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Pres-Lam: An innovative and collaborative timber solution.

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ABSTRACT

The pressing need for resilient structures in earthquake-prone regions has led to the development of innovative seismic solutions. Among them Pres-Lam, with a combined used of timber and adding a compression force with post tensioning stands out as a groundbreaking approach. This paper offers an overview of the core principles and advantages associated with Pres-Lam systems from design through to construction.

This paper focuses on typical issues and questions which may arise when seeking to adopt Pres-Lam within a building's footprint/structure. Post-tensioning is applied to these elements, and this process is a critical part of the on-site process. The authors consider some of the practical difficulties of post-tensioning timber, including how to allow for the lower stiffness and higher creep characteristics compared to concrete. They discuss the quality control processes necessary to achieve the required tensions, along with the design approaches adopted to accommodate this increased uncertainty.

One of the standout features of Pres-Lam systems is its rapid construction. By leveraging on prefabricated sections, construction timelines can be significantly reduced, minimizing on-site labour requirements and expediting project completion.

The combination of the natural strength and sustainability of timber combined with the robustness and flexibility of the post-tensioning offers a unique solution for constructing buildings with enhanced earthquake resistance, addressing the need for both resilience and sustainability in the built environment.

1 INTRODUCTION

Timber is a material which in New Zealand is historically associated with one or two storey residential dwellings due to the limited spans and structural capacity which can be achieved with sawn timber. With recent design/research developments, a greater awareness around sustainable and carbon neutral buildings there is increasing awareness of the adaption of other construction materials and methodologies and how they can be utilized to lower the overall carbon consumption we as a society aim to achieve.

Pres-Lam has been developed by PTL at the University of Canterbury and extensively tested in the structural laboratories of the university (Palermo 2005). The system, building on concepts originally conceived for use in concrete structures (Priestley 1999), utilizes the near century old technique of post tensioning to create a compression force between elements combined with the enhanced structural properties of the engineered wood products such as laminated veneer lumber (LVL), cross laminated timber (CLT) or glue laminated timber (Glulam or GLT). Many examples of the use of Pres-Lam in structures now exist in New Zealand and around the world (Dekker 2012, Devereux 2011, Sarti 2017).

There are a few advantages over more traditional construction materials which timber, coupled with prestressing offers. These include the lower embodied carbon, the reduction in building weight, enhanced structural seismic performance and the ability to reduce overall construction programme through prefabrication. The system also lends itself well to the adoption of prefabrication and the use of displacement-based design.

In this paper the authors will discuss the steps taken to progress the design on three recent projects from concept to construction including some of the key decisions for choosing timber, and more specifically Pres-Lam as the preferred structural medium. The authors will cover detailing and issues which arose during construction and the lessons learned for future projects. Some of the design considerations which the authors will discuss in this paper include, the low stiffness exhibited by timber and how this effects the creep of the structure, changes noted in stiffness due to hygroscopicity of the material, design approaches to accommodate this and other uncertainties with prefabricated members. Finally, the authors will also touch on corrosion protection of prestressed elements and any access and geometric issues encountered in the projects described.

