# From research to practice: A case study on mixed angle screw hold-down connections for a 6-Storey CLT shear wall building

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## ABSTRACT

Mass timber structures are a growing topic in the New Zealand design environment. To design mass timber buildings to the moderate or high seismic demands of New Zealand, strong stiff, and ductile seismic systems are required. One such system recently developed and tested at the University of Canterbury is the mixed angle screw hold-down connection for Cross Laminated Timber (CLT) shear walls. Through the innovative use of large European self-tapping screws installed at mixed angles with respect to the grain, the strong and stiff performance of screws installed at 45° can be combined with the ductility and displacement capacity of screws installed at 90° to the grain, providing an overall strong, stiff, and ductile connection.

Taking research and implementing it into practice isn't always easy. Especially in the context of timber buildings, where design and guidance is still in development.

This paper explores the application and practicality of mixed angle screw hold-down connections in a 6 storey (Concrete podium, 5 storey CLT wall) CLT wall structure designed for a zone of high seismic hazard. Key challenges from the design of this building and their associated learnings are presented. Challenges that had to be overcome included the strength prediction, stiffness prediction, and NZS AS 1720.1:2022 requirements for displacement amplification. These challenges are discussed in detail, and some future outlooks for design are given.

# 1 INTROUDCTION

The number of large mass timber buildings being constructed in New Zealand continues to increase. As the number of projects, increases so does the industry confidence, and thus the timber buildings are getting, larger, taller, and more complex.

Many of these projects benefit from the extensive research programs that have been untaken in the timber research field at the University of Canterbury and the University of Auckland. Through these two universities the PRES-Lam system (Smith et al. 2014) and the Tectonus system (Hashemi et al. 2017) have been developed, and seen use worldwide (“Peavy Hall – Pres-Lam,” n.d.; “Seismic Hold Downs for Rocking CLT Shear Walls | Case Study,” n.d.). Most recently research at the University of Canterbury has focused on high-capacity timber structural systems, with component testing of high-capacity dowels (Ottenhaus, Li, and Smith 2018) and mixed angle screws hold-down connections (Wright et al. 2023), as well as system level testing of coupled walls with (Brown et al. 2021) and without (Moerman et al. 2023) post-tensioning.

Despite this large research effort, it would be unrealistic to say that we have solved all the problems in mass timber construction. There are still many challenges and catches that require careful consideration when taking these innovative and well researched systems and implementing them in an actual design.

This paper aims to provides a summary of the challenges faced and discussion of the design of the 6-storey Haven Road Apartments building, which utilises mixed angle screw hold-down connections developed at the University of Canterbury in the Cross Laminated Timber (CLT) shear wall lateral load resisting system.

# 2 HAVEN ROAD SUMMARY

Haven Road Apartments is a 6-storey (5 CLT platform construction, one reinforced-concrete podium) structure located in Nelson New Zealand (Figure 4). The Project team consisted of RM Designs (Christchurch) and Aaron Walton (Nelson) as architects, ENGCO as design engineer, PTL as peer reviewer and SCOTT Construction as the design and built contractor.

Many options were considered for the lateral load resisting system at the concept stage. Given the large number of intertenancy walls typical of a multi residential structure (Figure 1), a CLT shear wall system was selected as the most efficient system for both directions. Keeping CLT shear walls as the lateral load resisting system for both directions also ensured the relative stiffness of this L-shape building was similar in both directions making it a more comprehensible system for the modal response analysis. Due to the podium structure, the analysis was carried out as a two-stage approach in accordance with ASCE 7–16 Section 12.2.3.2. To satisfy these requirements it was shown the lower portion (concrete podium) is more than 10 times stiffer than the upper portion (CLT structure), satisfying 12.2.3.2 (a), and when incorporating lateral flexibility at the base of the model (to represent stiffness of the podium), the period of the structure increases by a factor of 1.012, less than the maximum limit of 1.1 defined in 13.2.3.2. Using this approach compliance was achieved as an alternative solution.

Choosing CLT for floors and all other gravity walls provided the optimal system for passive fire protection by charring and for speed in construction for a site with difficult access, storage, and propping constraints. Certain encapsulation with Fyreline was however still required to reach the 30min FRR of the sprinkler protected building for individual heavy loaded walls.

