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Review and suggestions on timber buildings with hybrid lateral force resisting systems

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ABSTRACT

Timber-framed structures have long been the default structural form for residential construction in many countries, including New Zealand. However, for some complex low-rise and mid-rise buildings, hybrid Lateral Force Resisting Systems (LFRS) are used, where structural timber is used in combination with other materials, such as reinforced concrete, structural steel or reinforced concrete masonry, allowing the seismic criteria to be met. A large number of such structures are now being constructed in NZ. There is little design guidance and no standards providing simplified design methods for these structures. This paper provides an overview of modern hybrid timber-based structures, reviews previous studies on timber buildings with hybrid LFRSs, and evaluates their performance based on available research and first-principles considerations. The advantages and disadvantages of different systems are discussed. Research gaps in the seismic behaviour of hybrid timber-based structures are identified, and recommendations for future research are provided.

1 INTRODUCTION

Timber-framed and mass timber structures that use Cross-Laminated Timber (CLT), Laminated Veneer Lumber (LVL) and Glued Laminated Timber (Glulam), etc., have considerable research data available. In complex low-rise and some mid-rise buildings, timber is often used in combination with other materials to satisfy the acceptable seismic performance criteria. Timber-based buildings that use elements constructed using other materials such as Reinforced Concrete (RC) floors or walls, steel frames or braces, RC masonry walls, etc., are called hybrid timber structures. Hybrid structures can effectively utilise the benefits of each type of element for lateral and gravity loads resisting systems. Currently, there is a large variety of timber-based hybrid structures, with some of those types already implemented in construction. For instance, due to urban population growth and limited land supply, the residential construction sector in New Zealand is moving towards Medium Density Housing (MDH) solutions, which often require LFRSs constructed from different materials to be used. Currently, there is little design guidance for hybrid timber-based structures in New Zealand.

The objective of this paper is to provide a review of some timber-based hybrid structures, including the most recent developments and a discussion of their strengths and weaknesses. Various aspects of hybrid timber-based LFRSs, including displacement compatibility of different materials and assessment of construction and design practicality, are considered. Suggestions on the design methodology and improvements of several common hybrid systems are made.

2 REVIEW OF EXISTING RESEARCH

A state-of-the-art report on timber-based hybrid structures (Gallo and Carradine, 2018 and Gallo et al., 2020) covers experimental and numerical research, practical applications, and discusses the advantages and disadvantages of some types of these structural systems. This report focuses mainly on seismic resisting systems and concludes that combining timber with other materials is an efficient method to improve the lateral performance of the building, provided that each material is used in a way, so the inherent advantages are utilised. Based on their review, recommendations for future research topics are provided. Pastori et al. (2022) presented a literature review of hybrid buildings, including composite building components, connection systems, thermo-physical and acoustic properties, and fire performance. Ugalde et al. (2019) provided an overview of hybrid timber buildings incorporating seismic low-damage technologies. This study included a review of such technologies as supplemental damping, base isolation and controlled rocking structures.

In some cases, a steel Moment Resisting Frame (MRF) may be used as LFRS substituting timber shear walls. For instance, a steel MRF may be used where access to the garage is required or in architecturally designed low-rise houses to capitalise on available views. He et al. (2014) studied a Steel-Timber Hybrid Shear Wall (STHSW) system where an infill consisting of timber framing with OSB sheathing is placed within the steel MRF. They tested this system with monotonic and reversed cyclic loads. The specimen's layout and dimensions are shown in Figure 1. Experimental investigation confirmed that installation of the Light Timber-Framed (LTF) infill increased lateral stiffness compared to the steel MRF. Systems with double sheathing had twice the lateral stiffness of those with single sheathing.

