# A review of Eccentric Braced Frame (EBF) systems and their applicability for mass timber structures

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## ABSTRACT

As the world grapples with the challenges of climate change and global warming, reducing construction's carbon footprint has become a top priority. Timber, as a renewable construction material, offers a sustainable alternative to traditional materials like steel and concrete. Situated in a high-seismic zone and rich in timber resources, New Zealand faces a pressing need to develop innovative solutions that enhance the seismic resilience of timber structures, ensuring safety while reducing reliance on carbon-intensive materials. This paper explores the available solutions for improving the seismic performance of mass timber braced frames, ranging from conventional connectors to more advanced energy-dissipative systems and hybrid configurations. The effectiveness of these systems is assessed in terms of structural stability, repairability, and constructability. Furthermore, special attention is paid to Eccentric Braced Frames (EBFs), which have a successful history of implementation for steel structures. Low-damage EBF options such as modular yielding links and hybrid self-centring systems will be explored, which are designed to minimize residual drifts, reduce post-earthquake repairs, and ensure functional recovery. Key aspects of the EBF systems, such as yielding link behaviour, rotational capacity, loading history, and overstrength, will be explored for application in mass timber frames. This paper explores methods to bridge the gap between EBF systems and mass timber, offering insights into sustainable solutions for mass timber structures.

## 1 INTRODUCTION

As urbanization expands towards earthquake-prone areas the construction industry is at crossroads facing the two main challenges of environmental issues and sustainable building construction. Timber is a renewable material with lower carbon emission compared to the conventional materials like steel and concrete and has great potential in modern construction (Assadi et al. 2023). In New Zealand where timber is abundant and seismic risk is high, developing innovative construction techniques is critical. This study examines ways to enhance the seismic performance of mass timber braced frames with the aim of creating safer and more sustainable structures for the future.

Eccentrically Braced Frames (EBFs) have become widely recognized as an efficient seismic force-resisting system for steel structures that providing both ductility and the necessary lateral stiffness. Some recent developments such as modular yielding links and self-centring systems have also improved the EBF performance by reducing the residual drifts and facilitates the quick repair of the structure after an earthquake (Mortazavi 2023). As the construction industry continues to focus more on sustainability, using EBF systems for mass timber structures offers great potential. Engineered timber products (CLT, GLT) have many advantages including the environmental advantages and excellent strength-to-weight ratios. By combining EBFs with Mass timber braced frames, the hybrid system can overcome the seismic limitations of conventional timber designs, enabling taller and more resilient structures.

This paper first reviews the fundamental behaviour and design principles of EBFs, with emphasis on key aspects of link performance, rotational capacity and the effect of axial forces and concrete slabs on system response. Recent advances such as replaceable links and self-centring technologies are also highlighted to demonstrate their effectiveness in improving EBF resilience and reparability. Next, the paper looks at solutions specific to mass timber construction to enhance their seismic performance. All the current methods for strengthening timber structures for seismic applications are compared, and the potential for innovation in this fast-growing field is explored. Finally, the feasibility of integrating EBF systems with mass timber structures is assessed, evaluating their compatibility and the opportunity to construct taller, more sustainable and earthquake resistant buildings for urban environments.

## 1.1 MECHANICS OF ECCENTRICALLY BRACED FRAMES (EBFS)

EBFs are commonly used in seismic-resistant structures due to their ability to dissipate energy through yielding links. Figure 1 illustrates two of the most utilized configurations for them, highlighting the internal forces acting on the yielding link, beams, and braces in each configuration. In the configuration depicted in Figure 1 (b), where the yielding link is positioned on one side of the bay the yielding link experience axial forces along with a consistent shear force and a linear bending moment diagram.

Alternative configurations for EBFs, along with their corresponding plastic mechanisms, are presented in Figure 2. The focus of this paper is on the EBF setup depicted in Figure 1(a). In all EBF configurations, the yielding link consistently experiences a constant shear force diagram along with a linear bending moment diagram.

