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SEISMIC RESISTANT CROSS LAMINATED TIMBER (CLT) STRUCTURES WITH INNOVATIVE RESILIENT SLIP FRICTION (RSF) JOINTS

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Abstract

Multi-story timber structures are becoming progressively desirable for engineers and building owners owing to their aesthetic and environmental benefits and to their higher strength to weight ratio compared to other construction materials. Moreover, there is an increasing public pressure to have low damage structural systems to minimize the earthquake destruction after moderate to severe seismic events. This is important as the building could be reoccupied quickly with minimal business interruption and repair costs. A recent trend in timber building industry is toward cross laminated timber (CLT) panelised structures. CLT is a relatively novel engineered wood based product well suited for multi-story structures. Due to the precise prefabrication and easy installation of CLT panels, there is an increasing trend towards construction of timber panelised structures using them. Latest research findings have shown that CLT buildings constructed with traditional methods can experience high damages especially at the connections which generally consist of hold-down brackets and shear connectors with nails, screws, rivets or bolts. Several research studies have proven that friction joints can provide a perfectly elastoplastic behaviour alongside a stable hysteretic response under severe seismic excitations. Up until now, the main disadvantage of the frictions joints has been the undesirable residual displacements after a seismic event. The main objective of this study is to develop a ductile low-damage structural system for multi-story residential and commercial timber buildings using the innovative Resilient Slip Friction (RSF) joint. The proposed system includes resilient coupled walls and end column as the main lateral load resisting members. RSF joints are used as hold-down connectors which connects the wall to the foundation and also as ductile links between the adjacent walls or between the walls and steel end columns. The ductility and resilience of such system is provided by the RSF joints.

A series of joint component test has been conducted to experimentally evaluate the hysteretic behaviour of the RSF joints. The test results demonstrated a stable flag-shaped hysteresis which readily exhibits the self-centring behaviour and also a significant rate of energy dissipation representing the damping capacity of the joint. The Damper – Friction Spring Link element function in SAP2000 was used and proved to be able to accurately represent the load-deformation behaviour of a RSF joint. Additionally, displacement-control cyclic analyses of CLT coupled walls with RSF joints showed that this innovative system definitely has the potential to be recognized as an efficient resilient structural systems for timber construction which could be extended to steel and reinforced concrete buildings as well.

Keywords: Resilience; Cross Laminated Timber; Low damage; Energy dissipation

1. Introduction

Multi-story timber structures are becoming progressively desirable for engineers and building owners because of their aesthetic and environmental benefits and further for the higher strength to weight ratio of the wood and engineered wood products. More than that, there is an increasing public pressure to have low damage structural systems in order to minimize the earthquake destruction after moderate to severe seismic events. This is important as the building could be reoccupied quickly with minimal business interruption and repair costs.

Cross laminated timber (CLT) is a new generation of engineered wood product which was firstly developed in Europe in the 1990s and then in other parts of the world [1]. It is a strong, sustainable and dimensionally stable product that offers structural characteristics similar to that of a pre-cast concrete panel yet has relatively higher strength to weight ratio. More than that, CLT structures offer flexible planning and high level of prefabrication which significantly accelerate the construction progress and reduce the overall cost. Thus, CLT has been notably gaining popularity among building owners and designers and numerous CLT buildings have been built in different countries during the last decade.

During the PRESS (PREcast Seismic Structural Systems) program in the early 1990's, a new design approach for structural walls was introduced [2]. It was based on dry joints between the prefabricated panels to localize the inelastic deformation in addition to unbounded posttensioned members to provide re-centring behaviour. The dissipation capacity of such system highly depends on the type of the dissipaters, or sacrificial fuses, between the walls. For timber structures, Palermo et al. conducted preliminary experimental tests on laminated veneer lumber (LVL) walls with different types of fuses [3,4]. The results confirmed the enhanced performance of the system because of the jointed ductile connections. Smith et al. further extended the concept into coupled wall systems [5]. They proved that the design flexibility of the hybrid coupled wall systems combined with the speed of erection creates a significant potential for the construction of multi-story buildings. Iqbal et al. studied the application of U-shaped Flexural Plates (UFPs) as supplementary damping devices in post-tensioned LVL timber coupled rocking walls [6]. That concept had later been experimentally investigated and a design procedure was proposed [7]. The test results demonstrated an efficient energy dissipation mechanism over yielding the UFPs during the earthquakes. Sarti et al. experimentally investigated the seismic performance of the hybrid rocking walls with end columns [8]. Iqbal et al. tested coupled posttensioned rocking LVL walls with sacrificial nailed plywood sheets as hysteretic dampers [9]. The experimental results affirmed the performance of the system. Nevertheless, relatively lower hysteretic stability was observed compared to the similar systems with UFPs.

