ABSTRACT

Multi-storey Cross-Laminated Timber (CLT) buildings are gaining popularity throughout the world due to their many constructive and environmental advantages. Several researchers have proposed the use of post-tensioned rocking connections to improve the seismic performance of timber walled buildings. Although experimental results show that this system has a ductile behaviour and good energy dissipation characteristics, previous research also suggests that high inter-storey drifts and floor accelerations can develop in medium and high-rise timber buildings during earthquakes causing excessive non-structural and content damage. This paper studies the possibility of incorporating inerter-based dampers to reduce these demands and improve the overall seismic performance of Rocking CLT Walled buildings. Firstly, the seismic performance of a series of benchmark buildings designed using Direct Displacement Based Design (DDBD) procedures is assessed. Multiple Stripe Analyses (MSA) are performed to study the response of the buildings for a wide range of seismic intensity levels. The structural performance is examined in terms of peak inter-storey drifts and floor acceleration demands. Secondly, a Tuned InerterViscous Damper (TIVD) system is designed to obtain an effective mass ratio for the first mode of $\mu_r=0.1$. A numerical model for the TIVD is defined and incorporated into the structural models previously analysed. Response history analyses are then performed on complete numerical models and the corresponding performance parameters compared in order to assess the effectiveness of the protective measure.

Keywords: Cross-Laminated Timber; Post-tensioned Timber Buildings; Inerter; Tuned InerterViscous Dampers.

1. INTRODUCTION

Multi-storey Cross-Laminated Timber (CLT) buildings are gaining popularity throughout the world due to their many constructive and environmental advantages. Over the last years, several medium rise CLT buildings have been built around the world, mostly in non-seismic areas (Wells, 2011). One of the limiting factors for CLT construction in seismic regions has been the low deformation capacity of the mechanical connectors traditionally employed (Málaga-Chuquitaype et al. 2016, Demirci et al. 2018). To overcome this issue, several researchers have proposed the use of hybrid post-tensioned rocking connections. Although experimental results show that this system has a ductile behaviour and good energy dissipation characteristics, previous research suggests that high inter-storey drifts and floor accelerations can develop in medium and high-rise timber buildings during earthquakes causing excessive non-structural and contents damage (Ceccotti et al. 2006; Newcombe, 2011). One alternative to tackle this issue is the incorporation of a relatively new seismic control device called inerter. The inerter is a linear mechanical component that develops a resisting force proportional to the relative acceleration between its terminals (Smith, 2002). During the last decades, several inerter-based dampers have been proposed combining inerter with springs, tuned mass dampers and viscous energy dissipation (Giaralis and Taflanidis, 2015). When amplifying mechanisms such as ball-screw or geared wheels are used, high levels of vibration isolation can be achieved with low amounts of added mass (Ruiz et al. 2017).

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This work studies the possibility of incorporating inerter-based dampers to reduce inter-storey drifts and floor acceleration demands, and improve the overall seismic performance of low and mid-rise Rocking CLT Walled buildings.

Firstly, the structural systems under consideration and the results of the seismic design procedure are described. Three different buildings are considered in order to assess the performance of low and mid-rise post-tensioned timber structures. In a second stage, a Tuned InertioViscous Damper (TIVD) seismic control system is designed based on the methodology proposed by Ikago et al. (2012). A numerical model for the TIVD is developed in OpenSees and incorporated into the structural models of the benchmark buildings. Finally, the seismic performance of the protected and unprotected structures is assessed and compared in terms of peak inter-storey drifts and peak floor accelerations.

2. DESIGN OF BENCHMARK BUILDINGS

2.1 Description of the Prototype Buildings

Three different structures are considered in order to assess the seismic performance of low and mid-rise post-tensioned timber wall systems comprising 3, 6, and 10-storey prototype buildings. These buildings are formed of rectangular 10x12-meter modules with an inter-storey height of 3 meters. Figure 1 shows the plan and elevation view of the structural system. The structural plan, shown in Figure 1, consists of two frames in the Y direction supporting gravity loads, and two UFP-coupled post-tensioned CLT walls providing lateral load resistance in X and Y directions. The length and width of each wall panel are design parameters.

![Figure 1. Plan and elevation view of the structural system considered](image)

A dead load of 2.4 kPa and a live load of 3 kPa are considered for design purposes. The seismic weight, given in Table 1, is computed considering a tributary area of 60 m$^2$ per wall system in each direction. On the other hand, the gravity load per wall system is assumed to be 1/12 of the total weight of the floor.