The behaviour of EBFs is largely influenced by the length of the yielding link. According to Popov et al. (1988), shortening the link in a fixed bay length (L) increases the frame's stiffness. When the link-to-bay length ratio (e/L) approaches one, the frame behaves like a Moment-Resisting Frame (MRF) with reduced lateral stiffness. In contrast, as the ratio nears zero, the frame acts more like a concentrically braced frame (CBF), providing maximum stiffness.

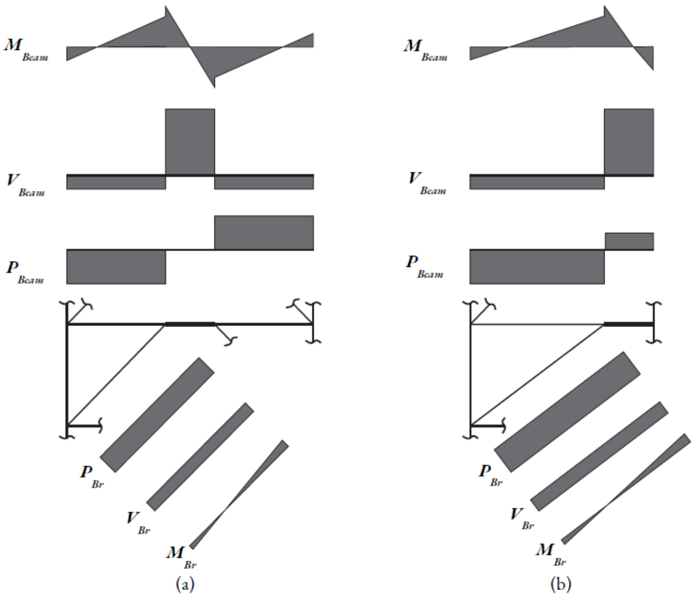

*Figure 1. Distribution of Internal Forces in Common Configurations of EBFs: (a) Eccentric Chevron Configuration, and (b) Single Brace Configuration (Mortazavi 2023,)*

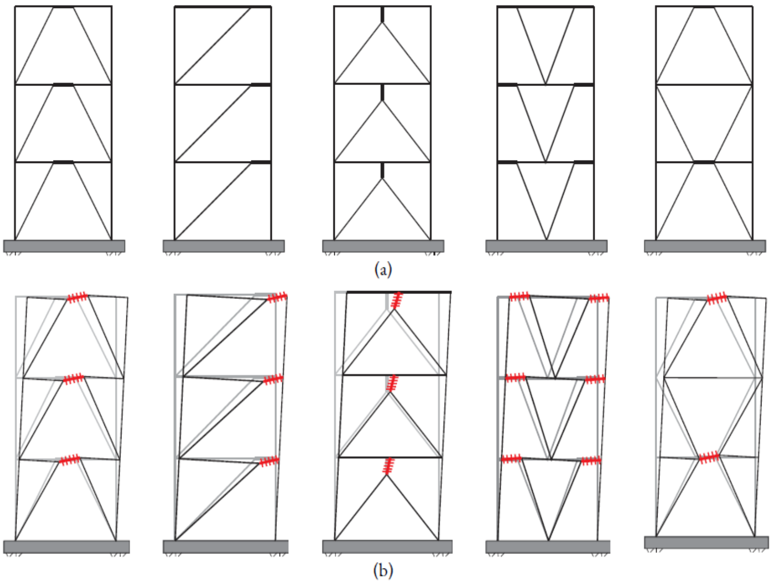


*Figure 2. EBF Configurations: (a) Undeformed Shapes, and (b) Deformed Shapes (Mortazavi 2023,)*