Passive friction based damping devices were originally proposed for steel structures. Popov et al. introduced symmetric slotted bolted connections which dissipates energy through friction during equilateral tension and compression cycles [10]. Popov's comprehensive experiments showed a stable rectangular shape hysteresis. Clifton et al. proposed the asymmetric sliding hinge joint for steel moment resisting frames which had non-rectangular yet stable force-deformation behaviour [11]. Khoo et al. developed design models for the asymmetric slotted bolted connections based upon numerous experiments and rigorous analyses [12].

For the first time in timber structures, Filiatrault used friction dampers in timber sheathed shear walls [13]. The results exhibited a significant improvement in hysteretic behaviour of the walls while large amount of seismic energy was absorbed. Loo et al. investigated the application of slip friction connections as a replacement of traditional hold-downs in LVL rocking walls [14,15]. The experiments showed excellent seismic performance in terms of hysteretic behaviour and minimized residual deflections. Additionally, and most importantly, the timber wall remained in the elastic region after several quasi-static tests and dynamic numerical analysis.

This paper presents research into CLT coupled rocking walls with innovative Resilient Slip Friction (RSF) joints [16] as the hold-down connections and ductile links between the adjacent walls or columns. A simple procedure to design the system is described and the results of RSF joint component tests are presented. Furthermore, a numerical model is developed to demonstrate the seismic performance of the proposed system. To investigate the seismic performance, the model is subjected to quasi-static displacement control cyclic loads.

1. Resilient Slip Friction (RSF) Joint

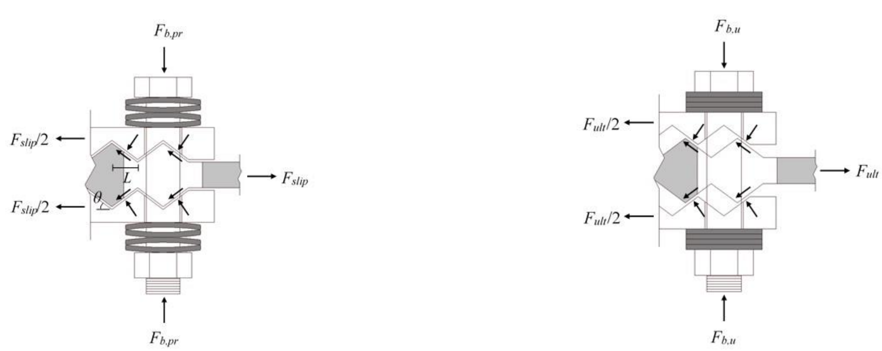
The concept of slip friction connections using flat steel plates sliding over each other has already been confirmed as an effective structural damping solution [11,17], [18]. The energy absorption mechanism of friction joints is one of the most efficient amongst passive devices. Nevertheless, the lack of re-centring behaviour in these joints requires the use of an additional system to bring back the structure to its initial position after a seismic event, which is always costly. One of the common techniques for providing self-centring is the use of post-tensioned tendons which has two major drawbacks. Firstly, approximately 30% (or even more in some cases) of tendon force losses can occur during the service life of the structure which considerably decreases the efficiency of the system [19]. To reduce the total loss, restressing of the cables is required which is only possible with a special type of accessible anchorage. Secondly, the post-tension force is highly depended on the humidity of the environment. Although controlling the humidity reduces the losses, however, it is not possible to control it in all situations.

In this paper, a novel friction joint is presented in which the components are formed and arranged in a way that the self-centring behaviour is achieved as well as damping, all in one device. Fig.1 shows the components and the assembly for the Resilient Slip Friction (RSF) joint [16]. The specific shape of the grooves combined with the use of Belleville washers (conical disc springs) and high strength bolts provide the desirable self-centring behaviour. The angle of the grooves is designed in such a way that at the time of unloading, the reversing force induced by the elastically compacted Belleville washers is larger than the resisting friction force between the surfaces. As a consequence, the elastic force of the washers re-centres the slotted plate to its initial position. Note that Fig.1 exhibits a double acting RSF joint in which two centre slotted plate are used.

(a) (b) (c)

Fig. 1 – RSF joint: a) Cap plates and slotted centre plates b) Belleville washers and high strength bolts c) Assembly

A design procedure has been developed for the capacity prediction of the RSF joint based on the free body diagrams shown in Fig.2 [16,20]. The slip force (F_{slip}) for a symmetric configuration can be determined by Eq. (1). Note that this design procedure is for the symmetric configuration for slip friction connections. Refer to [21] for more information about the differences between symmetric and asymmetric concepts in friction joints. The slip force (F_{slip}) for a symmetric configuration can be determined by Eq. (1).



(a) (b)

Fig. 2 – Free body diagrams for a symmetric RSF joint: a) Before slippage b) Ultimate deflection state

$$F_{slip} = 2n_b F_{b,pr}\left(\frac{\sin\theta + \mu_s \cos\theta}{\cos\theta - \mu_s \sin\theta}\right) \tag{1}$$

Where $F_{b,pr}$ is the clamping force in the bolt due to pre-stressing of the Belleville washers, n_b is the number of bolts, θ is the angle of the grooves and μ_s is the static coefficient of friction. Fig.3 shows the schematic hysteretic loop for a RSF joint. The residual force in the joint at the end of the unloading can be determined by Eq. (2) where μ_k is the kinetic coefficient of friction which can be assumed as $0.85\mu_s$.

