete topping is placed, the CLT had to be shored for the duration of the install and concrete placement. The shoring allowed an accurate survey of reference points once the first CLT half was in place to ensure that it was in the right location to receive the second half. Leaving the shoring underneath the stairs for two months after the concrete was poured also helped to reduce the creep of the concrete for the long-term deflection.

Furthermore, the installation on site was challenged by the fact that the main building was already fully enclosed and interior fit out had begun. The available space was so confined that custom rigging systems had to be designed to use the existing structure as anchor points and hoist the CLT in place.

Figure 10: Installation of first CLT half on site using rigging that is attached to existing structure

6. Comparison to a similar project

The following section provides a brief comparison to a similar project to put the spiral stairs into context to other precedent cases.

6.1 Cantilevered timber stairs at UBC Earth Science building (built in 2012)

The staircase at the UBC Earth Science building is a similarly complex and unique structure. It connects 5 floors and the architectural intend was to avoid any additional posts to the ground or tension ties to the roof. The structural solution here is a folded plate that is cantilevering off each floor with an intermediate landing between each stair run. Like the spiral stairs, this geometry induces a significant torsional demand into the stairs. At the UBC staircase the maximum torsion occurs at the intermediate landings where the two runs are going in alternating directions and thus applying shear forces to each other in opposing directions. The torsion here is resolved by a solid 62x254mm steel plate that is embedded into the timber parallel to the landing’s long direction and perpendicular to the stair runs [2]. The torsion of the spiral stairs is resolved by the reinforcement of the concrete topping slab. The UBC stairs utilizes HSK plates to create the moment fixed connection to the floors. The plates are slotted into the timber and then glued with epoxy [2] which is very similar to the moment splice connection that was utilized at the midpoint of the spiral stairs. One significant difference is the structural buildup of the stairs. While the spiral stairs consist of CLT in composite action with concrete, the UBC stairs are built with Glulam lying flat and solid steel plates for reinforcement in selected locations.

The stairs at the UBC also had to be shored during construction. Scaffolding was constructed from the ground up and for each level, the two stair flights that go in opposite directions were placed first and afterwards the horizontal landing panel was dropped in and connected. For the install, a small area of the roof was left open until the end to allow for crane access to the stair location. [2]

For the epoxied HSK plate connections, quality was controlled by adding vent holes to the slots and injecting the epoxy from the bottom up, which avoids air being trapped between the plates and adhesive. Additionally, the volume of adhesive that was used was constantly compared to the theoretical volume to avoid leakage or air entrapment within the connection. [2]

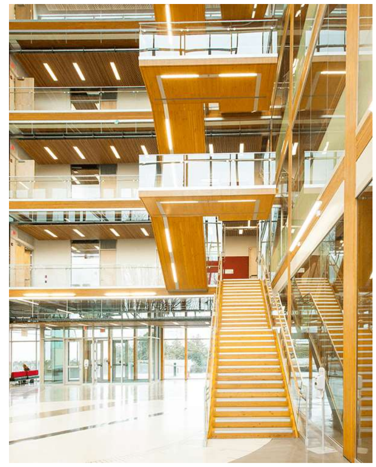


Figure 11: Stairs at the UBC [3]

7. Outlook and application to other uses

The technologies that are used on the KFA spiral stairs can be applied to other uses as well that go beyond the design and construction of stairs.

7.1 Timber-concrete-composite systems with notches

The use of timber-concrete-composite systems has been researched extensively in the past and it has become a popular solution for long spanning floor systems. Notched shear connections as used on the spiral stairs are a labor and cost-efficient solution to alternative shear connectors like glued-in mesh plates. Furthermore, the use of notched connections in TCC systems has been investigated for the use in bridge construction [4].

7.2 Use of perforated plates for moment splices

One of the big advantages of timber construction is the ability to pre-fabricate the building components to a high degree and reduce the time needed for on-site construction. However, this requires components to be proportioned in sizes that are possible to ship on trucks, trains and ships from the manufacturing facility to the site. To split larger components into smaller sections without having to design for a different structural system, the glued-in perforated plates are a good solution to create moment continuous splice. This can be applied for example to point supported CLT floors.

8. Conclusion

While the challenges that had to be overcome for the KFA spiral stairs seem very project specific at first, the take-aways on the different solutions can be transferred to other applications as well. Notable is also the unique design-build approach that was followed on this project that integrated the structural engineering, 3d modelling, fabrication and install all within one party and thus allowed for the use of unconventional building methods that push the limits in timber construction while maintaining full control over quality assurance.

Acknowledgements

For the opportunity to work on this project we would like to acknowledge the client KF Aerospace and for the cooperation Meiklejohn Architects and the General Contractor Sawchuk Developments.

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