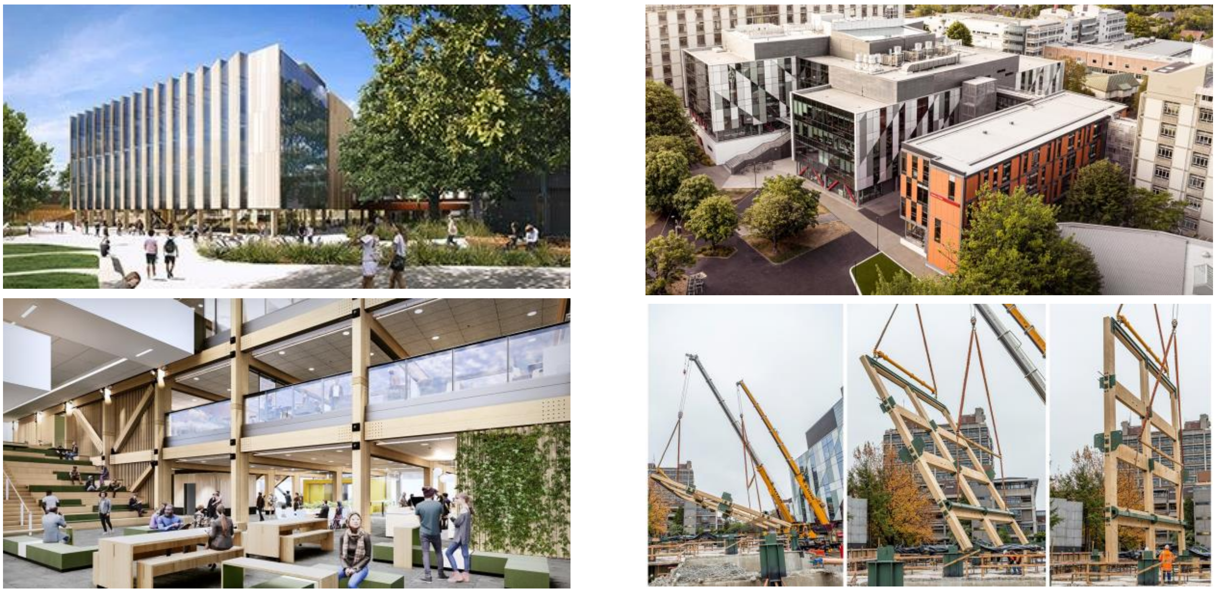
2 RECENT PROJECTS

Recently Contech, Beca and PTL have worked together on a range of projects. Contech provided technical guidance on the post tensioning products, supplied and installed the post tensioning, Beca were the design engineers and PTL provided peer review.

2.1 Pres-Lam moment frame projects.

AUT A1 at Auckland University of Technology which implements a series of Pres-Lam moment resisting frames (MRF) (Smith 2014). The MRF consists of large structural members made of LVL, used for the greater size, stiffness and strength properties when compared with sawn timber. The LVL frame also offers a relatively lightweight structural form which reduces overall building loads on the foundation as well as the seismic system. This system is similar to that implemented in the Beatrice Tinsley building at Canterbury University (Kirstein 2018).

The post-tensioning in AUT A1 consists of two unbonded Macalloy Bar at each level, extending the full width of the building. The post-tensioned connection between beam and column allows for seismic movement to be accommodated through ‘controlled rocking’, reducing the overall seismic loads on the building. The connection capacity can be tuned so that the structure behaves in a preferred manner – in this case, so that the columns do not fail in buckling nor exhibit a ‘soft-storey’ mechanism while maximising connection stiffness.



AUT A1 – Auckland University (2020-2024)

Beatrice Tinsley – Canterbury University (2016-2019)

Figure 1: Pres-Lam rocking frame projects. Image credits: Jasmax, Beca

2.2 Pres-Lam rocking wall projects.

Ashburton Civic Centre – Ashburton (2020-2024)

AgResearch – Lincoln (2021-2023)

Figure 2: Pres-Lam rocking walls projects. Image credits: Athfield Architects, Architectus, Beca

Two projects which have implemented Pres-Lam rocking walls: the Ashburton Library and Civic Centre and the AgResearch building. Both projects implemented CLT as the timber wall material for its strength and stiffness in both vertical and horizontal directions and high strength Macalloy steel bars for the post tensioning. Design constraints for the post tensioning are the same as if these were more traditional concrete walls but with greatly reduced building loads.

3 LEARNINGS FROM PROJECTS

3.1 Corrosion protection

Corrosion protection is an important consideration when using unbonded high tensile steel systems that are prone to surface oxidisation with moisture or when exposed in atmospheric conditions. In typical building structures the tendons may ultimately be within an enclosed environment, it is during the construction period that the post-tensioned tendons are typically exposed to external elements for extended periods of time.