<table>
<thead>
<tr>
<th>Dead Load, D [kPa]</th>
<th>Live Load, L [kPa]</th>
<th>Seismic D+0.25L [kPa]</th>
<th>Seismic Weight [kN]</th>
<th>Gravity Load [kN]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.4</td>
<td>3</td>
<td>3.15</td>
<td>189</td>
<td>31.5</td>
</tr>
</tbody>
</table>
2.2 Performance-based Seismic Design of the Prototype Buildings

The coupled post-tensioned timber walls were designed following Direct Displacement Based Design (DDBD) guidelines, considering a target drift of 1.2%, a linear displacement profile and an area-based approach for the equivalent damping (Newcombe, 2011). The NZS1170.5 spectrum for Soil D and a hazard factor of $Z=0.3$ was used for the displacement demand. The 5% damping displacement spectrum was reduced to account for the hysteretic damping of the nonlinear structure, considering the $R_\xi$ factor proposed in Eurocode 8. Since the equivalent viscous damping depends on the final design of the structure, the design procedure is iterative. Figure 2a shows the final (reduced) displacement spectra and the effective period of the equivalent SDOF systems.

![Figure 2. a) Design displacement spectra, b) Base moment versus top storey drift response of the structural systems](image)

Since the design displacement corresponding to a drift of 1.2% exceeds the maximum possible spectral displacement for the 10-storey building, the structure was designed for a drift of 1%, compatible with the damping corresponding to that displacement level. Based on the effective period, effective mass and design displacement, the effective stiffness and base shear of each equivalent SDOF structure were obtained. The base shear was then distributed vertically according to the assumed displacement profile. The cross-sectional analysis procedure proposed by Newcombe (2011) was applied for the design of the CLT rocking sections. Figure 2b shows the base moment versus top storey drift response of the prototype buildings considering a linear displacement profile.

3. DESIGN OF THE INERTER-BASED SEISMIC CONTROL SYSTEM

Over the last years, the alternative of using inerter-based dampers as passive vibration-control has gained attention. Already in 1999, Arakaki et al. (1999) developed a Viscous Mass Damper (VMD) consisting of a ball-screw rotatory cylinder within a tube fill with a viscous material. Such device can be modelled as an inerter acting in parallel with a linear dashpot. Based on this device and the concept of Tuned Mass Dampers (TMD), Ikago et al. (2012) proposed a Tuned Viscous Mass Damper by connecting a spring in series with a VMD and assessed the effectiveness of the device for the seismic control of a single-degree-of-freedom (SDOF) structure. In this paper, the feasibility and effectiveness of using Tuned InerterViscous Dampers (TIVDs) for improving the overall response of post-tensioned CLT walled multi-storey buildings is assessed.

The inerter-based seismic control system under consideration consists of TIVDs placed in each level of
the prototype buildings, connected to consecutive stories. The system is designed to obtain an effective mass ratio for the first mode of $\mu_r = 0.1$, such that:

$$\mu_r = \frac{M_{n,s}}{M_{n,p}} = \frac{M_{n,s}}{(\varphi_1)'} [M_p] (\varphi_1) = 0.1$$  \hspace{1cm} (1)$$

where $[M_p]$ is the mass matrix of the primary structure, and $(\varphi_1)$ is the first mode of the unprotected structure. Since the TIVD system is activated by inter-storey drifts of the primary structure, the effective modal mass of the protection system for the first mode can be obtained from (Ikago et al., 2012):

$$M_{n,s} = m_{r,1} \varphi_{1,1}^2 + \sum_{k=2}^{n} m_{r,k} (\varphi_{1,k}^2 - \varphi_{1,k-1}^2)$$  \hspace{1cm} (2)$$

where $m_{r,k}$ is the inertance (or apparent mass) of the interter placed in the $k$-storey, and $\varphi_{1,k}$ is the $k$-th component of the first mode of the unprotected structure. In this study, the inertances are distributed proportionally to the mass of each storey, $m_i$.

$$m_{r,i} = \alpha m_i$$  \hspace{1cm} (3)$$

Combining Equations 1, 2 and 3, the coefficient $\alpha$ required for the desired effective mass ratio, $\mu_r$, can be obtained:

$$\alpha = \frac{0.1 (\varphi_1)'^T [M_p] (\varphi_1)}{m_1 \varphi_{1,1}^2 + \sum_{k=2}^{n} m_i (\varphi_{1,k}^2 - \varphi_{1,k-1}^2)}$$  \hspace{1cm} (4)$$

Since all stories have the same mass, $m$, the distribution of inertances, $m_{r,i}$, is constant throughout the height the buildings. Table 2 shows the values of inertance obtained for each of the buildings under consideration. Although the additional masses are comparable to the masses of each storey, the actual required masses can be reduced by several orders of magnitude with the use of amplifying mechanisms such as ball-screw or geared wheels systems.