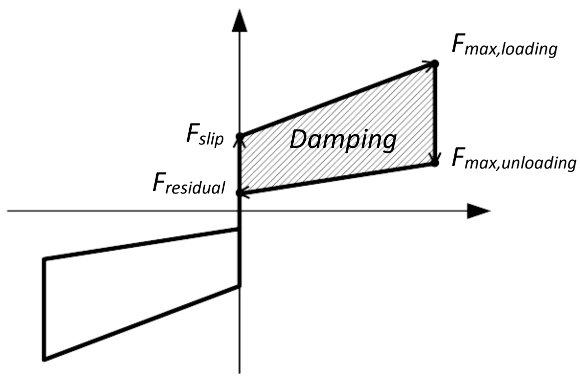


Fig. 3 – Schematic load-deformation loop for RSF joint

$$F_{residual} = 2n_b F_{b,pr}\left(\frac{\sin\theta - \mu_k \cos\theta}{\cos\theta + \mu_k \sin\theta}\right) \tag{2}$$

The ultimate force upon loading ($F_{ult,loading}$) and unloading ($F_{ult,unloading}$) can be calculated by replacing μ_s and $F_{b,pr}$ in Eq. (1) and Eq. (2) with μ_k and $F_{b,u}$, respectively. The ultimate force in the bolt ($F_{b,u}$) can be specified by Eq. (3) in which k_s and Δ_s are respectively the total stiffness of the of washers and their maximum deflection when they are fully compressed (the washers become flat).

$$F_{b,u} = F_{b,pr} + k_s \Delta_s \tag{3}$$

The maximum deflection in a RSF joint is given by Eq. (4) where n_j is the number of joints acting in a series (e.g. n_j equals to 1 for a single acting joint and equals to 2 for a double acting one).

$$\delta_{\max} = n_j \frac{\Delta_s}{\tan\theta} \tag{4}$$

The joint offers a self-centring characteristic providing that Eq. (5) and Eq. (6) are satisfied. In Eq. (6), L represents the horizontal distance between the top and bottom of a groove.

$$\mu_s < \tan\theta \tag{5}$$

$$L > \frac{\Delta_s}{\sin\theta} \tag{6}$$

3. Resilient Slip Friction (RSF) Joint Component Test

In order to experimentally investigate the hysteretic behaviour of the RSF joint, a series of joint component tests were conducted. Fig.4 displays the components and the assembly of the manufactured specimen which was a symmetric double acting RSF joint comprised of two centre slotted plate and two cap plates. The cap plates were manufactured using mild steel grade 350 and the centre plates were fabricated with high strength Bisplate 80 steel. The angle of the grooves was 15 degrees in order to maximize the deformation capacity of the joint. Two 220 mm by 75 mm mild steel stiffener plates had later been welded to the cap plates to restrain them against out of plane bending.

(a) (b) (c) (d)

Fig. 4 – RSF joint specimen: a) Cap plates and centre plates b) Belleville washers c) Assembly d) Test setup

The Belleville washers (conical disk springs) have maximum capacity of 110 kN and maximum deflection of 1.5 mm at the flat state. Two high strength 8.8 grade bolts with nine spring washers per side (washers were a series arrangement) are used. Table 1 presents the calculated design parameters and the capacity of the RSF prototype based on the described design procedure in the previous section.

Table 1 – Characteristics of the tested RSF joint

Item	n_b	μ_s	**Washer Thickness (mm)**	**Washer Height (mm)**	**Washer Capacity (kN)**	**Number of Washers Per bolt**
Value	2	0.19	6.5	8.0	110	18

For the tests of this section, a maximum connector deformation of 30 mm was used. The displacement schedule (see Fig.5(a)) was based on that adopted by Loo et al. [17] and only allowed upward movement as would be the case if the device were implemented as a hold-down connection for a shear wall. It should be pointed out that the previous experimental tests on different configurations of RSF joints have shown that this device can perfectly exhibit similar behaviour in both negative and positive displacements if it is designed for such as purpose [20].

The machine that was used for the tests was the Instron Universal Test Machine capable of performing both low and high force testing up to 100 kN. The load cell is mounted on the crosshead above the RSF prototype while the displacement was measured using a Linear Variable Differential Transducer (LVDT) device attached to the cap plates. To avoid a possible overpowering of the Instron machine, a maximum loading rate of 0.5 mm/s was adopted.

Altogether three tests were carried out on the RSF joint with 15, 24 and 31 kN of slip force (F_{slip}). In order to achieve these forces, the Belleville spring washers were compacted using the turn-of-nut method, in which the number of rotations of the nut required to achieve a targeted deflection was determined by dividing this deflection to the pitch of the threaded bolts. The resultant load-deformation curves for the three conducted tests are illustrated in Fig.5. Note that a specific lubricant is used between the cap plates and centre plates to increase the durability of the friction surfaces by controlling the possible galling and rusting. In this way, the static coefficient of 0.19 was found for the tested device.