Galvanising is not an option for high tensile steel due to the heat generation. Painting, while an option risks micro-cracking in the system as the bars are tensioned. The most common means of protecting unbonded bar tendons is to wrap the bar with a protective barrier containing oxygen scavengers such as the Denso range of products. This typically involves factory-application of Denso Tape with 55% overlap and with an outer layer of PVC tape. The Denso Tape is cold applied and remains plastic over a wide temperature range, is non-hardening and non-cracking and resistant to mineral acids, alkalis, salts and micro-organisms and highly impermeable to water, water vapour and gases.

With bar systems the individual tendon lengths are determined by the dimensions and configurations of the timber panels or beams so that couplers can be accessed to extend tendon lengths at defined positions within the timber element. While bars are ordered to a particular length and supplied with factory-applied Denso-PVC corrosion protection wrapping over the full length it is common for approx. 100mm each end of each bar remain exposed for local engagement of couplers or end anchorages at time of installation. These coupled sections would be locally wrapped for corrosion protection using the same system albeit manually applied. Anchorage ends may also be fitted with a galvanised cap fixed to the bearing plate for additional protection or for a more aesthetic appearance if visible. These caps may also be Denso grease filled if required.

With strand tendons the use of factory “greased and sheathed” strand where individual wires in a strand are opened up, passed through a hot grease bath, then closed again before the strand is fed into a 16mm diameter polyethylene tube which itself is pumped with hot grease. Strands may be used individually or grouped to suit a multi-strand anchor head to provide the capacity sought by the designer. In situations where the outer polyurethane (PE) tube is trimmed back behind the anchor head the bare strand requires protection within a steel stub, trumpet or transition pipe of sufficient length to ensure the bare strand when tensioned allowing for strand extension is positioned within this stub, trumpet or transition pipe. The multi-strand anchor head after stressing should be protected with a galvanised or plastic cap which is grease filled for corrosion protection.

3.2 Geometry

Vertical tendons are usually configured with a starter bar which is cast into a concrete foundation with a reaction plate and anti-burst reinforcing preventing break-out. Starter bars must be secured in the correct position and to the correct vertical alignment, with no possibility of movement within the foundation concrete pour, to ensure coupling connections with the main bars installed in wall panels that have limited capacity for movement within the CLT panel duct.

The starter bar would extend above the finished floor level allowing for coupling to the main bar length(s) once CLT panels are installed through an opening formed at or near the base of the panel. Depending on the height of the panel and length of tendon required there may be one or more openings in a panel to allow for coupling of individual bars at particular locations. It is critical that couplers along the length of the tendon are fully engaged at these openings and “snug tight”. A bearing plate of sufficient size to spread the load is fitted at the top with sufficient length extending to fit a stressing jack and tension to nominated lock-off loads.

Beca worked with CLT suppliers to determine the best way to provide voids for the post-tensioning in the walls. The CLT walls are formed out of lamellas, boards of sawn timber glue together in orthogonal layers to form the panel. During manufacture a vertical lamella was removed to provide a vertical void for each post tensioning cable. Therefore, the layout of the post-tensioning cables was set by the CLT lamella locations. Contech provided input on the dimensional requirements of the voids to allow installation of the bars.

For horizontal bars the design process determines the position of the coupler and size of the formed opening through beams and columns to allow the fit of the coupler outer diameter. The designer may provide a larger duct opening through the column for fitting the coupler with a smaller duct opening through the beam or provide a consistent duct opening through the beam and column. For the former, the frame assembly must be staged to allow bar installation and coupler engagement as well as positioning of the coupler to ensure no conflict when tensioning the tendon. For the latter, the bar can be individually installed, the coupler engaged, and the next bar coupled on, and tendon fed into the duct from one end of the beam to the other.

