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TRADITIONNAL SEISMIC FUSES IN TIMBER STRUCTURES – PROS AND CONS

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ABSTRACT: In earthquake-prone zones, timber structures are subjected to earthquake loadings that may govern their design. In order to reduce those loads, it is customary to induce ductility and this can only be done through the connections as timber tends to fail mostly in a brittle manner (in tension, parallel and perpendicular, in shear and in bending). Traditionnal seismic fuses or Potential Ductile Elements (PDEs) are designed with small diameter fasteners with material characteristics that ensure repeated strength capacity under cyclic loads. In this paper, the design principles used to detail PDEs are listed and the pros and cons of the different fasteners available to timber designers are provided and explained.

KEYWORDS: Earthquake, connections, ductility, crushing, stiffness

1 – INTRODUCTION

Mass timber buildings are here to stay and building jurisdictions around the world are relaxing their rules restricting their height in order to allow more multi-story timber buildings to hopefully change the trend in global warming CO_2 emissions resulting from the construction industry and be seen as green. But as one is building higher and higher, the challenge of delivering an all-timber solution is getting more and more difficult. Loads (wind and earthquakes) are increasing significantly, and the low stiffness of timber is compounding the issue. Serviceability is again making things difficult for timber solutions. There are few examples of all-timber multi-story buildings in the 1-4 story range but beyond that, steel and concrete is being used in the lateral load resisting system to achieve the desired structural solution. This is particularly evident for buildings where the seismic loadings are governing the design of members. This is reinforced by the fact that most of these multi-story buildings are designed by engineers that have multi-story building design experience using concrete or steel as the main material (Figure 1). It is only normal that they select design solutions that are known to work to resist these wind and seismic loads.

For the most part, engineers are not that familiar with the design of timber connections. This is a major issue as, for seismic loadings, to provide ductility and reduce the demand, ductility is provided in the connections. It is thus imperative that knowledge of the behaviour of timber connections, of their ductile and brittle behaviour, be known and controlled in order to come up with, if at all possible, all-timber structural solutions and maximise the reduction in the usage of concrete and steel.

Seismic energy dissipation in timber structures occurs primarily through ductile connections, friction, and energy absorption by fasteners. The effectiveness of fasteners in mitigating seismic damage depends on their mechanical

Figure 1: Timber building with concrete cores.

properties, installation method, and their ability to allow

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controlled deformation while maintaining structural integrity.

2 - TIMBER FASTENERS AND THEIR SEISMIC RESISTANCE CAPABILITIES

In order to provide a comprehensive account of what fasteners have in terms of capabilities to resist, or not, seismic loads, a list is provided and pros and cons are given (Table 1). No fastener is given preference in terms of abilities to transfer seismic loads in a ductile manner and be able to be detailed to provided the additional required characteristics (fire protection, small deformation, etc…)

Table 1: Seismic capabilities for different generic timber fasteners.

Fasteners	Characteristics	Pros	Cons
Dowels	Steel rods inserted in tight-fitted holes used to transfer forces between timber and embedded steel plates. Holes are plugged to provide fire protection.	• Transfer lateral loads in bearing • Yield capacity well defined using the European Yield Model • Yield deformation somewhat well-known. • Dowel material can be well controlled ($F_{y\ minimum}$ and $F_{y\ maximum}$). • Can be fire-protected with the right timber cover and plugged holes.	• Need a larger volume of timber surrounding the dowel group to avoid timber brittle failure. • Quantity of ductility is not well defined (Δ_{ult} = ?) • Requires configuration testing for the ductility to be fully defined. • Bolts must be used in addition to dowels to prevent timber member splitting.
Bolts	Available in different sizes and materials, including steel and galvanized coatings for corrosion resistance. Typically used with washers and nuts to ensure a firm grip on timber members. Provide high load-bearing capacity and are often used in heavy timber construction. Can be pre-stressed to improve resistance to cyclic seismic loads. Require precise drilling and installation to prevent timber weakening.	• Provide strong and stable connections, effectively transferring loads between timber members. • When properly designed, bolted connections exhibit some ductility, allowing controlled deformation before failure. • Bolts can be easily inspected and replaced if they show signs of wear or damage after seismic activity. • Suitable for large-scale timber structures where high-strength connections are necessary. • Bolted joints can sustain multiple seismic events when combined with appropriate washers and pre-stressed configurations. • Small bolts are easier to install and allow for more localized energy dissipation due to their flexibility, whereas large bolts provide higher strength but may lead to stress	• If the bolt is undersized or not properly designed, brittle failure can occur under extreme seismic forces. • Under cyclic seismic loads, bolts may loosen, reducing the connection's effectiveness. • Large bolt holes can reduce the cross-sectional strength of timber members, making them more vulnerable. • Properly installing bolted connections requires precise drilling and alignment, increasing construction time and labour costs. • Larger bolts may lead to stress concentration points, which can increase the likelihood of timber splitting or localized failure in high seismic events. • Need multiple smaller diameter bolts to ensure the proper ductile mode of failure.