The choice to use mixed angle screws as the hold-down system was carefully considered. The relatively high seismic demand of Nelson required a high-capacity hold-down solution beyond what can reasonably be provided by off the shelf cold-formed steel brackets. To reduce the seismic demand, a system with ductility of $\mu = 2$ was preferred. Also to consider was the concrete transfer structure sitting below the CLT wall systems which needed to remain practically sized due to consent limitations in the overall height of the building. To keep these members a reasonable size, the overstrength of the connections needed to be limited to an acceptable level. To allow for fewer stronger walls, a stiffer hold-down was preferred to avoid being displacement governed. To achieve these considerations a strong, stiff, and ductile hold-down system was required.

Given the large previous experience of the design team with mass timber structures and various forms of hold down connections, a preference for the use of self-taping screws was identified. The use of self-tapping screws allows for the easy and straight forward construction of the structure and avoids some of the issues encountered with previous projects that used dowelled hold-downs. Through collaboration with the University of Canterbury, a mixed angle screw hold-down connection was selected. The mixed angle screw system provided the high strength, stiffness, and simplicity required to get the project over the line, with the potential outlook of repairability in the event of a large earthquake.

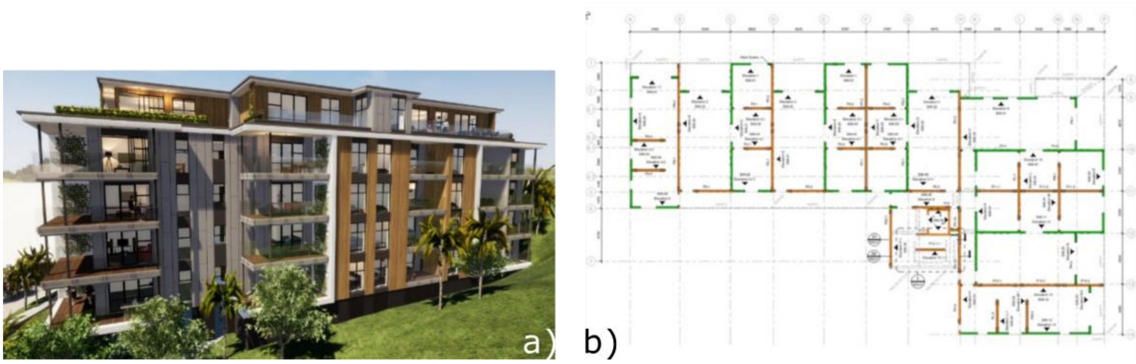


*Figure 1 - a) Architectural concept of Haven Road Apartments, b) Floor Plan with CLT shear walls in Orange and CLT loadbearing walls in Green.*