With strand tendons the individual strands would be fed through from the most accessible end of the element with anchorages detailed at each end with a bearing plate and multi-strand stressing head. Strands may be tensioned individually using a mono-strand jack or as a group using a multi-strand jack.

3.3 Access

- Sufficient access is required vertically and horizontally for tendon installation and tensioning. For vertical bar tendons and depending on bar size, length and weight this may require craneage assistance for installation of individual tendons.
- Tensioning requires up to 1 meter at bar anchorage ends allowing for a bearing plate, flat washer, nut, bar extension, stressing trestle, stressing jack and allowance for bar extension. If a client is considering permanent load cells to be fitted for the purposes of real-time monitoring of tendon load over the life of the structure, then the dimensions of these load cells and fit within the architectural envelope will require consideration.
- For strand tendons tensioning of the tendon may be as a group using a multi-strand jack, or given the strands are individually greased and sheathed may be tensioned individually with a mono-strand jack – although the latter requires multiple iterations to ensure even load application on each multi tendon anchorage.
- Access should also be considered for future load checks if required – for example after a significant seismic event or to comply with a designer’s long-term maintenance and monitoring programme. For bars, this requires leaving sufficient bar thread protruding behind the nut to allow engagement of a coupler and short bar extension with one metre clearance for the stressing operations (trestle, stressing jack). For strand, the load check will require primary installation of a threaded anchor head allowing for a future threaded coupler to be engaged to lift the tendon group. Individual strand stressing should not be undertaken due to risks of unseating the wedge or losing the strand. Between two and three metres of access behind the anchor head would be required for engagement and fitting a multi-strand jack. In situations where re-stressing in planned, the external cladding design should consider the need for future access to tendon anchorage ends and for example curtain wall designs and layout may provide for a window positioned in line with the anchorage that could be opened or removed allowing for future load checks.
- For vertical bars, consideration of individual bar lengths versus panel openings for engagement of couplers needs to be part of the design development phase in order for panel openings to be positioned at defined points over the bar length to allow for coupling of individual bars. Access is needed at coupler positions to engage the subsequently installed bar and to apply the corrosion protection to the coupled

connection. These panel openings may be covered after the connections are completed with a timber block or a clear glass or PVC block if intending to retain as a visible feature.

- Starter bar threads protruding above finished floor levels should be protected against concrete slurry splatter by the application of Denso-PVC as a temporary measure and for corrosion protection of the exposed bar thread. This needs to remain in place for protection of the protruding length until panels are ready to install when they may be trimmed back to the required dimension above the finished floor level for coupler engagement within the lowermost panel pocket.

3.4 Construction timeline and approach to installation

- Starter bars, bearing plates and anti-burst would typically be pre-assembled for installation in foundations as a “group” which is usually co-ordinated with conventional reinforcing installation.
- For vertical tendons the main bars would be installed into the panel while on the ground and when the panel is lifted into position bars are already in place with a temporary block fitted to elevate the tendon avoiding a clash with the protruding starter bar while the panel is positioned. When the panel is secured the bar weight can be held, the temporary block removed, and the bar lowered allowing for engagement of the coupler with the protruding starter bars cast into foundations.
- For horizontal tendons the bar or strand would be installed in the frame also while still on the ground and when the moment frame is assembled the load would be applied on the ground – in the case of AUT the tendon was taken to 55% UTS – so the frame was tensioned before being lifted. Once the entire building is erected including floor levels and before the architectural cladding is in place load checks would be carried out to ensure the intended design load is applied to the tendon.
- For all tendons the corrosion protection measures would then be applied to anchorage ends and coupled connections.