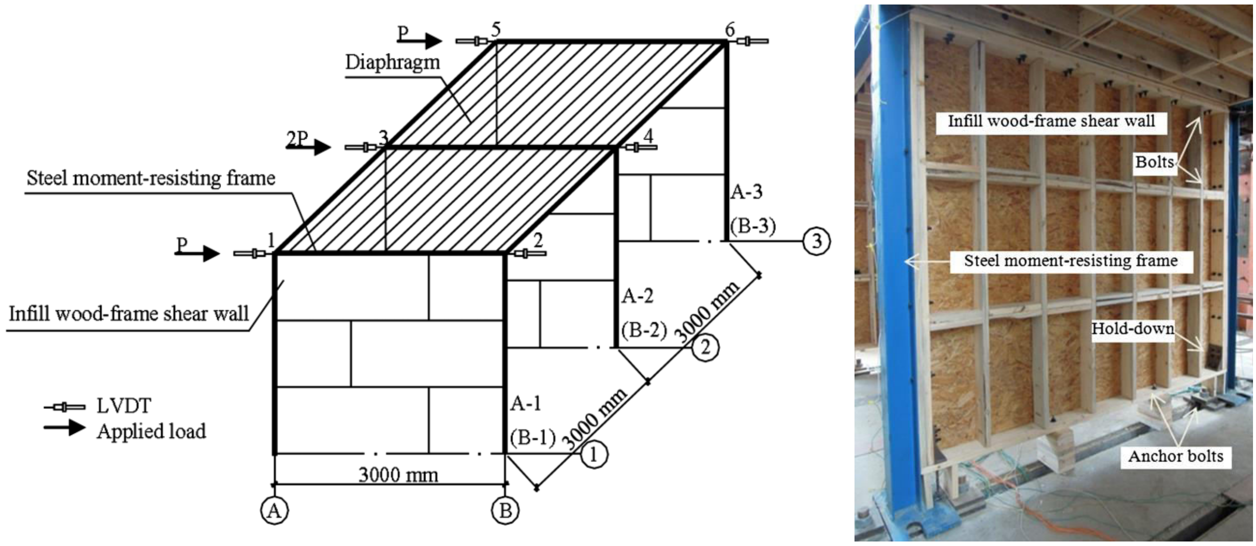

Figure 1: Layout and dimensions of test specimen (He et al., 2014)

Their investigations identified that the LTF infill was effective at the initial loading stages. As damage developed in an infill, a substantial part of the load was re-distributed to the steel MRF. The timber-framed infill provided energy dissipation until the system reached 2% drift, and the steel MRF provided dissipation for higher drift levels. A further assessment of this structure based on a performance-based design principle was carried out by Li et al. (2018). The assessment was completed for both structural and non-structural elements under Immediate Occupancy (IO), Life Safety (LS) and Collapse Prevention (CP) performance levels. The target drift for the LS performance level had a little effect on the design of the structure. It was proposed that the main design criteria should be based on (i) sufficient elastic stiffness for IO performance level, and (ii) sufficient post-yield stiffness for CP level.

Quasi-static cyclic tests were conducted on two single-storey single-bay STHSW specimens (Li et al., 2019a). The wall-to-frame connection significantly affected the lateral performance of the system, and higher loads were resisted when the infill wall-to-frame connection was made stiffer and stronger. Following the experimental tests, a finite element model was developed. Additionally, performance objectives were calibrated, and a design method was developed (Li et al., 2019b). The study determined the inter-storey drift levels corresponding to the IO and CP levels as being 0.5% and 2.5%, respectively. A four-storey building design example was included and verified by Non-Linear Time History Analysis (NLTHA).

A shake table test was completed on a four-storey specimen comprising an STHSW system (He et al., 2018). The structure reached a maximum drift of 0.85% under significant shaking. The steel MRFs did not show any damage, while infill walls showed minor damage, such as nail connection failure and OSB sheathing panel crushing. The test results were in good agreement with numerical model predictions. The damage evaluation of this shake-table test was conducted by Li et al. (2021a). The initial nail connection failure in the form of nail withdrawal, flake debonding, local crushing and pull-through was observed at 0.6% lateral drift. The system was found sensitive to PGA, frequency content and shaking duration. The test specimen also included door/window openings. However, the influence of the openings was only briefly described.