## 1.2 CLASSIFICATION OF YIELDING LINKS

In EBFs, yielding links are classified based on their yielding length ($e_y$) and their plastic shear strength ($V_p$) and plastic bending moment ($M_p$). The link length ratio (ρ), defined as the ratio of the link's length (e) to the ratio of the plastic moment ($M_p$) to the plastic shear ($V_p$), helps to classify yielding links ($\rho = e / (M_P / V_P)$). A shear-critical link is characterized by a link length ratio $\rho<1.6$, where shear deformation in the web predominates. A flexural link exhibits a length ratio $\rho>2.6$, where bending dominates. Links with a ratio between 1.6 and 2.6 are classified as intermediate, where both shear and flexural yielding occur simultaneously. Shear-critical links dissipate seismic energy through shear yielding in the web, resulting in uniform energy dissipation. However, their performance relies heavily on web stiffeners to maintain stability under large rotations. To enhance their performance and minimize the risk of web buckling, shear links are typically designed for a maximum allowable rotation of 0.08 radians (Hjelmstad and Popov, 1983b; Kasai and Popov, 1986).

On the other hand, flexural links dissipate energy through the formation of plastic hinges at their ends, where the largest bending moments are induced. Flexural links can experience localized damage, particularly flange local buckling, when the rotation exceeds 0.02 radians (Engelhardt, 1987). The performance of shear-critical links and flexural links is compared in Figure 3.

## 1.3 LINK ROTATION DEMAND AND CAPACITY

The ability of a yielding link to undergo significant inelastic rotations without losing its shear strength is crucial for the seismic resilience of EBFs. Links with higher inelastic rotation capacity can greatly enhance a structure's energy dissipation, improving overall earthquake performance. In EBF systems, the total link rotation angle (γ) represents the angle between the link and the adjacent beam, while the plastic portion of this rotation is known as the plastic link rotation angle ($\gamma_p$).

The maximum inelastic rotation capacity, $\gamma_p^{max}$, is the highest inelastic rotation a link can sustain during cyclic loading before its shear strength drops below a specific threshold. This threshold is typically defined as 80% of the maximum shear force recorded during testing (0.8Vmax) (X. Ji et al., 2015; P.W. Richards et al., 2005).

Figure 4 illustrates how to determine $\gamma_p^{max}$ based on experimental data from Okazaki et al., (2006), offering valuable insights into link behaviour under cyclic loading conditions. Experimental investigations have revealed that the rotation capacity of links is influenced by a variety of factors, including the link length ratio, loading history, compactness, and the presence of web stiffening.

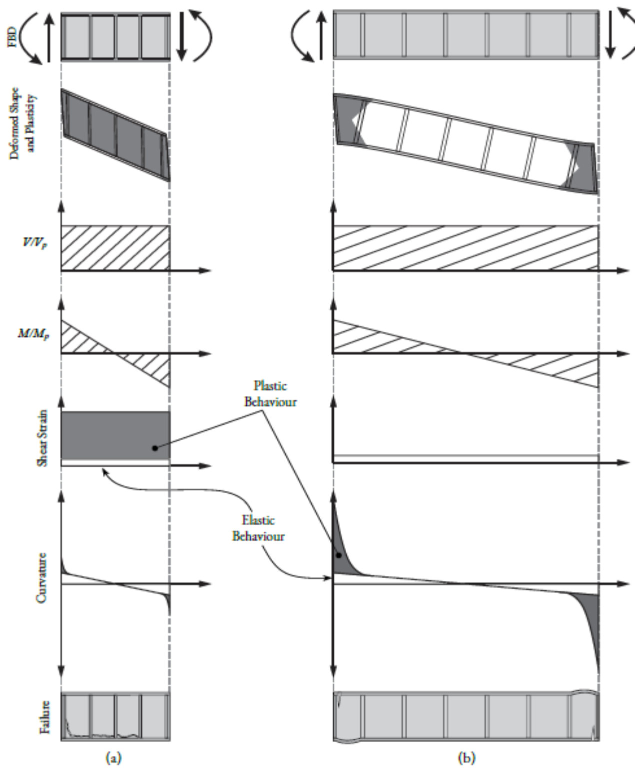


*Figure 3. Comparison between the Yielding Mechanism between Shear-Critical and Flexural Yielding Links: (a) Shear-Critical Links, and (b) Flexural Links*