3.5 Potential Issues

- Contract Award v Procurement lead times. Global events have an impact on supply chains and in recent years, with the conflict in Eastern Europe impacting on global steel supply, Covid disruptions, shipping industry route and schedule changes, we have seen the lead times for materials procurement extending. Client commitments to a project often overlook the procurement lead times where materials are sourced from specialist offshore suppliers. In most cases the procurement of long lead time materials is highlighted in bid submissions, but this point tends to be lost awaiting agreement between the Principal and main contractor. One of the early requirements for installation is the starter bars and if not available in NZ stocks at the time, any shipping delays can impact on main contractor’s programmes.
- Starter bar alignment in foundations – it is essential that the starter bars are set up in the correct position and to the correct alignment and secured in the concrete pour. When panels are erected, there is limited tolerance within the duct for the main bars to move and align for engagement of couplers to connect between starter bars and main bars. Any misalignment could result in additional friction and variability in observed extensions.

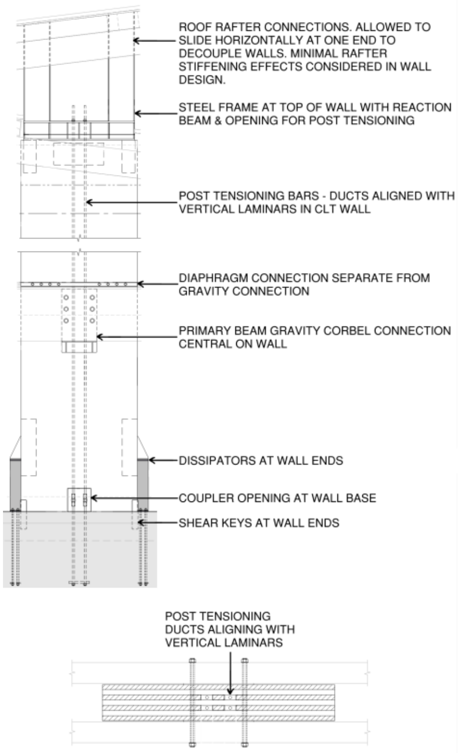


Figure 3: A typical Ashburton Civic Centre Pres-Lam CLT wall (Coulthard, 2021)

- Environmental – wet weather impact on timber components – elements are exposed until the structure is enclosed.
- Access constraints where contractor's programme and progress on architectural elements constrains working room for structural works. For example, at Ashburton Civic Centre access was constantly changing due to other site activities occurring concurrently.

3.6 Specific Learnings from Ashburton

The Ashburton Civic Centre project required collaborative work between Contech and Beca to ensure the construction of the walls fit in with the overall building construction and ensured a quality outcome.

3.6.1 Design of post tensioning

Timber's lower strength and stiffness means the walls are more sensitive to the axial force imposed on them which constrains the allowable post tensioning. Determination of the post tensioning stress force in the bars needs to balance the following:

1. The tension needs to be high enough that no rocking should occur in a large wind event (ULS wind).
2. The tension needs to be high enough that building drifts are limited to acceptable levels.
3. The tension must be limited so that the toe of the wall doesn't crush excessively when the wall rocks in ULS/MCE earthquake loading.
4. The tension must be limited to ensure timber wall creep is kept to an acceptable level.

Post tensioning losses are expected over the life of the building. In design, Beca made allowance for a 30% reduction in post tensioning force over the 50-year design life of the building (Granello, 2018). This allowance was made based on recommendations from research and the implication of applying the long-term deflection factor (k_2) to the wall and computing the resultant reduction in post tensioning force.

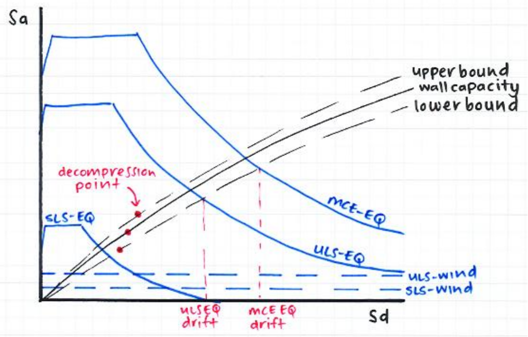


Figure 4: Example pushover plot of a wall

Beca used a bounded approach to ensure the walls would meet the four criteria above both the day it is tensioned (when post tensioning forces will be highest) and after the 50-year design life when timber creep and bar relaxation will have reduced the post tensioning force. An additional margin was added to account for some inaccuracy due to limitations in the post tensioning equipment and procedures. Figure 4 shows an example of a pushover for a specified post tensioning level.