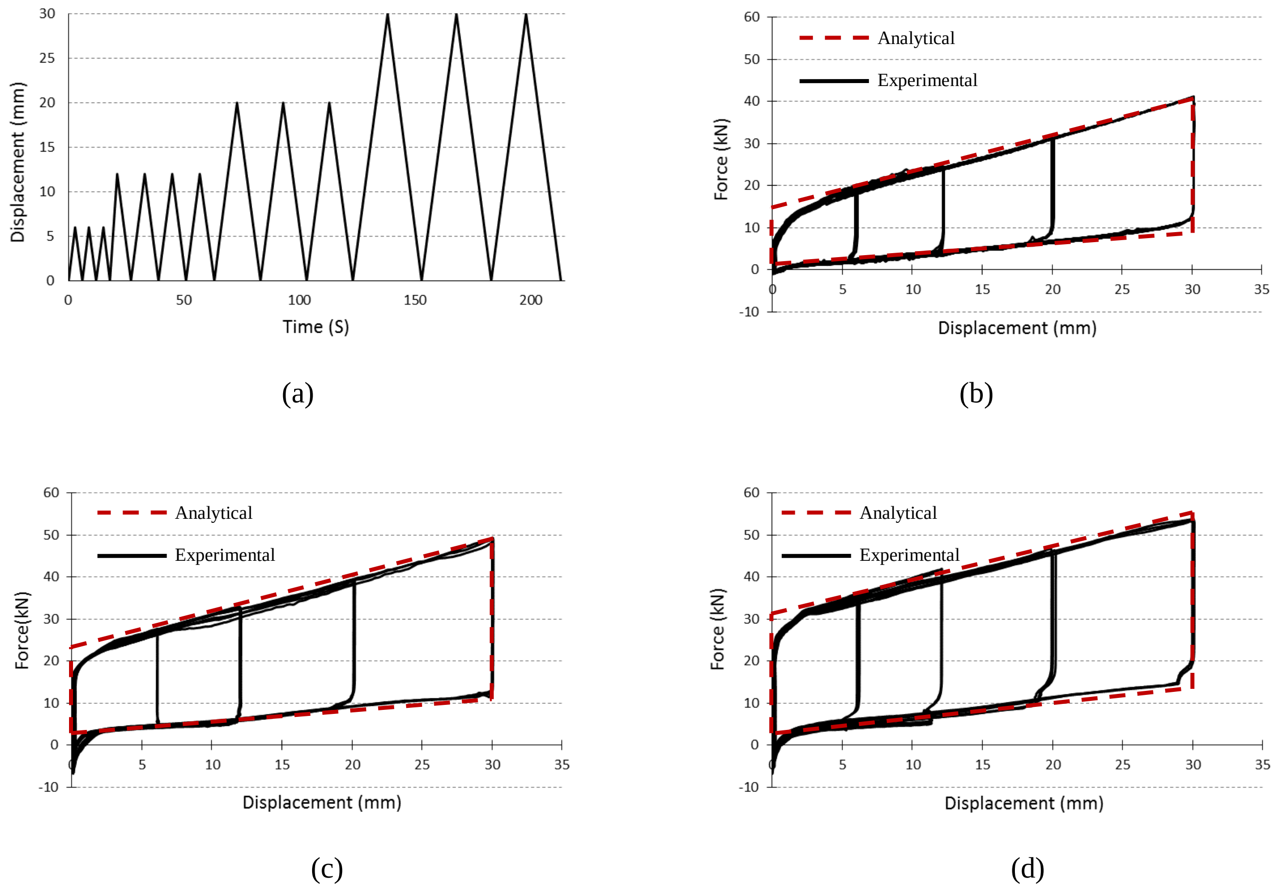
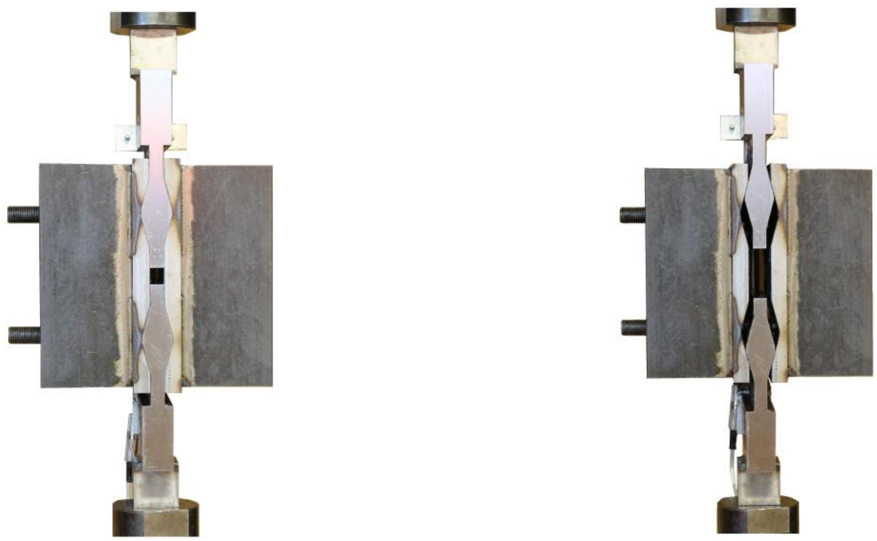