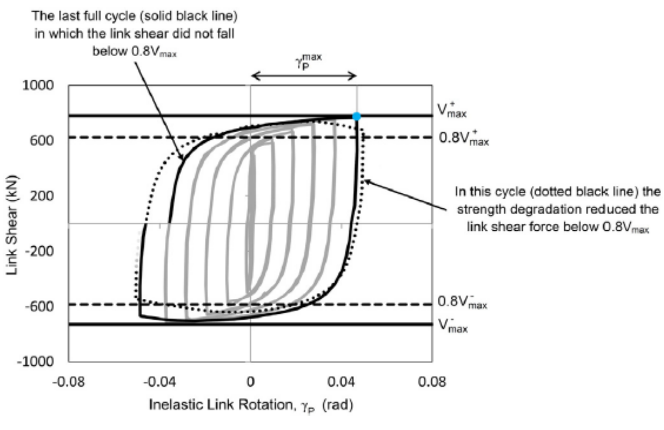


*Figure 4. Inelastic link rotation capacity for the UTA 9 specimen (data courtesy of T. Okazaki)*

## 1.4 EFFECT OF AXIAL FORCE

Links in structural systems can experience axial loads due to the axial restraining effects of adjacent members, as well as the specific loading schemes and geometries employed (see figure 1b). Research by Kasai and Popov (1986) revealed that axial forces negatively impact the performance of EBF links, reducing their energy dissipation capacity and altering their failure mechanisms, such as asymmetric flange buckling. Their findings have since influenced the provisions of AISC 341-10 for links under axial loads.

Further studies by Ghobarah and Ramadan (1990), found that longer links with length ratios around 1.6 experienced up to a 37% reduction in plastic shear strain. Dastmalchi (2014), conducted nonlinear time-history analyses, indicating that axial compression can reduce the shear strength and ductility of short links, and these effects become more significant in longer links.

## 1.5 EFFECT OF LOADING HISTORY

Research projects have emphasized that the loading history used in experimental tests significantly affects the plastic rotation capacity of EBF links. Richards and Uang (2006) further investigated this issue, showing that the rigorous loading protocol used by Okazaki et al., (2005), based on AISC 341-02, led to premature fractures in short links before reaching the code-specified rotation limit of 0.08 radians. This raised concerns about the reliability of older test results and their influence on design standards. To address these concerns, Richards and Uang (2006) conducted nonlinear time-history analyses on prototype EBF structures. Their findings contributed to the development of a new loading protocol adopted in AISC 341-05. When Okazaki et al., (2005) re-tested specimens under the revised protocol, they observed a 52% increase in maximum plastic rotation capacity ($\gamma_P^{max}$), highlighting the significance of appropriate loading protocols. These findings reinforce the critical relationship between loading history and EBF link performance, emphasizing the need for continuous evaluation. They also underscore the importance of having a low-damage link that can be repaired or replaced after the earthquake.

## 1.6 OVERSTRENGTH

To comply with the principles of capacity design, it is essential to accurately estimate the maximum shear force $V_{max}$ that a link can develop under extreme loads. This is an important factor since other parts of the structure need to remain elastic and effectively resist the forces from a fully yielded and hardened link. Any miscalculation of the maximum link force can lead to detrimental failures in adjacent structural members.

The concept of link overstrength is vital for determining Vmax, defined as:

$$V\ max = \Omega(R_y V_n) = \Omega V_e$$

Here, $R_y$ represents the ratio of expected yield stress to nominal yield stress, and $V_e$, signifies the expected shear capacity of the link. The overstrength factor Ω accounts for strain hardening effects and is a critical aspect of ensuring that the design can withstand unexpected loading conditions. Early experimental findings by popov and colleagues. (1989, 1993) suggested a standard value of ($\Omega = 1.5$) for design purposes, a benchmark that remains widely accepted in contemporary seismic design specifications. However, typically higher factors have been used in practical design.