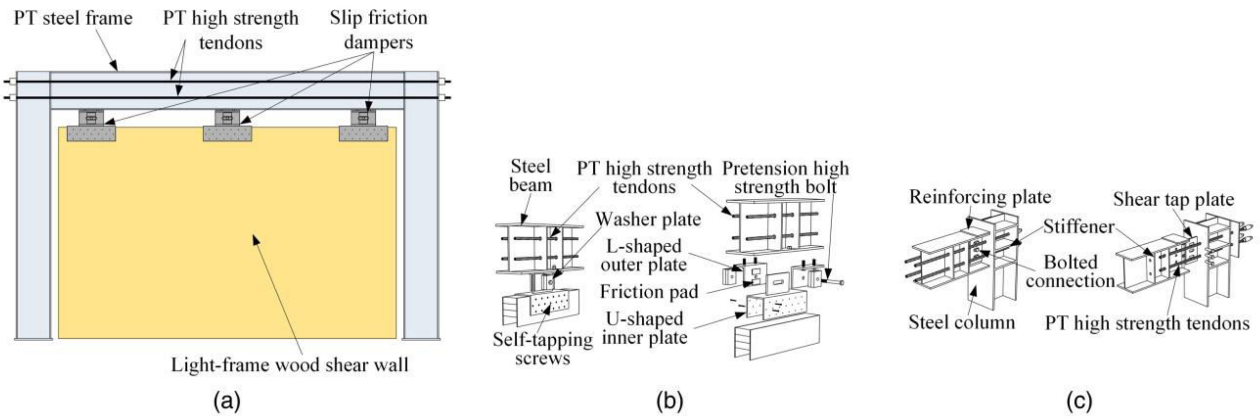

Figure 2: Self-centring steel timber shear wall with slip-friction dissipators: (a) system layout; (b) slip-friction dissipator; and (c) PT connection (Li et al., 2021)

Supplemental friction dissipators were added to STHSW by Li et al. (2017) to upgrade the seismic performance. Cyclic testing confirmed that the major non-linear system deformation occurred in the dissipators, thereby dissipating energy and protecting the structural members. Another recent development based on STHSW proposed by He et al. (2014) is a self-centring hybrid shear wall with slip-friction dampers (Li et al., 2021b). The general layout of the system and the configurations of the slip-friction damper and PT connection are shown in Figure 2. Numerical simulations and experimental testing were performed for the proposed system. The PT system achieved a flag-shaped hysteresis loop inherent to PT self-centring structures and significantly reduced residual deformations typical for conventional STHSW. The proposed system represents an alternative to other self-centring seismic resisting systems often used in timber structures. One of them is Pres-Lam, studied by Palermo et al. (2005) and developed based on a PREcast Seismic Structural System (PRESSS) (Priestley and MacRae, 1996). Another self-centring system suitable for mass-timber construction is a Resilient Slip Friction Joint (RSFJ) studied by Zarnani et al. (2016) and based on Sliding Hinge Joint (SHJ) concept (MacRae et al., 2010).

An adapted version of STHSW for New Zealand was proposed by Kho (2018), where OSB sheathing was replaced with structural plywood, which is typical in New Zealand construction practice. Experimental testing was completed for the main timber-to-steel connections. Based on the obtained data, a finite element model was created, and parametric studies were carried out. STHSW with plywood sheathing also demonstrated a very ductile behaviour and a higher level of stiffness and strength compared to conventional plywood shear walls. A design example using a displacement-based design approach was provided.

A hybrid structure consisting of a steel MRF and CLT infill was proposed by Dickof et al. (2014). The CLT panel was connected to the frame via steel brackets and was installed with a gap between the CLT panel and MRF along the sides and top. The panel is expected to remain in place while the frame and connections deform. A parametric study was completed using static pushover analysis. The gap size between the panel and MRF directly influenced the system's ductility. Steel frame ductility demands were small, and a design displacement ductility of 2.5 and an overstrength factor of 1.25 were recommended. Brackets are designed to yield and be replaced under minor earthquakes. Replacement of the frame and CLT wall panel may be required following major earthquakes. While the system upgrades the stiffness of the steel MRF, it remains sensitive to gap size. Major earthquakes may result in direct contact of the CLT panel with the steel frame, which would have an immediate effect on the stiffness and, therefore, performance of the system.