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		concentration in timber members. Large bolts are better suited for heavy timber applications, while small bolts are preferable in light-frame constructions.	
Screws	Typically made of hardened steel with different head types (e.g., flat, round, hex) for varied applications. Offer strong withdrawal resistance due to their threaded design. Used in both structural and non-structural applications, particularly in engineered timber products. Available in self-tapping and pre-drilled varieties to suit different construction needs. Provide better holding power compared to nails due to their grip on timber fibers.	• Screws provide excellent grip and resistance against pull-out forces, improving joint integrity during seismic movements. • Self-tapping screws, particularly in engineered timber, allow controlled yielding under seismic loads. • Screws generally offer better long-term durability compared to nails in resisting seismic-induced vibrations. • Screws are an effective solution for reinforcing existing timber structures against seismic risks. • Compared to nails, screws cause less splitting, preserving the integrity of timber members.	• Screws are susceptible to shear failure if subjected to excessive lateral loads. • Requires pre-drilling in dense timber or engineered wood, increasing installation time. • Not ideal for large-scale timber construction where heavy loads demand more robust fasteners. • Prolonged exposure to moisture and seismic-induced micro-movements may lead to corrosion, weakening the connection over time.
Nails	Made of various materials, including stainless steel and galvanized coatings for corrosion resistance. Available in different lengths and thicknesses, commonly used in light-frame timber construction. Installed using hammering or pneumatic nail guns for quick fastening. Provide less withdrawal resistance compared to screws but exhibit better ductility. Often used in shear-dominated joints to resist lateral seismic loads.	• Among the fastest fasteners to install, making them ideal for rapid construction projects. • Exhibit significant deformation before failure, allowing them to absorb and dissipate seismic energy effectively. • Compared to bolts and screws, nails are inexpensive and widely available. • Provides good lateral load resistance when used in shear-dominated joints. • Particularly effective in light-frame timber construction, which benefits from high redundancy and distributed fasteners.	• Have relatively weak withdrawal resistance, leading to potential failure under cyclic seismic loading. • Over time, timber can become brittle, making nailed connections more prone to sudden failure. • Exposure to moisture and chemical reactions can cause nails to corrode, reducing their effectiveness. • Can cause splitting, especially when installed near the edges or in thin timber members. • In heavy timber structures, nails may not provide sufficient strength to withstand seismic forces.
Timber Rivets	Typically made of steel, used in pre-drilled holes in steel plates and set using a specialized riveting tool. Provide strong, permanent	• Riveted joints provide excellent resistance to lateral seismic loads.	• Requires specific tools and expertise, increasing labour costs.

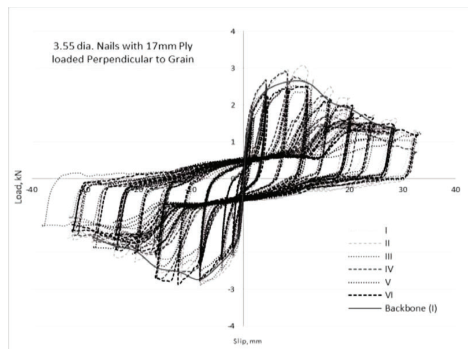
	connections with high resistance to shear forces. Offer excellent clamping force, which enhances joint stability. Often used in engineered timber applications where precision, strength and stiffness are required.	• Rivets do not loosen over time, ensuring long-term performance. • Helps in evenly distributing forces across the connection, reducing stress concentrations. • Riveting does not require extensive drilling, preserving the timber's strength.	• Once installed, rivets are challenging to remove or retrofit. • Unlike bolts, riveted connections cannot be tightened or adjusted after installation. • Under large displacement, rivets will "push" steel plate away from timber member. This can be corrected by securing the steel plates using bolts.

3 - DYNAMIC BEHAVIOUR OF CONNECTIONS USING GENERIC TIMBER FASTENERS

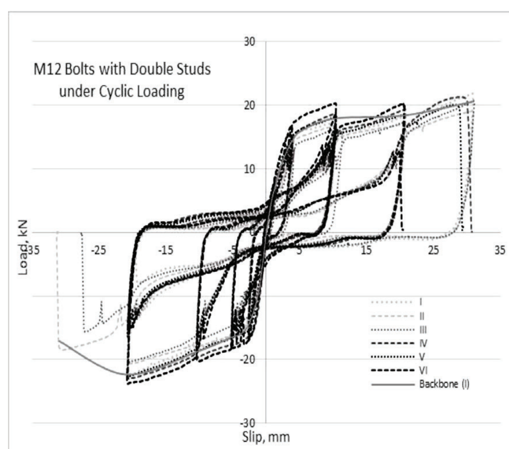
Over the years, the dynamic behaviour of connections using generic fasteners has been assessed. Connections using dowels, bolts, nails and rivets have all been investigated with some measure of success. Connections with screws, used in lieu of nails as they have better holding resistance, do not show reliable outcome because of their inability to bend under numerous loading cycles.