Fig. 5 – RSF joint experimental test: a) Displacement schedule b) hysteretic curves for F_{slip} = 15 kN c) hysteretic curves for F_{slip} = 24 kN d) hysteretic curves for F_{slip} = 31 kN

From Fig.5, it can be seen that the load-deformation behaviour of the RSF joint represents "flag-shaped" hysteretic curves which obviously imparts the self-centring behaviour as well as energy dissipation. Furthermore, the red dashed line in Fig.5(a), 5(b) and 5(c) shows the behaviour prediction of the joint determined by following the described analytical design procedure in the last section. It can be seen that the proposed equations can closely predict the behaviour of this innovative connection.

It should be noted that as the pre-stressing force in the bolts (consequently F_{slip}) increases, the maximum displacement capacity of the joint decreases. This is because of the pre-compression of the spring washers to provide the targeted slip force. Therefore, an optimized relationship between the slip force and the targeted ultimate displacement should always be targeted in order the have an efficient connection. Another important observation from the test results is the stable behaviour of the connection. Symmetric flat slip-friction connections, in which the external mild steel plates slide directly against the hard steel slotted centre plates, have previously demonstrated performance in terms of maintaining strength, stiffness and hysteretic stability [17]. The mentioned characteristics which play a significant role when a low damage seismic solution is aimed for, are observed as well for the RSF joint in addition to the self-centring behaviour. From Fig.5, it can be noticed that the joint maintained its stiffness and strength through numerous cycles of loading and unloading.

Fig.6 shows the configuration of the tested RSF joint before and after slippage. The compaction of the Belleville washers allows the device to be expanded (see Fig.5(b)). Upon unloading, the preserved force in the springs brings back the centre plates to their original position.



(a) (b)

Fig. 6 – RSF joint specimen: a) Before deformation b) After deformation (expansion of the plates)

4. Numerical Modelling of CLT buildings with RSF joints

4.1. The concept of CLT coupled walls with RSF connections

This section describes the numerical modelling of CLT coupled walls with RSF joints. The proposed system consists of coupled CLT walls joined together by two types of RSF joints that are hold-down connections and ductile links. The RSF hold-down device connects each wall to the foundation and the RSF ductile link connects the walls to any adjacent rocking CLT walls and/or the end columns. A schematic view of the proposed concept is displayed in Fig.7.

On the brink of rocking, the acting forces on each wall are RSF hold-down slip force (F_H), the sum of RSF ductile link slip forces ($\sum F_j$) and the vertical loads (W). It should be pointed out that this concept is mainly proposed for structural systems where the lateral load resisting system is separated from the gravity load resisting members. Therefore, the only considered vertical load in this paper is the self-weight of the CLT walls. Nevertheless, the introduced system is capable to mitigate all other types of gravity loads such as permanent and imposed loads.

Taking the moments about the rocking point of each wall, the total slip force for each wall ($F_H + \sum F_j$) can be determined by Eq. (7). If the walls have different geometry or material properties, the slip force for each one can be separately specified by following the same procedure with different h and b.