One way to upgrade a timber building's lateral strength and stiffness is to connect the timber structural members to a stiffer lift shaft/stairwell core. Zhou et al. (2014) studied LTF buildings with RC masonry cores. Experimental investigations under reversed cyclic load were completed on two specimens consisting of two-storey LTF walls longitudinally connected to RC masonry walls (Zhou et al., 2017). The author concluded that both components and assemblies showed inelastic performance. In the first specimen, the failure cause of the connection between two subsystems was that the RC masonry wall was stronger than the connection itself. In the second specimen, the RC masonry wall subsystem failed first due to the LTF displacement capacity being larger, and the relatively high connection strength. The energy was dissipated mainly by the LTF and the RC masonry wall. Unlike the STHSW, this system had a smaller force transferred to the LTF infill, as the RC masonry core was stiffer, causing displacement incompatibility.

Coupled CLT walls with a ductile steel link and capacity-designed connections were studied by Moerman et al. (2022). For stiffer connections between the CLT and the steel link, the link yielded at a lower chord rotation. Simple analytical methods were developed to determine the Self-Drilling Dowel (SDD) connection strength and stiffness. Moerman et al. (2022) indicated that the coupled wall system had advantages over standard cantilevered walls in terms of enhanced ductility, strength, stiffness, and reduced demand on hold-down connections.

Buckling-Restrained Braces (BRBs) can act as effective ductile elements for energy dissipation under seismic loads. Dong et al. (2020) completed an experimental study on Glulam frames with BRBs. The study included in-plane cyclic testing of two full-scale 8 m wide and 3.6 m high frames with both (i) dowelled and (ii) screwed connection options. Such frames can exhibit high ductility compared to conventional timber frames with traditional timber or steel braces. Eurocode 5 methods considerably overestimated the stiffness of both connection types. Further investigations of Glulam frames with BRBs (Dong et al., 2021) identified more accurate models to estimate the stiffness of the connections. Blomgren et al. (2016) and Murphy et al. (2021) studied a hybrid system where BRBs had a timber glulam casing instead of conventional steel option.

A vertical hybrid LFRSs arrangement is also commonly used in modern construction. For instance, a number of bottom storeys may be constructed of RC, forming a podium for timber superstructure. This may be used to provide a carpark, or in case timber structure does not have sufficient strength/stiffness to resist higher loads at the bottom storeys. An example of such an arrangement is the Brock Commons Building (Fast et al., 2016), which is an 18-storey structure built in a seismic zone in Vancouver, Canada. This building includes an RC concrete podium with other storeys made of CLT floors and Glulam columns, except for the top storey, which is constructed from steel. The LFRSs was provided by two RC core walls.

3 DISCUSSIONS

As LFRSs in hybrid structures often incorporate elements made of different materials possessing different properties (i.e., strength, stiffness, ductility, damping, etc.), the peak strength may not be the sum of the strengths of the individual elements, or elements may sustain damage at different drift levels. This compatibility issue was confirmed by observations following 2010-2011 Canterbury Earthquake Sequence (Buchanan et al., 2011) and further discussed by Liu (2017). Liu (2017) proposed performance criteria for specifically designed LFRSs to improve displacement compatibility between different types of LFRSs. However, the proposed method was considered on a concept level, and further investigations, including numerical simulations and experimental testing, should be conducted to develop rigorous design provisions.

Many multi-unit houses include up to three types of LFRSs: LTF shear walls, steel MRFs and RC masonry firewall between tenancies, as shown in Figure 3. These LFRSs have significantly different properties. The RC masonry firewall has the largest strength and stiffness and would have a smaller lateral deflection capacity compared to the LTF shear wall located on the opposite side of the building. This displacement incompatibility means that damage may occur to different LFRSs at a particular response displacement, as described by Liu (2017). Irregular LFRSs arrangements can also result in coupled translational and torsional responses influenced by the diaphragm stiffness (Liu and Shelton, 2018). Further investigations need to be completed on the torsional response of buildings with hybrid LFRSs, considering diaphragm strength and stiffness.