The optimum angular frequency and damping ratio of the TIVDs are obtained using the fixed-point method (Saito, 2008). For an equivalent SDOF system of angular frequency $\omega_1$ equal to the fundamental frequency of the primary structure, the optimal angular frequency, $\omega_r^{opt}$, and damping ratio, $\xi_r^{opt}$, of the TIVD are given by:

$$\omega_r^{opt} = \frac{1 - \sqrt{1 - 4\mu}}{2\mu} \omega_1 \hspace{1cm} ; \hspace{1cm} \xi_r^{opt} = \frac{\sqrt{3(1 - \sqrt{1 - 4\mu})}}{4}$$  \hspace{1cm} (5)$$

therefore

$$k_b = (\omega_r^{opt})^2 m_r \hspace{1cm} ; \hspace{1cm} c_d = 2\xi_r^{opt} \omega_r^{opt} m_r$$  \hspace{1cm} (6)$$

Table 2 summarizes the fundamental frequencies of the prototype buildings and the design parameters of the TIVD seismic control systems.

<table>
<thead>
<tr>
<th>Building</th>
<th>$\omega_1$ [rad/s]</th>
<th>$\alpha$</th>
<th>$m_r$ [Ton]</th>
<th>$k_b$ [kN/m]</th>
<th>$c_d$ [kNs/m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-Storey</td>
<td>14.5</td>
<td>0.41</td>
<td>7.91</td>
<td>2105</td>
<td>53.06</td>
</tr>
<tr>
<td>6-Storey</td>
<td>7.1</td>
<td>1.27</td>
<td>24.56</td>
<td>1556</td>
<td>80.37</td>
</tr>
<tr>
<td>10-Storey</td>
<td>5.4</td>
<td>3.16</td>
<td>60.79</td>
<td>2277</td>
<td>152.97</td>
</tr>
</tbody>
</table>
4. NUMERICAL MODELS

4.1 Coupled Post-Tensioned Timber Walls Model

The analytical model for coupled post-pensioned walls proposed by Newcombe (2011) is adapted and implemented in OpenSees (Mazzoni et al., 2009). The structural system can be divided in three main components: timber walls, post-tensioned tendons, and UFP coupling devices. A schematic diagram of the model is shown in Figure 3.

![Schematic diagram of the model](image)

Figure 3. Numerical model of the coupled post-tensioned timber wall system

The CLT wall panels are modelled as a series of Elastic Beam-Column elements, which include axial and flexure deformations. Shear deformations, which can be significant in timber structures, are captured with a horizontal zero-length spring connecting wall elements of successive stories. The CLT-foundation contact zone is modelled with a multi-spring element implemented with a stack of 32 vertical zero length elements allowed to develop only compression forces (ElasticPPGap material) and connected to the free base node through rigid links. The distribution and stiffness of each spring is determined using a Lobatto integration method (Spieth et al. 2004). To transfer the shear force without inhibiting rocking action, the horizontal degree-of-freedom of the bottom and top spring nodes are constrained using the equalDOF command. Secondly, the post-tensioned tendons are modelled as a corotational truss element connected to the central fixed base node and the central top floor node. A tension only bi-linear material model (ElasticPPGap) is used for the post-tensioning steel. An initial strain is applied to the material model such that the post-tensioned tendon strain is at the target value after losses due to the axial deformations of the timber walls. Finally, the UFP devices are modelled using vertical zero-length spring elements with an Elastic Perfectly-Plastic material model. The UFPs nodes are connected to the CLT walls through rigid links, such that when the system rocks the UFP couplers deform. It is assumed that the UFPs have effectively infinite stiffness and that there is a 1 millimetre slip per anchorage. Therefore, the yield point of the devices is at 2 millimetres of axial displacement.

The predictive capabilities of the analytical model have been assessed comparing numerical predictions with experimental results from quasi-static tests (Ganey, 2015). Overall, the moment versus drift responses showed similar stiffness, strength and hysteretic behaviour for low to medium drifts (up to
5\%\). More important differences were observed for higher drifts due to the inability of the model to simulate sudden strength loss caused by damage in the CLT matrix.