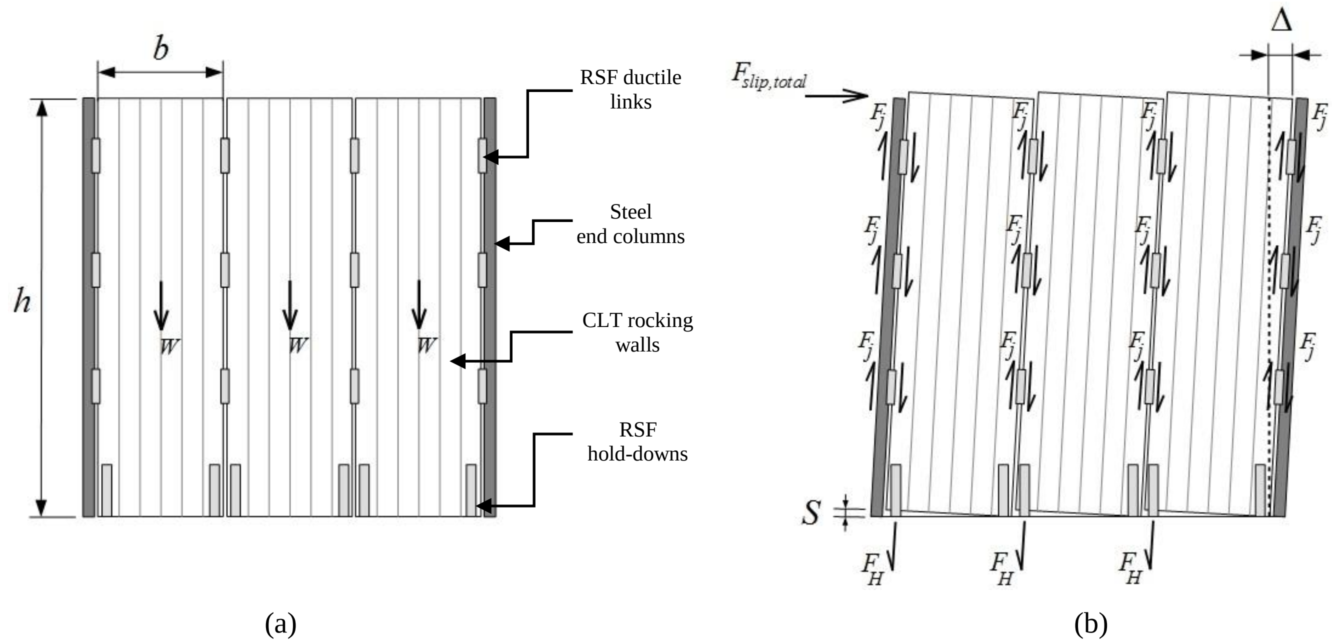


Fig. 7 – The concept of CLT coupled walls with RSF joints: a) Before rocking b) After rocking

$$F_H + \Sigma F_j = F_{slip,total}\frac{h}{b} - \frac{W}{2} \tag{7}$$

The RSF devices can be designed by Eq. (7) considering the fact that sum of the slip forces of the RSF ductile links has to be less than the RSF hold-down slip force. Otherwise, the sliding would first initiate in the hold-downs and the adjacent walls may be locked together. The slot length for RSF ductile links has to be twice that of the RSF hold-downs for the reason that they are designed to slide in both upward and downward directions while the hold-downs are intended to only move upward. Accordingly, the slot length for all hold-downs (S) and ductile links (2S) can be determined by Eq. (8) with respect to the required lateral displacement (Δ) (see Fig.7(b)). If the walls have different geometry, the slot lengths for the connections within each one of them should be calculated separately.

$$S = \Delta * \frac{b}{h} \tag{8}$$

4.2. Damper – Friction Spring Link Element

In order to model the RSF load-displacement behaviour, the Damper – Friction spring Link element in SAP2000 software package is adopted. This link element which is available in version 17 and above has many parameters. In order to model the RSF hysteretic behaviour, these parameters should be accurately calibrated in accordance with the design parameters of the RSF joint such as slip force, loading stiffness, maximum loading force, maximum unloading force and the residual force. To verify the accuracy of this link element in prediction of a RSF joint, a numerical model in SAP2000 is developed based on the experimental data of the tested RSF joint with a slip force of 15 kN (see Fig.(b)). The calibrated parameters for the friction spring link element are presented in Table 2. These parameters were determined according to the characteristics of the tested RSF specimen and the specifications of the associated Belleville springs.

Table 2 – Design parameters for the Damper – Friction Spring Link Element

Slipping stiffness (loading) (N/mm)	Slipping stiffness (unloading) (N/mm)	Pre-compression displacement (mm)	Stop displacement (mm)
828	156	-18.12	86.5

Fig. 8 compares the numerically obtained hysteretic loop with the experimental results. It can be seen that the Damper – Friction Spring Link element can accurately predict the load-displacement behaviour of a RSF joint. Because the RSF joint can represent a similar behaviour in tension and compression if it is designed for this purpose, the Spring Link element can accordingly be defined to respectively work in both directions.

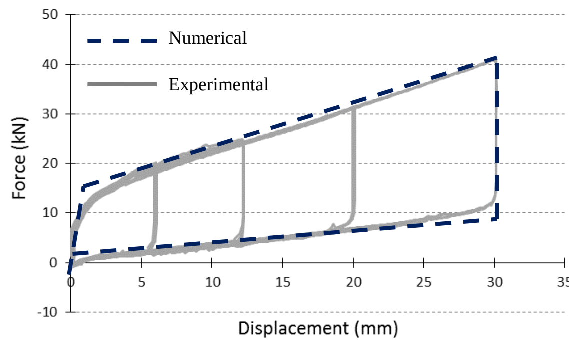


Fig. 8 – Comparison of the Friction Spring Link element and experimental data

4.3. Maximum Force in a Rocking CLT Walls with RSF joints

This study seeks to develop a low damage seismic solution comprised of rocking CLT walls with innovative RSF joints. In all low damage concepts in timber structures, the key point is that timber elements have to remain elastic including any connection between the timber and steel components and the ductile behaviour should be provided by the steel connections. These connections can be traditional mechanical fasteners such as nails, rivets and screws or can be more advanced connectors such as RSF joints. Accordingly, the first step in the design and modelling of CLT rocking walls with RSF joints is to determine the maximum tolerable lateral force at the top of a wall (F_E) which will allow the wall panel to remain elastic.