3.6.2 Temporary construction case tensioning design

The main contractor adopted a temporary works bracing methodology that had less constraint than the permanent restraint provided in the final constructed state. As the floors and roof diaphragms are required to restrain the walls for out of plane buckling under their full post tensioned force the temporary works case needed to be considered.

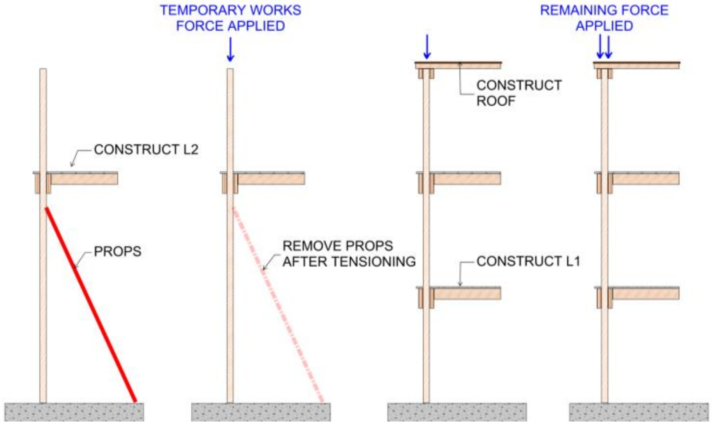


Figure 5: Construction methodology

A temporary works tensioning determined by Beca was applied so that the props could be removed from the walls and construction continue. This temporary works (initial tension) force was typically about half of the final force and each wall was checked for buckling with only the Level 2 diaphragm in place. The second tension was carried out after the Level 1 and Roof diaphragms were in place.

3.6.3 Tensioning procedures for the temporary construction case

The additional temporary works tensioning step introduced an extra level of uncertainty from a design perspective. This was introduced due to the unknown level of creep that would occur between the initial and second tensioning processes and what that would mean for the walls. The design allowed for an upper and lower bound tension expected to occur over the building's life due to bar relaxation and timber creep. This additional uncertainty leads to a wider spread of potential tensioning levels which made it harder to sit within the bounds summarised above. An additional risk was that if the walls experienced different conditions or time frames between the stressing procedures a variation in the final tension in the walls could lead to a concentration of loads on an overstressed wall.

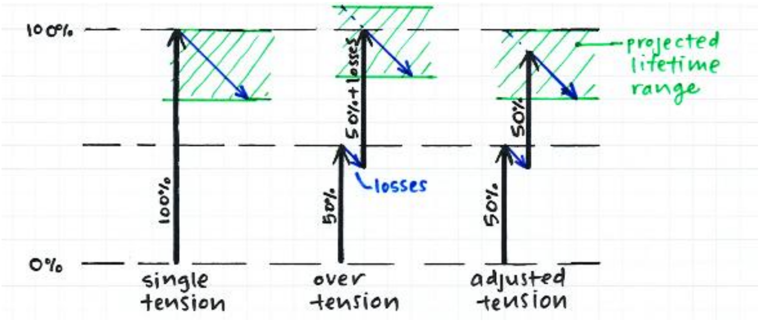


Figure 6: Visualisation of creep during the building life due to different temporary works procedures

To mitigate the risk of the walls being over tensioned due to 'cranking up' a tensioning procedure for the second tension was put together. These procedures were in addition to the standard requirements to tension bars in an order that limits unbalanced loads on the walls. A pick-up test was required prior to the second tension, any losses found in the pick-up test would then be deducted off the second tensioning level. This was to make the load input into the wall and the expected stiffness over its design life closer to if the wall had been tensioned in one go. As a failure due to over tensioning was deemed the less preferable failure, the specified post tensioning level was treated as a maximum, not a target minimum. Figure 6 shows a visualisation of how this methodology could affect the final tension on the walls.