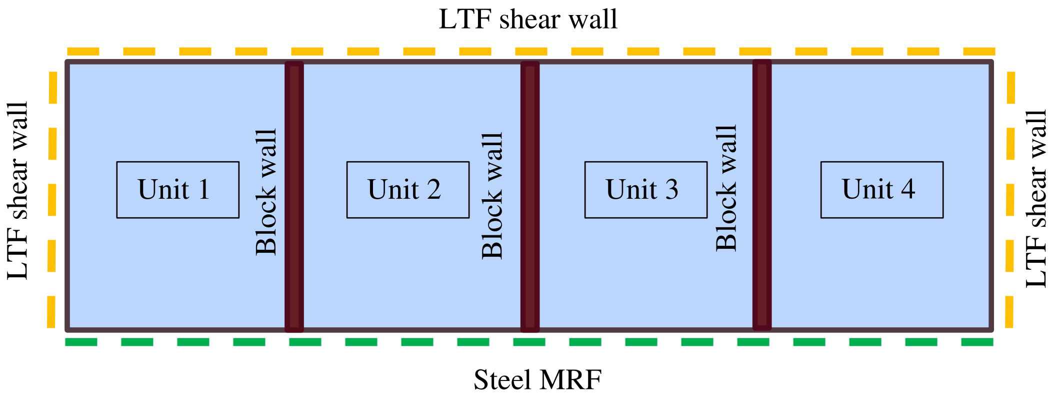

Figure 3: Example of LFRS layout in multi-unit buildings

MDH often requires a budget solution in terms of both design and construction. Therefore, some of the recently developed hybrid systems may not be suitable due to their complexity in design as well as construction. Some systems require structural design outside of the scope of the NZ Building Code (NZBC, 1992). These are classified as "Alternative Solutions". This further increases building costs due to the required peer review and possibly higher building consent fees.

MDH developments in NZ are commonly low-rise buildings of mainly LTF construction with hybrid LFRSs. One common hybridisation in MDH buildings is that steel frames with solid or penetrated plywood or plasterboard sheathings are utilized to help meeting the bracing requirements. LFRSs with such infill arrangements are similar to STHSW. In general, the design ignores the infill contribution to the lateral strength and stiffness. However, the infill panel may have considerable compressive stiffness and strength, influencing the lateral response. For instance, multi-unit buildings with a garage on the ground storey may have a steel MRF as LFRS. The building's upper storeys often have timber infill within the steel MRF. As a result, the ground storey stiffness/strength is likely to be significantly lower than on the upper floors, increasing potential for developing a soft-storey mechanism under major earthquakes. The storey characteristics also depend on the openings for doors and windows.

Considering the STHSW system described above, the structure may be simply designed to act in a hybrid manner using appropriately designed connections between the steel MRFs and timber-framed infill. In this way, the beneficial aspects of the hybrid action may be realised, and the strength/stiffness of each storey may be more correctly considered and identified making a better, and safer, structural system than if the infill is placed arbitrarily. The increased strength may also contribute to the economy of the structure. While current design fees may be greater for the “Alternative Solution”, by popularising the system, and incorporating it into NZ standards, it will become an “Acceptable Solution” removing the additional fees.

Previous investigations (e.g. that described above by He et al., 2014), confirmed that appropriately considering and designing timber-framed infill in LFRS may improve strength and stiffness, provided these are designed and detailed correctly. Also, design procedures have been established for STHSWs with LTF infill. However, the influence of openings, such as that required for windows and doors, has not been evaluated in detail. Consideration of such openings, by experiments and numerical studies, is important for the development of standards to normalise the STHSW construction form. Such studies with the development of simple design procedures and incorporation of these into standards will improve reliability and building costs.

A research project, supported by BRANZ and the University of Canterbury, involving numerical and experimental testing of STHSWs with plywood sheathing with and without openings is being conducted by the authors. Design guidance for LTF buildings with hybrid LFRSs is being developed.

4 CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

This paper reviews some hybrid timber-based systems for resisting seismic loads. The conclusions obtained from this study are:

- Hybrid timber-based structures can utilise benefits provided by each material and can effectively improve the lateral behaviour of the building. Some available systems are reasonably simple to design and construct and are a good option for mass construction.
- Experimental and numerical investigations have proven that STHSWs may be effective in resisting seismic loads. Further research is required to understand the STHSWs with openings.
- Current design practice normally ignores contribution of a timber-framed infill to the strength and stiffness of an MRF. The infill may have an unaccounted effect on the seismic response of the structure. Further study is required to quantify this effect on the seismic performance.
- Currently, there is little design guidance for hybrid timber-based structures in New Zealand. Further investigations and development of design guidelines can improve the economy and performance of new buildings and reduce compliance costs. Such work is underway by the authors.

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