# Seismic resilient multi-story timber structures with passive damping

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## 1. Introduction

It is a well-known fact that in a seismic resistant timber structure, the timber elements have to behave elastically during an earthquake and all of the energy dissipation has to occur in the connections. In traditional timber structures in which the connections include conventional metal fasteners such as nails, screws, rivets or bolts, the required ductility and energy dissipation are provided by the connections. However, since the energy dissipation in timber connections always involve plastic deformation of the fasteners, irrecoverable damage to the connections is highly probable. Thus, the structure requires serious repair and may need to be dismantled. Moreover, the stiffness and strength of the structure may significantly decrease making it highly vulnerable even to a minor aftershock. As a result, a mixing of the timber members and novel energy dissipation devices is required for the structure to be able to tolerate a severe seismic event and the associated aftershocks.

Conventional slip friction connections with flat plates sliding on each other have always been recognized to have one of the most efficient passive damping mechanisms. The provided hysteresis which is close to an elastic-perfectly-plastic one combined with the cost effectiveness of these devices has made them very favourable. Nevertheless, the lack of self-centring behaviour is a major disadvantage which may result in considerable residual displacements after an earthquake.

The aim of this project is to develop damage avoidance concepts for lateral load resisting systems in multi-story timber and hybrid structures that offer compatibility of deformations for all the elastic timber systems in the structure and that can dissipate the energy through friction. The performance of the conventional slip friction connections in seismic resistant structures is investigated and the consequent damage caused by the lack of self-centring behaviour is studied. To provide the self-centring behaviour, alternative novel solutions are proposed. The performance of the structures containing the proposed solutions is examined by joint component testing, large scale experimental tests and numerical analyses. Analytical design procedures are proposed and validated by the experimental data. This report contains the summary of conducted research and the developed solutions. Each of the following sections is a chapter in the thesis and also published as a journal paper. A list of publications including all of the journal papers and conference papers is presented at the end.

## 2. A numerical study of coupled timber walls with slip friction damping devices

In this section, the application of slip friction connections in timber coupled walls is investigated by developing and analysing detailed numerical models. The proposed structural concept includes rocking Cross Laminated Timber (CLT) or Laminated Veneer Lumber (LVL) walls with slip friction hold-downs at the base and friction ductile links between the adjacent walls.

The components of the system transfer the lateral forces to the foundation while providing the required ductility at a given drift. The walls are typically CLT or LVL which the type is generally determined based on the required capacity. A numerical model for the proposed system is developed and was subjected to displacement-control quasi static and non-linear dynamic time-history simulations. Furthermore, the numerical results were compared with the results from a similar model with the slip friction connections replaced with traditional nail plates. This comparison showed that the proposed concept has a superior seismic behaviour relative to traditional systems yet showed residual displacement after the seismic events. The outcomes are published as a journal paper in Construction and Building Materials. The reader is referred to the following link for more information.

https://doi.org/10.1016/j.conbuildmat.2016.05.160

## 3. Seismic performance of hybrid self-centring steel-timber rocking core walls with slip friction connections

In this section, an innovative damage avoidance steel-timber rocking core as the main lateral force resisting system is developed to efficiently lessen the post-earthquake damage. This system includes rocking timber walls, steel corner columns and supplementary slip friction dampers to dissipate the seismic energy. Moreover, high strength post-tensioned steel strands were used through the steel beams to self-centre the structure after the earthquake. The efficiency of this system is inspected by displacement-control quasi-static and non-linear dynamic time-history analyses. Furthermore, a design procedure based on the Displacement Based Design (DBD) approach is introduced to design the system in accordance with the induced seismic loads. Finally, a numerical model for the proposed timber rocking core system is developed and subjected to dynamic time-history simulations. The results showed that the system has a fully self-centring behaviour with a significant decrease in peak roof accelerations when compared with traditional systems. The outcomes are published as a journal paper in the Journal of Constructional Steel Research. The reader is referred to the following link for more information.