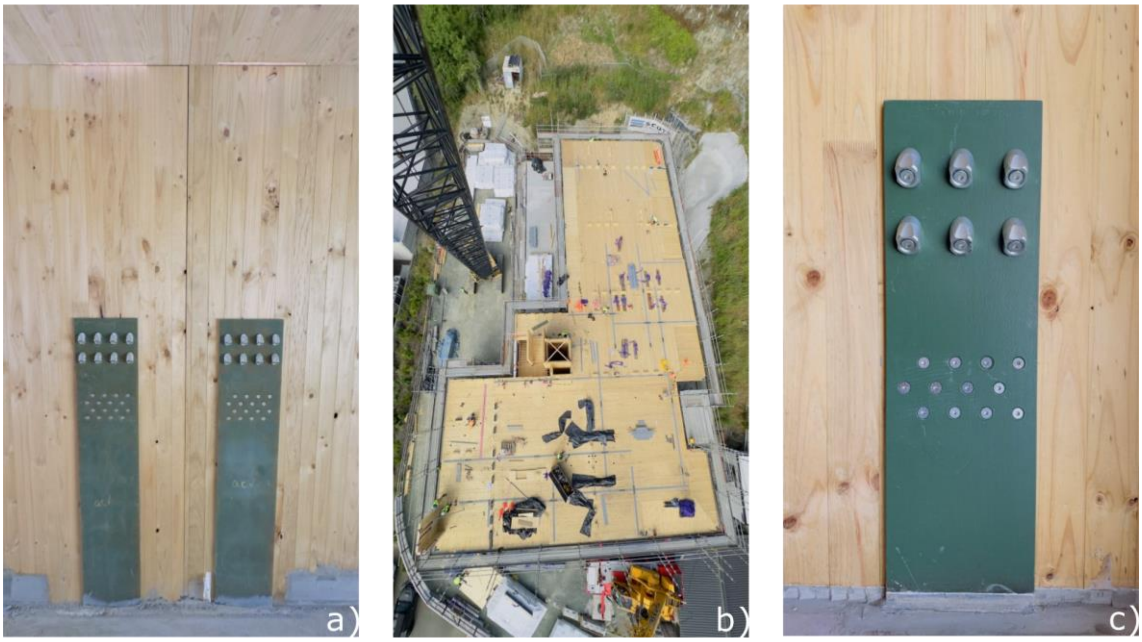


*Figure 2 – a)/c) Typical Hold-Down Connections installed on Haven Road Apartments, b) Site under construction showing floor plan*

## 3 MIXED ANGLE SCREWS

European self-tapping screws with large threads and small shank diameters are an increasingly popular timber fastener due to their ease of installation and high capacity. Research by (Blaß and Bejtka 2001) has found that European self-tapping screws performed most efficiently at an inclined angle to the grain where they can resist a portion of the load axially rather than the dowel type action seen in nails or coach screws. However, as the angle of the fastener to the grain is reduced from 90° the ductility and displacement capacity of the screws drops. To achieve the benefits of screws on inclined angles, and also allow for a level of ductility (Tomasi et al. 2006) proposed a timber-to-timber joint which incorporates both screws at an inclined angle and screws at 90° as shown in Figure 1. By installing screws both at an inclined (commonly 45°) angle to the grain and a 90° angle to the grain, the performance of the two sets of screws can be superimposed. The inclined screws resist some load axially and provide high strength, initial stiffness, but have little to no ductility or displacement capacity. The 90° screws act as dowel type fasteners in shear and have high strength with low initial stiffness, but provide high displacement capacity. By combining the two contributions an overall strong, stiff, and ductile behaviour is achieved. Further research by (Hossain et al. 2018) has extended this mixed angle screw concept to in-plane joints in coupled CLT wall systems, and this was further extended by (Brown et al. 2021) for orthogonal panel joints.

Most recently, research at the University of Canterbury has extended this concept to the hold-down connection as shown in Figure 3/Figure 4. Research by Wright et al. has identified the appropriate ratios of inclined to 90° (Wright et al. 2023), shown the connection can be repaired post earthquake (Wright 2024; Wright et al. 2022), identified the overstrength (Wright et al. 2023; Wright 2024), and discussed the impact of pinched hysteretic behaviour on the structure under Non-Linear Time History Analysis (T. Wright 2024). The performance of mixed angle screw hold-downs in CLT wall systems was confirmed with comprehensive large scale wall testing (Ben Moerman et al. 2023) as shown in Figure 5.

Overall, the performance of these mixed angle screw connections has been proven through rigorous experimental testing. The system is overall strong, stiff, and ductile with significant capacity benefits over small light gauge nailed hold-downs and significant stiffness benefits over large scale dowelled connections.