3.6.4 Unexpected pick-up test results

The expected lifetime losses in design of the walls were approximately 30% as discussed above. Beca had not specifically calculated the expected losses between the initial and second tension as the loss calculations used in this case were not that precise and there were to be measurements from these walls at each tensioning stage.

The building was split into 3 stages in plan. Stage 1 wall pick-up tests recorded no losses in some lightly loaded walls, 2-4% losses in some heavier loaded walls and one heavily loaded wall with 9% losses. It was concluded that the losses were generally reasonable given the precision of the gear but flagged the outlying wall to be revisited when other similar walls were tensioned in later stages.

For the Stage 2 walls recorded losses in the pick-up tests for second tensioning were highly variable, with some walls having recorded losses of 0% and others of up to 26%. The losses were so variable and far in excess of expected ranges that stressing was halted while investigation into the cause was carried out and a course of action was determined.

The investigation included review of the data from the onsite post tensioning logs, a desktop numerical investigation into various mechanisms that contribute to post tensioning losses and additional pick-up tests on selected walls.

3.6.4.1 Elevated creep

The detailed desktop investigation into the expected creep was to determine what expected values might be, and how various components of creep might be affected by the conditions experienced on site – most noticeably variations in moisture content. This site experienced significantly higher than historic rainfall during construction which required a collaborative effort from the contractors and the design team to mitigate.

Beca based the investigation into creep on the model described in Granello (2018) which is a simplification of the Toratti (1992) model. The model showed that if the ambient conditions were consistent meaning the timber was a constant moisture content both in time and through its section, then the expected loses over 2 months would be in the range of 4-6%. However, if the walls were stressed with an elevated moisture content (28%) and then dried out over the period in consideration (to 18%) then the PT losses could be up to 27%. The most influential mechanism in this case is inelastic deformation in the timber, which is also called 'hygro-expansion' in other places. This means that if a wall was stressed at a time when its moisture content was higher than it will be in the longer term (which will be low, in an air-conditioned office) then the post tensioning losses could be significant.

3.6.4.2 Post tensioning stressing sequence.

The bars in each individual wall are tensioned in a sequence that limits the eccentric loading during tensioning (see sequence in Figure 7 below). From calculation Beca inferred that in a six-bar wall the first bar tensioned may lose up to 10% of the load originally applied by the time the sixth is tensioned due to elastic compression of the timber. The outcome of the pick-up test at the beginning of the second tension was therefore greatly affected by which bar is chosen for the pick-up test. This can be allowed for in the design of the stressing sequence for future projects.

3.6.4.3 An unknown combination of effects

A test was conducted on two of the walls which had yet to experience any tension in order to isolate any immediate recorded losses from long term losses. Test walls were stressed to their initial tensioning level. A pick-up test was performed 2 hours later, at which point losses of 25% were reported. This loss could be attributed to elastic compression and procedural factors. Based on this there was less concern that creep and bar relaxation happening at an accelerated and alarming rate.

The most likely scenario is that all the factors have contributed in some way to the unexpected recorded losses. There could be other contributing factors such as some local end grain inelastic distortion due to timber swelling and shrinking. As the contact point of the post-tensioning in a Pres-Lam wall system is typically on end grain, and the end grain is an area more prone to the rapid absorption of moisture, this may have also played a part.