## 1.7 REPLACEABLE LINKS

In recent decades, researchers have explored innovative solutions to enhance EBFs by improving their resilience and ease of repair after earthquakes. Conventional EBFs often suffer significant damage, leading to costly and time-consuming repairs. To address this, Stratan and Dubina (2004) explored the feasibility of using bolted connections with flush end-plates between links and beams in EBFs. Mansour (2010) conducted full-scale cyclic tests on replaceable shear links in EBFs, demonstrating their excellent ductility and stable yielding behaviour. Bozkurt and Topkaya (2018) introduced a direct brace attachment link with gusseted connections, which simplified link replacement while maintaining structural integrity. McCormick et al. (2008) suggest a 0.5% residual drift limit, beyond which repairs may be impractical. FEMA P-58 (2012) defines two damage states: DS1 (0.2% drift) allows repairs without realignment, while DS2 (0.5%) may make repairs economically unfeasible. Steel castings have gained attention due to their material and geometric versatility. Traditional shear-critical links in EBFs often require complex detailing and face challenges like weld fractures and buckling. To overcome these issues, Tan and Christopoulos et al., (2016) introduced replaceable cast steel links, enhancing rotation capacity and fatigue life. Mortazavi (2023) further advanced this concept with cast steel modular yielding links (CMLs), promoting uniform yielding and reducing failure risks.

## 1.8 REPLACEABLE LINKS WITH SELF-CENTRING

While energy dissipation in structures is crucial for preventing collapse during major earthquakes, it can result in substantial direct losses, including casualties and repair expenses, as well as indirect losses like business disruptions. Furthermore, the plastic deformations that occur in structural elements often lead to significant residual drifts, which may hinder a building's ability to be repaired. To overcome these challenges, researchers have explored alternative solutions to replaceable links that focus on improving damage control and self-centring capabilities—allowing the structure to return to its original position after an earthquake. Cheng et al., (2012) proposed a self-centring rocking link design for EBFs, where rocking motion between the link and adjacent beams is controlled by post-tensioned strands and enhanced by frictional hinge dampers for greater energy dissipation. Tong et al., (2019) conducted an experimental study on a D-type self-centring EBF system composed of post-tensioned strands and replaceable hysteretic damping devices. Al-Janabi and Yang (2021) developed a self-centring friction-based EBF (SCFB-EBF) by using self-centring conical friction dampers (SCFD). Another self-centring link (SC-link) proposed by Lettieri et al., (2023) integrates post-tensioned high-strength steel bars and friction devices, creating a flag-shaped hysteretic response that restores the frame to its original position after an earthquake.

## 2 SOLUTIONS FOR MASS TIMBER STRUCTURES

Traditional mass timber structures are designed to exhibit ductile behaviour during earthquakes, mainly through plastic deformation of connectors and the crushing of timber fibers. However, this approach often leads to irreparable damage, stiffness degradation and leaving the structure vulnerable to aftershocks. Repairing or replacing damaged connectors is not only challenging but may also render the structure impractical to fix, sometimes leading to demolition.

While current building codes focus on the ‘life safety’ criterion, modern designs are increasingly adopting a low-damage philosophy. This approach concentrates damage within easily replaceable components, known as “fuses,” which absorb seismic energy through controlled inelastic deformation. By limiting damage to these sacrificial elements, ensuring better resilience against aftershocks while maintaining the primary structure’s stiffness. Studies on mass timber structures with conventional connectors have shown good seismic performance. Ceccotti et al. (2013), through the full-scale Sofie project shake table tests on a seven-story CLT building, confirmed the structure's resilience. However, the tests also revealed that the energy absorption capacity of the connectors declined as the building's lateral stiffness decreased after repeated seismic events. Popovski and Gavric (2015) explored the seismic behavior of CLT wall assemblies equipped with conventional connectors. Yasumura et al. (2015) also conducted full-scale tests on a low-rise mass timber structure with conventional connections. Their research demonstrate that the ultimate capacity of these panels exceeded the design load by 60–80%.