In order to evaluate the response of the CLT walls subjected to lateral loads, a 200 mm thick CLT wall (which will be used further in the numerical model) was modelled using the ABAQUS software package. The wall is 2 m wide and 8 m tall. All of the timber boards within the panel (longitudinal and transverse layers) were assumed to have a thickness of 45 mm, a width of 183 mm and an elastic modulus of 12000 MPa (MSG12 timber [22]) along the board's main axis (parallel to grain). The density of the timber was assumed as 540 kg/m^3. The timber boards were tied together at top and bottom to represent the glued surfaces. The only assumed value for the applied vertical loads was the self-weight of the panel. From the numerical analyses, it was found that the maximum horizontal force at the top of each wall that would result in the CLT boards reaching their characteristic strengths (f_t = 14 MPa and f_c = 25 MPa) is F_E = 87.6 kN (equals to overturning moment of 700.8 kNm). Fig.9 shows the general arrangement of the developed numerical model including the mesh and stress distribution. This numerical approach for modelling of CLT panels has previously been used by the authors and demonstrated promising results [18],[20],[23],[24],[25].

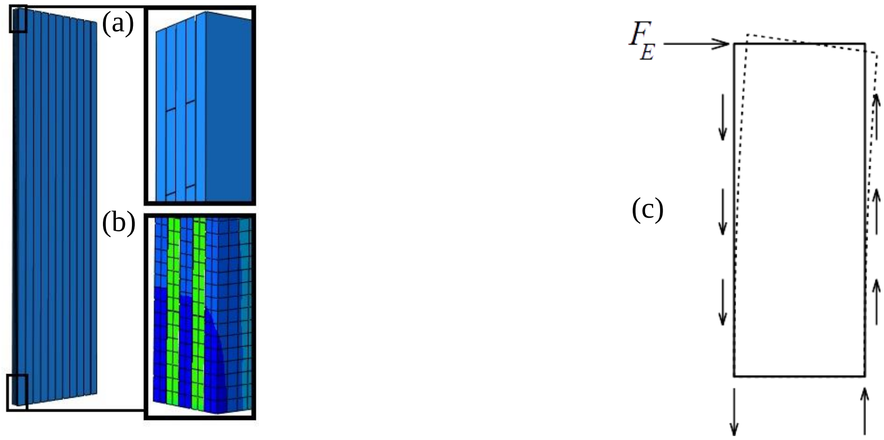


Fig. 9 – Numerical model of the CLT wall: a) Assembly b) Stress distribution c) Elastic deflection of the wall

4.4. Displacement-Control Quasi-Static Analyses of CLT Coupled Rocking Walls with RSF joints

The general arrangement of the proposed coupled wall system to be studied under displacement-control cyclic loading in SAP2000 is displayed in Fig.10. The system consists of three identical CLT walls with 8 m height and 2 m length. The walls have a thickness of 200 mm with the material properties similar to the wall model that was described in section 4.3. The investigated system includes two 400*400*10 mm steel box columns at the ends which are assumed to be pinned to the base. All three walls are attached to the foundation by RSF hold-downs. Furthermore, the walls are connected to the adjoining panels and/or the adjacent steel columns by RSF ductile links. The RSF joints are designed in accordance with the proposed design procedure in section 2 and also Eq. (7) and Eq. (8). Considering a self-weight of 17 kN for each one of the walls and based on the numerically obtained F_E = 87.6 kN from section 4.3, the maximum forces for the RSF joints attached to each wall are determined as 220 kN for the RSF hold-downs and 40 kN for the three assumed RSF ductile links along the edge of the walls (Eq. (7)). In this model, F_{slip} is considered as 40% of the maximum load in the joint ($F_{max,loading}$). However, for multi-story buildings, F_{slip} should be specified based on the Ultimate Limit State (ULS) earthquake loads and the total stiffness of the Belleville washers that are exploited. Also, the CLT panel is modelled using layers shell element.