Dowels, bolts, nails and rivets all have shown reliable cyclic resistance. All these fasteners behave in the same manner in transferring a lateral load: in a simplified description, the load is transferred from one member to the next (either timber to steel or timber to timber) through shear of the fastener. The fastener resists/transmits the load to the members through bearing. The bearing resistance is limited by the buckling capacity of the wood fibre. This buckling capacity of the wood fibres allows the timber connection to exhibit a quasi elasto-plastic behaviour and provide the required ductility. The buckling of the wood fibres (also described as the crushing/bearing resistance of the wood), is normally also accompanied by the bending of the fastener. This bending of the fastener is desirable as it is an important contributor to the reliable ductility behaviour (plastic bending of a steel fastener is more reliable than the crushing resistance of wood fibres). This plastic bending of the steel fastener is also the contributor to the residual stiffness of the connection after numerous cycles of irreversible wood fibre crushing. This bending resistance of the fastener is apparent in the pinching portion of the load-displacement curve under cyclic loading.

Typical load-displacement curves for nail, bolt and timber rivet connections are shown below in Fig. 2.



(a) (from Kho et al. 2018).



(b) (from Kho et al. 2018).

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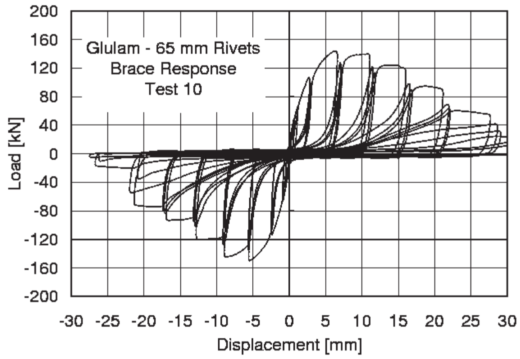

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(c) (from Popovski and Karacabeyli 2008)

Figure 2: Typical load-displacement curves for nailed (a), bolted (b) and timber rivet connections (c) under cyclic loading.

In the load-deformation curves for nailed and bolted connections shown in Figure 2, the pinching behaviour is very apparent. It is not so much evident in the timber rivet connection shown. However, this is not necessarily a feature of timber rivets but mostly the result of the design ductile failure mode for the connection configuration as the length of rivets used was 65mm. The pinching behaviour would be observed in a joint with rivets of 90 mm in length.

It is possible, using the European Yield Model included in most timber design standards, to design a timber connection to fail in a ductile manner and ensure that the mode of ductile failure will be providing this residual stiffness/resistance at subsequent cycles. This residual stiffness/resistance is normally provided if the fastener is to fail in a ductile manner by exhibiting two plastic hinges per shear plane, as shown in Fig. 3 for connections in single and double shear.

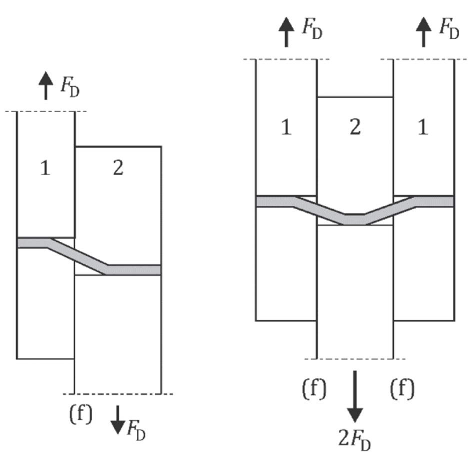

Figure 3: Ductile failure mode with two plastic hinges per shear plane in a fastener.

One important aspect of timber connections used as seismic fuses is that brittle failures of the wood surrounding the fasteners, be avoided. All fasteners are prone to these wood failures. Fortunately, more is known on the resistance of these brittle failure modes and they can be avoided with proper detailing of the connections.

4 – CONCLUSIONS

Each type of traditional generic timber fastener has distinct advantages and disadvantages in dissipating seismic energy in timber buildings. The selection should be based on structural demands, seismic intensity, and installation feasibility.

It is possible, using the European Yield Model design approach, to ensure that timber connections that are to exhibit a ductile failure mode, be able to exhibit a residual stiffness and resistance (the pinching behaviour). This is normally provided with fasteners that deform and exhibit two plastic hinges per shear plane.

5 – REFERENCES

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