3.6.5 Final tensioning design and procedure

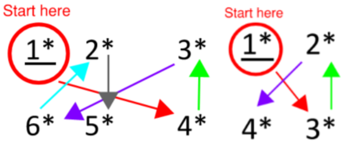
As the existing records could not be solely relied on and the design team needed to ensure the building was delivered with confidence that each wall had an appropriate level of post tensioning, a new methodology was created for the completion of the project. The methodology would take away reliance on any previous data, would remove creep due to future changing moisture levels from the equation and would require an elevated level of quality assurance.

A new final tensioning level for each wall was determined which took into account a calculated level of creep that may have already occurred and a more precise calculation of expected lifetime creep. As over tensioning was a primary concern the new tensioning level was lower than the original level specified in the original design. This was done by narrowing the calculated lifetime tensioning range with more precise calculation of the creep. Beca rechecked this range against the pushover curves to confirm the design requirements set out in section 3.6.1 would still be achieved.

All walls were revisited for a final tensioning procedure, even if they had previously been fully tensioned. The procedure is shown in Figure 7 includes some original procedures in addition to the additional requirements.

Full Tensioning Methodology for Final Tensioning

1. Confirm correct orientation of workers relative to the wall (i.e., same as on the previous stressing log)
2. Pick-up the same first bar as the previous stressing log
3. Record force and bar extension. Bar extension is to be monitored during stressing process – bar extension for each bar stressing is expected to be less than 1mm.
4. Tension the first bar to the "Updated Final Total PT force per bar (kN)"
5. Repeat steps 2-4 for remaining bars in the previously agreed order (shown below), recording this order on the log.



6. Return to the first bar and carry out a pick-up test and record force.
7. If the stress has reduced from the target force, tension to the "Updated Final Total PT force per bar (kN)" Tolerance – 5kN.
8. Repeat steps 6-7 for all bars in the same order as the first round.
9. If any bars required re-tensioning in step 7 repeat steps 6-8 again.
10. Wall is complete when all bars are consistently at their target force (within tolerance). Ensure all pick-up test, tensioning steps and the bar order are clearly recorded.

Note stop and request further input if any of the following:

- The post tensioning team have any concerns about the process.
- If steps 6-9 have been repeated twice and drops in tension force are still being recorded.
- If in further rounds of steps 6-9 are causing the bar extension to continue to increase.
- There is any observed distortion/pull-in to the wall end grain.

CLT Wall Moisture Content Requirements

- The walls shall be dry prior to stressing.
- The walls shall remain dry after stressing (measurement points are provided to the contractor).
- In this context, dry shall be interpreted as less than 18% moisture content in all areas (ideally less in future projects).

Figure 7: Final tensioning procedure

4 SUMMARY

In summary in this paper the authors have discussed recent Pres-Lam projects, focusing on observations at the Ashburton Civic Centre, it discusses how Pres-Lam was involved in these projects and the considerations involved around detailing post tensioning in a timber structure.

Ensuring that the post tensioning has sufficient corrosion protection is sometimes overlooked due to the consideration of the tendons being in a permanently enclosed environment, however the high tensile steel in which tendons comprise of, is prone to corrosion even when exposed for the briefest of periods during construction to the elements.

During tension operations, much more consideration to sequencing is required than was initially applied to this project, due to timber having a lower stiffness in comparison to concrete, which causes greater elastic strain during stressing. Furthermore, the intrinsic relationship between moisture content, moisture variation and creep of the timber can lead to increased losses in prestress. Effects of the adopted construction sequencing and potential exposure of the timber causing elevated moisture levels within the timber need to be considered. Sequencing of the tensioning was completed in an iterative process to check and recheck the levels of tensioning/compression force introduced into the structure to satisfy the design requirements under ULS levels while ensuring the structure is not over stressed. For future projects, this iterative procedure could be reduced or eliminated by allowing for elastic panel movements during stressing.

Finally, ensuring balanced load is being transferred into the structural element, checks and rechecks completed and being aware that all of the above could well present losses which differ from the theoretical are topics which any designer and builder should be aware of when undertaking these exciting, innovative timber engineered structures.

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