Considering these studies, many researchers have begun to explore alternative connector designs to enhance the seismic performance of mass timber structures. These advancements aim to enable the system to withstand multiple earthquake events. Iqbal et al. (2015) investigated the use of nailed plywood sheets as seismic fuses in coupled Laminated Veneer Lumber (LVL) walls. They found that, while the nailed connections sustained damage during seismic events, the LVL walls remained largely intact. Kramer et al. (2015) conducted experimental studies on steel dissipaters applied at the base of CLT wall panels. The study showed that the proposed wall-to-floor connection system effectively reduced lateral drift. Similarly, Wrzesniak et al., (2016) performed large-scale reversed cyclic experiments on a glue-laminated timber panel coupled with lead extrusion dampers. Another sacrificial steel component is introduced by Bloomgren et al., (2019). The full-scale shake table tests demonstrated that the proposed system effectively controlled building deformation under code-specified levels of DBEs and MCEs. Loo et al., (2014) and Hashemi and Masoudnia (2016), Hashemi and Quenneville (2020), conducted studies on the implementation of slip friction connections in rocking single and coupled timber walls. The connection demonstrated stable hysteretic behaviour and maintained its strength through multiple loading cycles.

However, achieving reliable re-centring capabilities requires the incorporation of additional components, which enable the structure to return to its original position after an earthquake. In this way, Sarti et al., (2015) incorporated U-shaped flexural plates (UFPs) and Bahmani et al., (2016) utilized energy dissipative hold downs into mass timber systems as seismic fuses. To further enhance the system's resistance and enable effective re-centring, they integrated post-tensioned elements along the vertical span of the timber walls. The concept of utilizing friction sliders within braces was initially introduced by Pall et al., (1982). These low damage devices slip during seismic events, dissipating energy and eliminating the need for repairs or replacements of the braces after a major seismic event. To improve re-centring capabilities, researchers have explored adding elastic or semi-elastic systems. Tremblay et al., (2008) and Christopoulos et al., (2008) combined post-tensioned elements with friction-damped steel braces, creating a self-centring system with a flag-shaped hysteretic response. Similarly, Zhu and Zhang (119) integrated superelastic Nitinol strands into friction-damped braces, further enhancing the system's ability to return to its original position after seismic events.

Chou et al. (2016) introduced an innovative telescopic friction bracing (DC-SCB) mechanism that utilized post-tensioned components to facilitate the re-centring of sliding telescopic members. Additionally, Dezfuli et al. (2017) developed a self-centring friction-damped brace that incorporates aramid fiber cables, offering an alternative method to enhance resilience in seismic applications. A major advancement in friction-based self-centring systems is the Resilient Slip Friction Joint (RSFJ) (Zarnani et al., 2016), which removes the need for extra restoring components. Unlike traditional friction dampers, RSFJs use grooved sliding plates and semi-stressed disc springs to store elastic energy during loading. Hashemi et al., (2017) also carried out full-scale experimental tests on rocking CLT and LVL panels with RSFJ hold-down connections. Their findings demonstrated a low-damage system and showed that RSFJs can be seamlessly integrated into different timber systems.

## 3 SUITABILITY OF EBF FOR TIMBER STRUCTURES

With growing concerns about carbon emissions and climate change, engineered timber is emerging as a sustainable alternative to traditional materials (Sun et al., 2020; Shu et al., 2022). However, designing mass timber structures for seismic resilience presents challenges, especially due to timber's low ductility and reliance on fasteners, that introduce uncertainties in energy dissipation, overstrength, and connection performance. These limitations can result in inefficient cross-sections and height limitations; therefore, it is crucial to develop more ductile lateral force-resisting systems for multi-story timber buildings (Yang et al., 2022; Li et al., 2022)

One possible solution could be the integration of steel and timber where strength and flexibility of steel can be combined with the sustainability and light weight of timber. In this context, Eccentrically Braced Frames (EBFs) could be an effective solution and one possible approach in this context might be to employ Glulam as diagonal braces and steel for the active link to enhance ductility compared to conventional timber solutions. Researchers are increasingly exploring these steel-timber hybrid structures to improve seismic resilience and expand the possibilities of timber construction in earthquake-prone regions.