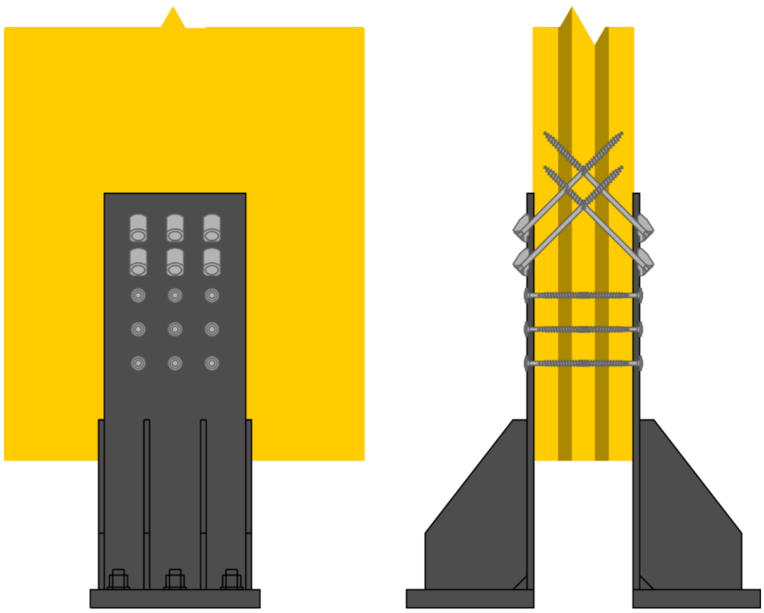

*Figure 3 - Example connection layout used in experimental testing. Approximately 600 kN ultimate capacity*

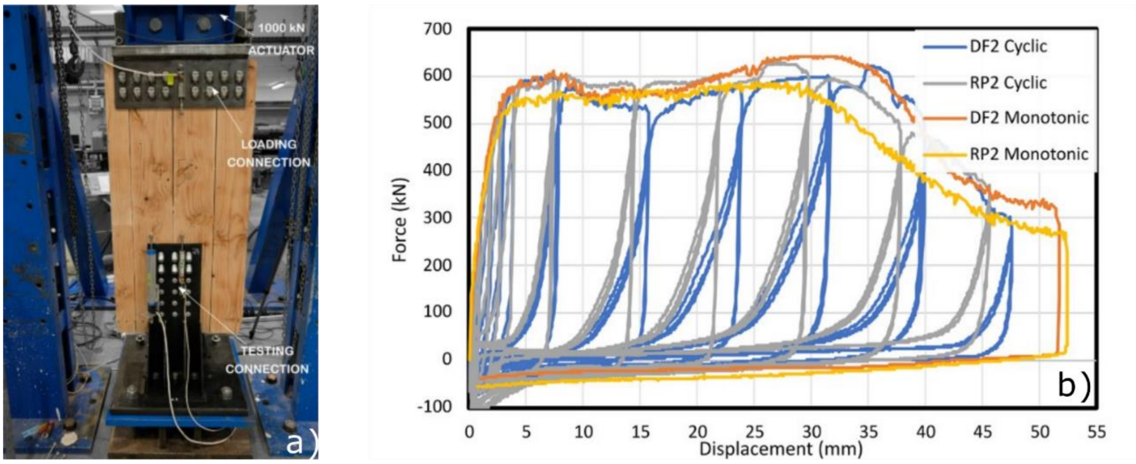


*Figure 4 – Component testing of mixed angle screw hold-down connections a) Testing setup, b) Force displacement results for typical mixed angle screw results from Haven Road Apartments (Wright et al. 2023)*