https://doi.org/10.1016/j.jcsr.2016.07.022

## 4. Seismic resistant rocking coupled walls with innovative Resilient Slip Friction (RSF) joints

In this section, a damage avoidance timber coupled rocking wall system with innovative Resilient Slip Friction (RSF) joints as the ductile links between the adjacent walls or columns is developed. In this system, boundary steel columns at the ends of the coupled walls are considered instead of the hold-down connectors. Owing to the unique characteristics offered by the RSF joints, this innovative lateral load resisting system is able to provide self-centring behaviour in addition to significant rate of seismic energy dissipation. A simple procedure for designing the joint is presented and the results of RSF joint component tests are discussed. Furthermore, a numerical model is developed to demonstrate the seismic performance of the proposed system. The numerical technique used for modelling of the RSF joints is verified by the experimentally obtained data. To investigate the efficiency of the system, the model is subjected to displacement-control quasi-static cyclic simulations and non-linear dynamic time-history records. The results showed a fully self-centring behaviour given no residual displacement was recorded. Moreover, the maximum recorded displacements were within the indicated thresholds by the New Zealand standard for the Ultimate Limit State (ULS) seismic events and Maximum Credible Earthquake (MCE). The outcomes are published as a journal paper in the Journal of Constructional Steel Research. The reader is referred to the following link for more information.

https://doi.org/10.1016/j.jcsr.2016.11.016

## 5. Experimental testing of rocking Cross Laminated Timber (CLT) walls with Resilient Slip Friction (RSF) joints

This section presents the large scale experimental testing of the concept of rocking CLT walls with RSFJ hold-downs as the lateral load resisting system. The hysteretic behaviour of this innovative system is verified and the feasibility and effectiveness of the adopted solution for connecting the RSF joints to the CLT wall was confirmed. Furthermore, an analytical design procedure for predicting the hysteretic behaviour of the wall was developed and verified by comparing the experimental results with the analytically obtained hysteretic loops. Also, a numerical tool for modelling the structures containing the proposed concept is introduced. Overall, the test results showed an excellent seismic performance which suggests the potential for application in seismic resilient structures when a damage avoidance design philosophy is adopted. The outcomes are published as a journal paper in the Journal of Structural Engineering (ASCE). The reader is referred to the following link for more information.

https://doi.org/10.1061/(ASCE)ST.1943-541X.0001931

## 6. Seismic resilient lateral load resisting system for timber structures

In this section, a seismic resilient solution for timber and hybrid timber-steel structures is developed and investigated on the system level. The proposed system includes rocking wall panels with RSF joints (as the hold-down connectors) and load-bearing components on the two sides of the wall panels. This system offers adequate ductility for the building while energy dissipations and self-centring are provided by the RSF joints. A preliminary design procedure for the proposed system based on the Displacement Based Design (DBD) approach is also introduced. To further investigate the seismic performance of this system, a numerical model for a five-story prototype building was developed and subjected to non-linear dynamic time-history records. The results were compared with those obtained from similar models in which the RSF joints were replaced with conventional connectors such as symmetric friction dampers and nailed connections. Additionally, the models were subjected to sequences of earthquakes to investigated the resiliency of the concept in a series of seismic event. The results showed excellent seismic behaviour in terms of self-centring behaviour, response accelerations and peak roof drifts. The outcomes are published as a journal paper in Construction and Building Materials. The reader is referred to the following link for more information.

https://doi.org/10.1016/j.conbuildmat.2017.05.112

## 7. List of publications:

**PhD thesis:**

**A. Hashemi**, "Seismic Resilient Multi-story Timber Structures with Passive Damping," A thesis submitted for fulfilment of the requirements of the degree of Doctor of Philosophy, University of Auckland, Auckland, New Zealand**.**

**Journal papers:**

**A. Hashemi**, P. Zarnani, and P. Quenneville, "Damage Avoidance Self-Centering Steel Moment Resisting Frames (MRFs) Using Innovative Resilient Slip Friction Joints (RSFJs)," Key Engineering Materials, vol. 763, pp. 726–734, 2018.

