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

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A B S T R A C T

While structures with conventional lateral force resisting systems are designed to meet the life safety criteria for the residents during and after a seismic event, they are allowed to tolerate the expected structural damage. This damage might be because of the residual displacements after the earthquake or the lack of ductility in the system. Despite the fact that the allowable damages are intended to be repairable, however, in most cases the repairs are highly uneconomical. A self-centring hybrid steel-timber rocking core wall system (SC-RW) is developed to provide sufficient ductility in addition to a significant amount of energy dissipation while it limits the residual drift and the associated damage. This system is comprised of one or more rocking cross laminated timber (CLT) walls with slip friction connections as the main lateral resisting system and steel beams and columns to resist against gravity loads. Horizontally oriented post-tensioned strands through the beams provide additional moment resistance at the beam-column interface to re-centre the structure after the earthquake. The efficiency of the proposed system is investigated under cyclic and seismic loading regimes. Furthermore, a preliminary displacement based design approach for a SC-RW system is introduced. Dynamic time-history simulations confirm an excellent behaviour in terms of drift capacity, residual displacement and peak roof accelerations.

1. Introduction

Structural walls provide excellent seismic resistance and are commonly used as the main lateral resisting system in buildings. During the past seismic events, these walls were found to represent superior seismic performance compared to other alternative structural members [1–3]. Those walls constructed with prefabricated components have additional advantages including offsite fabrication, improved quality and speed of construction. During the 1994 Northridge earthquake, several commercial precast parking structures experienced significant damage [2], however, this damage was mainly because of incompatibilities between the lateral and gravity resisting systems and no considerable damage was observed in the walls themselves. Furthermore, during the 1995 Kobe earthquake, precast concrete buildings with structural wall systems performed well with negligible post-earthquake damages.

Recently, there has been an extensive interest towards the design and construction of multi-story timber structures with engineered wood products such as Cross Laminated Timber (CLT) and Laminated Veneer Lumber (LVL) panels. However, the application of these products in seismic regions as the primary lateral resisting system was limited firstly due to the lack of information about their seismic behaviour, secondly the subsequent restrictions imposed by the design codes and thirdly because of their non-ductile behaviour which leads to relatively high response accelerations. During the large-scale experimental investigation of a seven story building made of CLT panels within the SOFIE project, accelerations as high as 3.8 g were recorded [4]. Despite the fact that these accelerations may be acceptable for human health, they are uncomfortable and unpleasant for the habitants. As an important outcome of the SOFIE project, other research studies were commenced in order to mitigate the earthquake damage by developing new solutions to absorb the seismic energy and decrease the ensuing response accelerations.

This study seeks to develop an innovative steel-timber rocking core as the main lateral force resisting system to efficiently lessen the post-earthquake damage. This system includes supplementary slip friction dampers to dissipate the seismic energy along with high strength post-tensioned steel strands through the beams to self-centre the structure after the earthquake. The efficiency of this system is inspected through displacement control quasi-static analyses. Furthermore, a displacement based design approach is introduced to design the system in accordance with the induced seismic loads. Finally, the designed system is subjected to dynamic time-history simulations to investigate its seismic performance in terms of provided ductility, self-centring capacity and the peak roof accelerations.

2. Research background

Rocking mechanism for earthquake protection dates back to the Greek era, where segmental construction of columns led to gap opening

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at the joints when exposed to seismic activity. However, it was not until 1950s that it had been studied for application in seismic resistant structures. Housner is recognized as the first researcher to investigate the rocking behaviour to describe why many slender and tall structures survived the 1960 Chilean earthquake [5]. Palermo et al. proved that utilizing the "controlled rocking" concept in bridge systems is an effective alternative for the traditional systems [6]. The possibility of accommodating the inelastic demand at the specific elements (mild steel bars in that case) when rocking takes place, led to a significant damage reduction in the pier component. Ma et al. proposed simplified mathematical expressions derived from the equation of motion [7]. As a practical example of the application of rocking behaviour in seismic resistance structures, the South Rangitikei rail viaduct in New Zealand can be mentioned [8,9]. That structure was designed to allow for rocking of the piers on the pile cap which resulted in notable decrease in the base shear demand.

Henry et al. proposed the PreWEC system (precast concrete wall with end columns) for earthquake resistant structures [10]. This system comprised of single or multiple precast concrete walls attached to end columns with special energy dissipative connectors. The efficiency of the proposed system has later been validated by experimental tests [11]. Iqbal et al. studied the application of U-shaped Flexural Plates (UFPs) as supplementary damping devices in post-tensioned LVL timber coupled rocking walls [12]. The system had later been experimentally investigated and a design procedure was proposed [13]. Sarti et al. tested coupled LVL walls with UFP connectors and also with fuse type damping devices at the base of the walls [14]. The results was promising in terms of energy dissipation rate and the residual damage.