Iqbal et al., (2020) suggested combining Steel Plate Shear Walls (SPSW) with timber frames to create a more effective lateral load-resisting system. Dong et al., (2020) conducted full-scale experimental tests on BRB-braced timber frame system with various connection methods. The results demonstrated effective engagement of BRBs in resisting lateral loads and enhancing overall seismic performance (see Fig 5). Ponzo et al., (2021) demonstrated that adding lateral load-resisting sub-systems, like steel-timber hybrids, can effectively enhance the strength and stability of timber structures. Abraik and Iqbal (2023) investigated the seismic performance of timber braced frames incorporating Shape Memory Alloy (SMA) dampers to improve their response under seismic forces. Development and the incorporation of friction braces into heavy timber frames have been proposed by Gilbert et al., (2019). through cyclic loading tests on braced GLT frames. Their study confirmed the feasibility of using GIR connections to effectively connect friction braces to the timber frame. Chen et al., (2023) explored ways to improve the seismic resilience of steel-timber hybrid frames by adding additional damping and stiffness (ADAS) braces. Experimental tests comparing a conventional PT timber frame with the hybrid system showed remarkable improvements in strength and ductility. Offerman and Bompa (2023) used steel frames with CLT floors and shear walls. Their numerical modelling showed that substituting concrete with timber led to a reduction of more than 32.7% in embodied carbon, while still meeting the same level of structural performance. Haase et al., (2024) examined steel-timber hybrid beams, which incorporate steel profiles into timber cross-sections using adhesive bonding to create shear-resistant connections. Liu et al., (2025) introduced an innovative low-damage glulam frame (ILF) equipped with energy-dissipating braces to improve seismic performance in glulam structures. The results showed that the ILF exhibited 20 % more lateral stiffness and energy dissipation capacity approximately 150% higher than the CLF. In general, timber structures can enjoy EBF concepts with lower over-strength factors. This factor usually governs the type and size of the fasteners used for capacity-protected elements that are pricy.

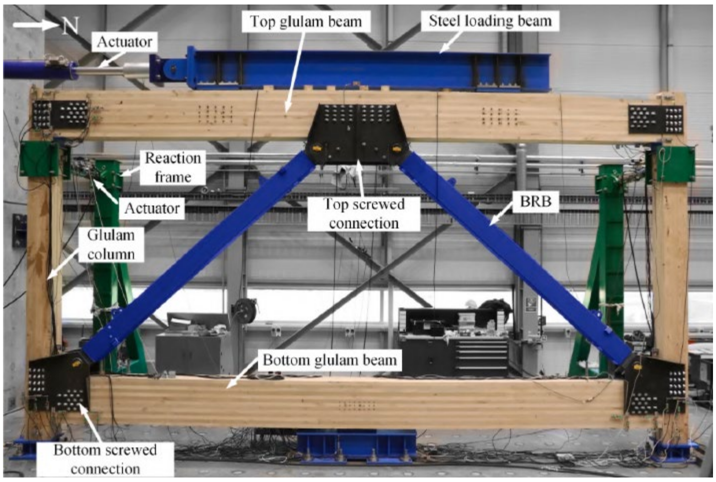


*Figure 5. Test specimens (S-S with the screwed connection)*

## 4 CONCLUSIONS

This article has examined the feasibility of incorporating Eccentrically Braced Frames (EBFs) into timber structures. The integration of EBFs into timber structures can be regarded as a compelling way to improve the seismic strength of structures while maintaining the environmental advantages of timber construction. This hybrid design approach provides a balanced solution that taking the best from both worlds: the ductility and energy dissipation capacity of EBFs, and the sustainability and aesthetic qualities of timber. Nevertheless, there is still a major gap between the experimental studies and real-life application of this system. Hence, it is crucial to develop design guidelines, standardize testing protocols, and further innovation to fully exploit this system. Therefore, further research and development of EBF-integrated timber structures can pave the way for new trends in the construction of sustainable, modern, and tall buildings.

## 5 ACKNOWLEDGEMENTS

The authors would like to thank New Zealand Natural Hazards Commission Toka Tū Ake and QuakeCoRE for supporting this research. This is QuakeCoRE publication number 1026.

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