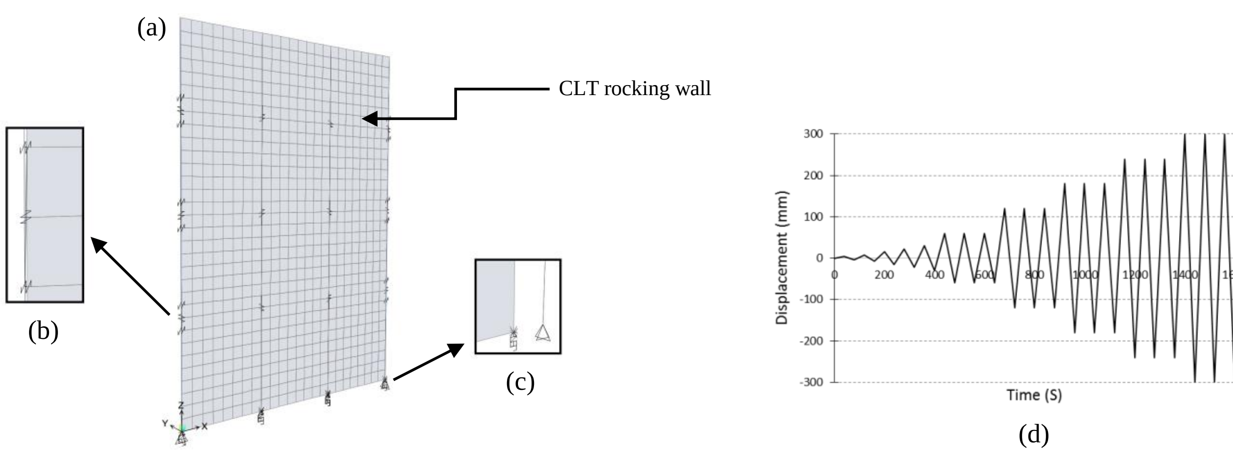


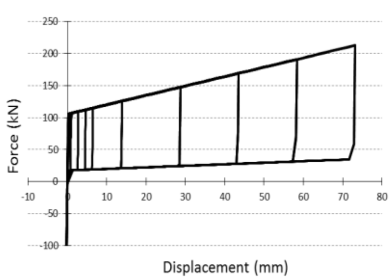
Fig. 10 – Numerical model of the CLT coupled walls with RSF joints: a) General arrangement b) RSF ductile link c) RSF hold-down d) Displacement-control load schedule

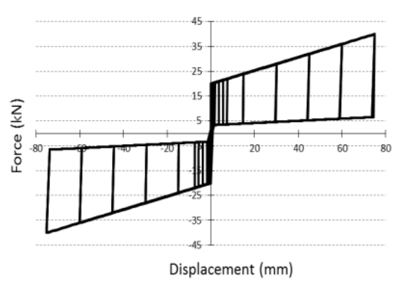
The RSF joints are modelled using the Damper – Friction Spring Link Element. The calculated design parameters are presented in Table 3. The displacement-control load schedule in Fig.10(d) is applied at the top of the system to evaluate the total load-deformation behaviour. The maximum displacement in the load schedule is 300 mm representing 3.75 % of lateral drift.

Table 3 – Design parameters for the Damper – Friction Spring Link Elements representing the RSF joints

Value	Slipping stiffness (loading) (N/mm)	Slipping stiffness (unloading) (N/mm)	Pre-compression displacement (mm)	Stop displacement (mm)
RSF hold-down	1467	242	-75	75
RSF ductile link	267	44	-75	75

Fig.11 shows the numerical response of the system under the applied cyclic load regime. It is observable that the RSF hold-downs and the RSF ductile links have a flag-shaped hysteretic behaviour. Fig.11(c) illustrates the total lateral response of the coupled wall system. It can be seen that the system exhibits self-centring behaviour which can be attributed to the hysteretic behaviour of the exploited RSF joints. It should be emphasized that the only considered vertical load in this model is the self-weight of the wall. This means that the self-centring behaviour of the proposed structural system does not rely on the gravity loads neither on the use of post-tensioned cables. Moreover, Fig.11 evidently demonstrates the low damage characteristic of the proposed system as the hysteretic behaviour remained stable after numerous cycles of loading and unloading. Hence, the bounded area between the hysteretic loops increases over time. This clearly represents a significant rate of energy dissipation which furthers confirms the potential to have a resilient low damage seismic solution. Further experimental and analytical studies are being conducted by the authors to extend this innovative technology to different structural systems.





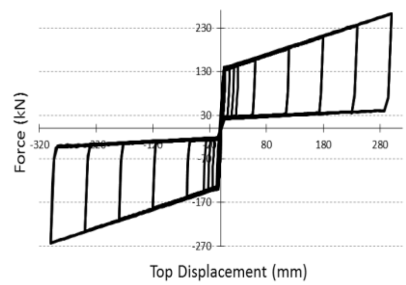


Fig. 11 – Numerical results of the CLT coupled walls with RSF joints: a) RSF hold-down hysteresis b) RSF ductile link hysteresis c) Total load-deformation behaviour of the system

5. Conclusions

From this study, it is evident that there is potential to significantly improve the seismic performance of timber structures by using the innovative Resilient Slip Friction (RSF) joints. Experimental joint component tests carried out on a RSF joint with three different levels of slip force exhibited stable flag-shaped hysteretic loops demonstrating the re-centring capacity as well as energy dissipation.

The Damper – Friction Spring link element in SAP2000 is introduced to represent the RSF joints in numerical modelling and the consequent numerically obtained hysteresis is validated by the component test results. A new structural system comprised of rocking CLT walls with RSF hold-downs at the foundation level and RSF ductile links along the edge of the panels is introduced. This system also includes steel end columns to de-couple the vertical movements of the perpendicular walls due to bi-directional rocking motion. The preliminary numerical results evidently confirms the potential to have a new resilient structural system for timber construction. The resilience of the system is attributed to the hysteretic behaviour of the RSF joints. Therefore, the proposed structural system can effectively be extended to steel and reinforced concrete structures.

6. Acknowledgment

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