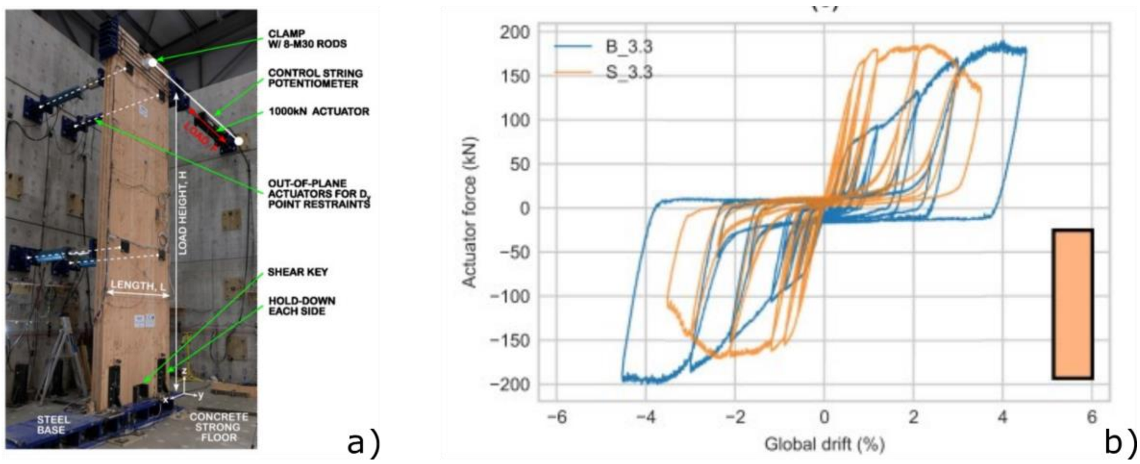


*Figure 5 – System testing of mixed angle screw hold-downs in large scale CLT wall systems a) Testing Setup, b) Force displacement results for a bolted (Blue) and mixed angle screw (Orange) hold-down connection. (Moerman et al. 2023)*

## 3.1 Key Challenges Identified in Design

Research does a great job of identifying and developing new technologies, however there can still be many gaps to fill and problems to solve when implementing these new technologies in real world building projects.

In the design of Haven Road Apartments three key challenges were identified in the design stage of the CLT shear wall systems.

1. How to accurately predict the strength and limit the overstrength in connection design.
2. How to accurately predict the stiffness of timber connections and how to apply drift amplification factors.

3. How to make the structure easily constructable by allowing for sufficient tolerances and speed in construction, to reduce the overall open time of the timber structure and exposure to weather during construction.

These challenges are not unique to Haven Road Apartments or to mixed angle screw CLT shear walls systems. With the strong research background from the University of Canterbury and collaboration with the design engineers from ENGCO, these questions could be answered, a satisfactory solution reached as discussed below, and with agreement from the peer reviewer to demonstrate compliance with B1 of the New Zealand Building Code.

# 4 DISCUSSION

## 4.1 Strength Prediction and Overstrength

A key issue faced in the design of Haven Road Apartments was the accurate prediction of strength and overstrength. As mentioned previously, the first floor of Haven Road Apartments is a concrete podium on which the CLT shear walls are landed. Due to height constraints the section sizes in the concrete transfer structure had to remain efficient whilst also retaining the strength to ensure capacity design principles are adhered to and a ductile failure mode can be achieved in the yielding connections of the timber walls above. To allow for this an accurate prediction of not just the strength but also overstrength was required.

The accurate prediction of strength in timber connections is a key issue to be overcome in any ductile timber design. It is well recognised that the timber material itself is a natural and inherently variable material. To address this design equations are typically based off a characteristic 5$^{th}$ percentile value which is defined as the 75$^{th}$ percentile confidence interval for 5$^{th}$ percentile value. That is if 100 samples were taken, the 5$^{th}$ percentile of the sample would exceed the characteristic 5$^{th}$ percentile in 75 of them.

Typically, this leads to quite conservative prediction of strength, especially for connections where there are many fasteners and multiple layers of timber penetrated. This is noted by (Wright 2024) where it was determined that for self-tapping screws in withdrawal the characteristic 5$^{th}$ percentile experimental strength observed in testing exceeded the calculated strength by a factor of 1.5.

These low predictions of strength provide safe and conservative design for timber connections and result in a high margin between design and actual strengths. However, when designing a building for seismic loading, a predictable ductile yielding response is paramount for a robust and predictable design.

To achieve a ductile response the hold-down connection needs to yield before other brittle mechanisms occur to maintain a clearly defined strength hierarchy.

Due to the high conservatism in design values, the overstrength values proposed by (Ottenhaus et al. 2018; Ottenhaus et al. 2022) for dowels and (Wright 2024; Wright et al. 2023) are quite large. For the mixed angle screw connection, the scatter of results observed is quite low for timber, especially for large scale tests with a high number of fasteners, however, an overstrength factor of 2 is still recommended due to the inherent conservatism of the design predictions for fasteners in withdrawal.