Loo et al. introduced the application of symmetric slip friction hold-downs for LVL rocking timber shear walls [15]. A symmetric slip friction hold-down offers a bidirectional hysteretic behaviour results in efficient energy dissipation. Furthermore, it provides constant resistance force against the overturning moment. The proposed configuration had later been experimentally tested and demonstrated a stable hysteretic behaviour which is the key characteristic of a low damage system [16].

After the Northridge earthquake, multiple new concepts for steel frames were developed which were intended to lessen the onsite welding as much as possible and also to avoid high inelastic deformations caused by the yielding of the members [17]. Ricles et al. proposed an alternative moment connection for steel structures with significant reduction in residual damage in the beams and little remaining lateral drift after an earthquake [18]. In the proposed concept, high strength steel strands are employed to self-centre the structure. Additionally, the inelastic deformations were localized at the connections by the opening of the gap in the beam-column contact surface. This concept was further developed by several researchers on account of its simplicity and excellent behaviour under quasi-static and dynamic loads in terms of stiffness, strength and deformation capacity. Garlock et al. introduced a step by step design approach for steel PT frames based on the lateral applied forces [19]. Tsai el al. designed and tested four PT steel moment frames under cyclic loads [20]. They reported stable and efficient performance providing that the lateral drift is under 5%. Kim et al. combined the PT frames with frictions dampers installed on the top and bottom flanges of the beams [21]. The experimental results exhibited stable cyclic response, insignificant strength degradation and almost no residual drift. Lin et al. developed and tested a full scale PT steel moment frame with friction dissipative devices attached to the bottom flange of the beams [22].

Most of the previously developed self-centring mechanisms for hybrid rocking walls were focused on the application of vertical post-tensioned cables up the height of wall while they are anchored to the foundation. Although this system demonstrated a promising self-centring behaviour, however, the relaxation of the cables because of the imminent creep in the wood lessens the efficiency of the system [23,24]. This study presents an alternative low damage rocking core wall system that can efficiently absorb the seismic energy through slip friction damping devices. Additionally, the system is able to accommodate the uplift and rotation incompatibility at the floor to wall connection which might cause a substantial damage to the floor diaphragm.

3. Self-centring Rocking Wall (SC-RW) system with friction dampers

In this paper, a novel system consisting of rocking timber walls with slip friction damping devices and beam to column post-tensioned connections is proposed. As Fig. 1 shows, the Self-centring Rocking wall system, referred in short as SC-RW system, is comprised of different structural components: (i) rocking timber walls which normally are massive wooden panels such as Cross Laminated Timber (CLT) or Laminated Veneer Lumber (LVL) (they are the main lateral load resisting elements in the system) (ii) slip friction connections which connects the wall to the base and to the adjacent walls or columns (these connections absorb the energy through sliding) (iii) special steel beam (or floor) to wall connection which transfers the horizontal loads from the diaphragm to the walls yet is isolated from relative vertical movement between the floor and the rocking wall. These connections can accommodate the displacement incompatibility between the floors and the walls during rocking (iv) steel columns designed to resist the gravity loads transferred through steel beams (they are pin jointed to the base) (v) post-tensioned connections between the beams and

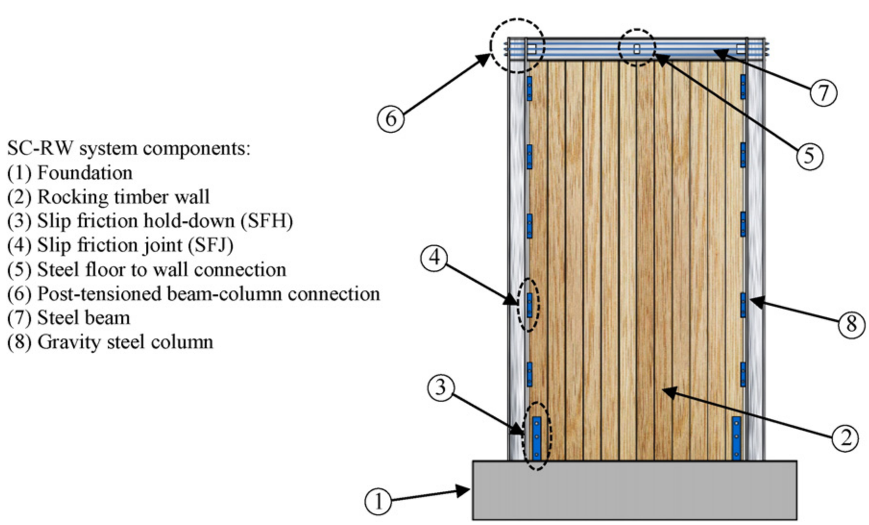

Fig. 1. General arrangement of the SC-RW system.