**A. Hashemi**, P. Zarnani, R. Masoudnia, P. Quenneville, "Seismic resilient lateral load resisting system for timber structures," Construction and Building Materials, vol. 149, pp. 432–443, 2017.

**A. Hashemi**, P. Zarnani, R. Masoudnia, P. Quenneville, "Experimental testing of rocking Cross Laminated Timber (CLT) walls with Resilient Slip Friction (RSF) joints," Journal of Structural Engineering (USA), vol. 144, Issue 1, pp. 04017180-1 to 16, 2017.

**A. Hashemi**, P. Quenneville, "Earthquake resilient timber structures using Cross Laminated Timber (CLT) walls coupled with Resilient Slip Friction Joints (RSFJs)," New Zealand Timber Design Journal, vol. 25, Issue 3, pp. 12-19, 2017.

**A. Hashemi**, P. Zarnani, R. Masoudnia, P. Quenneville, “Seismic resistant rocking coupled walls with innovative Resilient Slip Friction (RSF) joints,” Journal of Constructional Steel Research, vol. 129, pp. 215–226, 2017.

**A. Hashemi**, P.Zarnani, R. Masoudnia, P. Quenneville, “Novel self-centring friction damping system for seismic resistant cross laminated structures,” New Zealand Timber Design Journal, vol. 24, pp. 10-17, 2016.

**A. Hashemi**, R. Masoudnia, P. Quenneville, “Seismic performance of hybrid self-centering steel-timber rocking core walls with slip friction connections,” Journal of Constructional Steel Research, vol. 126, pp. 201-213, 2016.

**A. Hashemi**, R. Masoudnia, P. Quenneville, “A numerical study of coupled timber walls with slip friction damping devices,” Construction and Building Materials, vol. 121, pp. 373–385, 2016.

**Conference papers:**

**A. Hashemi**, S.M.M Yousef-Beik, B. Zaboli, F.M. Darani, G.C. Clifton, P. Zarnani, P. Quenneville, “Seismic Performance of Resilient Slip Friction Joint (RSFJ) Brace with Collapse Prevention Mechanism”, Proceedings of New Zealand Society for Earthquake Engineering Conference (NZSEE), Auckland, New Zealand, 2018.

**A. Hashemi**, P. Zarnani, P. Quenneville, “Earthquake Resilient Cross Laminated Timber (CLT) lateral load resisting system with innovative Resilient Slip Friction Joints (RSFJs)”, Proceedings of , Structural Engineering Society of New Zealand Conference (SESOC), Wellington, New Zealand, 2017.

**A. Hashemi**, P. Zarnani, P. Quenneville, “Seismic resilient structures with Cross Laminated Timber (CLT) walls coupled with innovative Resilient Slip Friction (RSF) joints”, Proceedings of New Zealand Society for Earthquake Engineering Conference (NZSEE), Wellington, New Zealand, 2017.

**A. Hashemi**, P. Zarnani, R. Masoudnia, and P. Quenneville, “Seismic Resistant Cross Laminated Timber (CLT) Structures with Innovative Resilient Slip Friction (RSF) Joints,” in World Conference of Earthquake Engineering (16WCEE), Santiago, Chile, 2017.

**A. Hashemi**, P. Zarnani, A. Valadbeigi, R. Masoudnia, P. Quenneville, “Seismic Resistant Timber Walls with New Resilient Slip Friction Damping Devices,” International Network of Timber Engineering Research Conference, Graz, Austria, 2016.

**A. Hashemi**, W. Y. Loo, R. Masoudnia, P. Zarnani, P. Quenneville, “Ductile Cross Laminated Timber (CLT) Platform Structures with Passive Damping,” in World Conference of Timber Engineering WCTE2016, Vienna, Austria, 2016.

**A. Hashemi**, P. Zarnani, A. Valadbeigi, R. Masoudnia, P. Quenneville, “Seismic resistant cross laminated timber structures using an innovative resilient friction damping system”, Proceedings of New Zealand Society for Earthquake Engineering Conference (NZSEE), Christchurch, New Zealand, 2016.