One way to reduce or limit the overstrength demand in a timber structure is provided by the NZS1720.1:2022 (Standards New Zealand 2022), which allows for the capping of overstrength at equivalent elastic demands. For a ductility of 2 structure this caps the overstrength between 1.55 and 2 depending on the structure's period and the resulting $k_\mu$. However it is noted that due to the conservative design prediction and subsequent large difference between analytically derived and experimental results seen for many timber connections, these connections are unlikely to yield under the loading they have been designed for, and an elastic building has effectively been designed with the higher associated force demands. Using a capped overstrength value may limit the ability of the structure to perform in a robust and ductile manner under larger than predicted loading as the strength hierarchy of capacity design is not necessarily maintained.

To allow for the more efficient design of the hold-down connection at Haven Road Apartments, test data from the University of Canterbury was used to the inform design. NZS1170.0:2002 (Standards New Zealand 2002) allows the use of test data with an appropriate factor to account for number of replicates. This approach allows a more efficient design of the structure, but it is not realistic to conduct testing for all timber structures, and a better approach is needed in the future.

### 4.1.1 Future Outlook

For timber connections we face a conundrum where the variability of the timber material means that design predictions should rightly be conservative to account for scatter in the testing data, but when we design large ductile connections with many fasteners such as those used in Haven Road Apartments the conservatism is huge and leads to very large overstrength demands. One solution that has been implemented in the past and could be considered to this is a probabilistic or reliability design approach. In a probabilistic approach the large number of screws and timber layers penetrated can be taken into account, and factors applied to increase the strength on the basis that the probability of all fasteners only achieving the 5$^{th}$ percentile strength is low. This could be through consideration of a parallel support factor similar to k4 in NZS3603:1993 (Standards New Zealand 1993), or through the consideration of a Eurocode 5 $k_{sys}$ factor similar to that used by (Ringhofer et al. 2015) where by some allowance is made for the number of layers penetrated. This approach is by no means new and is currently implemented for nailed connections through the use the $k_{17}$ factor which increases connection strength by 30% when more than 30 nails are used, however industry discussion and experimental validation are required before it can be extended to other connection types.

## 4.2 Stiffness Prediction and Drift Amplification Factor

A second issue encountered in the design of Haven Road Apartments is the difficulty in prediction of connection stiffness, and drift under seismic loading.

For a dowel type connections Eurocode 5 provides an approximate formula. However, previous research has found that this equation is inadequate and significantly overpredicted the experimental stiffness observed (Brown and Li 2021; Sandhaas and van de Kuilen 2017; Dong et al. 2020). For the prediction of screw stiffness in withdrawal the European technical approvals (ETA) provide an approximate formula. Due to the limited data on screw stiffness in New Zealand timbers, no conclusions can be drawn on its accuracy. Similar to the findings cited about for dowels, experimental research by (Wright et al. 2023) found that for mixed angle screw connections the stiffness was also overpredicted.

In lieu of a simple and efficient method to predict a design stiffness, the Haven Road Apartments project uses a simple upper and lower bound stiffness approach. Examining the experimental test results from the University of Canterbury (Wright et al. 2023), it is clear that the yield displacement is reliably reached between 2 and 3 mm of hold-down uplift. Using these upper and lower bound displacement values in combination with the design force a lower and upper bound stiffness can be derived. For calculation of the earthquake demand imposed on the structure, the highest stiffness (assumed 2 mm to initial yield point) is used to find the most adverse design loading. For calculation of the drift of the structure, the lower bound stiffness (3 mm to initial yield point) is used to find the most adverse drift. By considering both an upper and lower bound, conservative design is achieved for all cases.

For the determination of displacements NZS1720.1 Clause ZZ9.2.12.3 requires the consideration of displacement amplification factors to account for the pinched hysteretic behaviour common in timber dowel type connections. An empirical approach is provided in the NZ Wood Design Guides Seismic Design chapter (Smith 2020). This empirical approach derives an amplification factor $k_{dt}$ by relating the predicted inelastic displacement using an equivalent viscous damping approach commonly used in the Direct Displacement Based Design (DDBD) methodology (Priestley et al. 2007) with the $k_\mu$ factor commonly applied in NZS1170.5:2004 (Standards New Zealand 2004).

$$k_{dt} = \frac{\Delta_{EVD}}{\Delta_{k_\mu}} = \frac{\sqrt{\frac{7}{2+\xi_{eq}}}}{\frac{1}{k_\mu}} \rightarrow \sqrt{\mu}$$

Using NLTHA, studies by (Moerman et al. 2022) and (Wright 2024) have shown $k_{dt}$ to overpredict the maximum displacement of CLT shear wall systems with dowel type hold-downs.

In the design of Haven Road Apartments, compliance could be reached while using this $k_{dt}$ factor as the ductility demand was moderate ($\mu = 2$ instead of $\mu = 3$) and the mixed angle screw hold-downs used are very stiff keeping the yield drift of the structure low. If a less stiff hold-down system was to be used, it is likely the 2.5% ULS drift limit would not be met, and the compliance pathway is unclear. In this case compliance was achieved, but for a definitive conclusion further research is required to assess the applicability of dynamic amplification factors for pinched hysteretic curves in CLT wall structures.

#### 4.2.1 Future Outlook

For future projects, more accurate prediction of stiffness may be available though the use of beam on foundation modelling. Research by (Lemaitre et al. 2018; Lemaitre et al. 2019; Lemaitre et al. 2021; Schweigler et al. 2021) has shown promise for prediction of both strength and stiffness through the use of beam on foundation models. For mixed angle screws a simplified beam on foundation model is presented using commonly available finite element software (T. Wright 2024). This methodology shows promise, however further use is required in both real world projects and research to prove its viability as an efficient design method.

### 4.3 Simplicity and Constructability

A third consideration in the design of Haven Road Apartments is the simplicity and constructability. On the Haven Road Apartments project, a key goal was to keep the on-site work simple and straightforward, so there were no surprises for the contractor or client.

Timber buildings face many different challenges which are not typical for concrete and steel construction. A key challenge is moisture and dimensional stability of the timber members. To account for this it is best to allow tolerance, and keep the timber dry during construction.

For the hold-down connections, mixed angle screws provided a great alternative to either conventional or self-drilling Selbst Bohrender Duebel (SBD) dowels, through their easy of installation on site. To install a mixed angle screw connection, a small jig is simply placed into the prepared hold-down steel side plate, the hole predrilled at the appropriate angle, the screw inserted, and then torqued to the required specification. Previous projects the authors have experience with, have used large scale dowels or SBD. For conventional dowelled connections, it is typically very hard to install these well on site and to hit a tight tolerance to prevent any initial slip of the connection. Due to the moisture issues in timber, it is best to drill the timber on site rather than at the factory, which requires precision and care from the contractor. SBD dowels solve the construction tolerance problem by drilling through the steel plates as they are inserted. However, SBD require a consistently high amount of normal force to drill through the steel plate, and on site this puts quite a high demand on the installation team.

In contrast, the installation of mixed angle screw connections at Haven Road by the contractor has gone exceedingly well, with good feedback from the contractor as to the ease of installation, despite no previous large scale timber experience.

Another key benefit of the mixed angle screw connections is the ability to repair post-earthquake event. Research at the University of Canterbury has developed and tested a repair methodology (Wright et al. 2022) for these screwed connections using a slight shift in hold-down position and a minor epoxy repair to the timber. This repair methodology has been designed to be fast simple and cheap so as to provide minimal cost and disruption.

There are many options for low damage design in timber construction, however these are not the right for the needs of every project and client. By concentrating the primary damage to the structure at the first floor hold-down connections, and providing a comprehensive, simple, and proven repair methodology, some of the key outcomes of low damage design (e.g. not having to demolish or extensively retrofit the building post-earthquake) can be achieved without the added consideration, complexity, and (possibly) cost required for post tensioning or similar.

## 5 CONCLUSIONS

In conclusion, the Haven Road Apartments project showcases how through good collaboration between research and practice some of the key challenges can be faced by design engineers can be overcome.

Key conclusions include:

- Underprediction of connection strength is a problem which results in the likely design of elastic structures. Care needs to be undertaken when capping the overstrength demand as a robust ductile failure mechanism may not be achieved.
- Connection stiffness cannot be easily predicted and therefore simplified methods are preferred in lieu of the arrival of more complex methods that are currently in development.
- By keeping connection detailing simple and with tolerance through the use of self-tapping screws, common timber construction issues can be avoided on site.

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