4.2 Tuned IneretoViscous Damper (TIVD) Model

4.2.1. Inerter Model

Based on the rack-pynion-flywheel system described by Makris and Kampas (2016), a general analytical model for the inerter was developed and implemented in OpenSees. The proposed model consists of two nodes connected through a rigid link, and an angular mass assigned to the rotational degree of freedom of the system. A schematic diagram of the model is shown in Figure 4. In this figure, Node 1 represents the pivot of the flywheel, whereas Node 2 corresponds to the rack gear. The rack-pinion mechanism, which transforms the horizontal relative displacement between the terminals to a rotation in the flywheel, is modelled through a rigid link between nodes 1 and 2. Since a linear geometric transformation is considered for the link element, the horizontal relative displacement and the rotation of the system are related according to: $d_r = d_{2,1}(t) - d_{1,1}(t) = -\rho \theta$. A rotational inertia, $I_{w1}$, is finally assigned to the rotational degree of freedom in Node 1 to represent the flywheel inertial effect.

![Schematic diagram of the numerical model for the inerter](image)

Figure 4. Schematic diagram of the numerical model for the inerter

The force couple required to impose a relative displacement in the system, $F_R(t)$, can be obtained evaluating the rotational equilibrium at Node 1:

$$F_R(t) = \frac{I_{w1}}{\rho^2} \ddot{d}_r(t) = m_R \dddot{d}_r(t)$$  \hspace{1cm} (7)

Therefore, the reactive force developed by the model is proportional to the horizontal relative acceleration between nodes 1 and 2. As this is the general definition of an inerter, the proposed model can be used to represent not only rack-pinion-flywheel systems, but any type of inerter device. The parameters of the model, $I_{w1}$ and $\rho$, are defined in terms of the inertance, $m_r$, according to Equation 7. Moreover, the proposed model can be combined with different configurations of springs and dashpots in order to represent other forms of tuned inerter-based dampers.

4.2.2. Validation of the Inerter Model

The proposed inerter model was validated comparing the numerical response of a SDOF structure equipped with an inertial damper and the corresponding analytical response. The SDOF-inerter system of period $T=1\text{s}$ and $\mu_r = 0.5$ subjected to a single sinusoidal pulse of 0.5 seconds studied by Makris and
Kampas (2016) was selected as case of study. Figure 5 compares the absolute acceleration, velocity, displacement and transferred force response obtained with the OpenSees model, and the analytical solution of the equation of motion.

![Graphs comparing absolute acceleration, velocity, displacement, and transferred force response](image)

Figure 6. Absolute acceleration, velocity, displacement and transferred force response of the SDOF-inerter system

### 4.2.3. TIVD Model

The Tuned InertoViscous Damper (TIVD) can be modelled as an inerter and a dashpot in parallel connected to a spring in series, as shown in Figure 6. The numerical model described in Section 4.2.1 was used for the inerter device, while a zero-length element with a Viscous Damper Material was used for the dashpot. The spring is represented with a linear-elastic zero length element. The TIVD model was then incorporated into the analytical models of the building constraining the horizontal displacements of the terminals to the corresponding bottom and top nodes of the corresponding storeys.

![Analytical model of the Tuned Viscous Mass Damper (TIVD)](image)

Figure 6. Analytical model of the Tuned Viscous Mass Damper (TIVD)
4. ASSESSMENT METHODOLOGY: MULTIPLE-STRIPe ANALYSIS

For this study, Multiple-Stripe Analyses are performed using the set of 44 far-field records proposed in the FEMA p695 (2009) document. The \( \xi = 5\% \) damped spectral acceleration at the first structural period is chosen as the ground motion Intensity Measure (IM). Since the interest of the analysis is to assess the performance of the structures through a wide range of intensity levels and not only near the collapse point, an equally distributed grid of IMs with a step of 0.1 [g] was used for the analyses. The general response of the buildings is assessed in terms of peak inter-storey drifts and peak floor accelerations.

5. RESULTS MULTIPLE-STRIPe ANALYSES

The results from the multiple-stripe analyses are shown in Figure 7. The performances of the protected and unprotected buildings are compared in terms of the mean Structural State Variable for a given level of Intensity Measure. As discussed previously, the numerical model used to represent the structural system is not able to reproduce the response at large displacements. Therefore, a limit of 5% drift was considered for the analysis of the data obtained from the MSA. This limit is consistent with the objective of the study, which intends to assess the effectiveness of the protective measure for reducing inter-storey drifts and floor accelerations at low and moderate demand levels associated with the higher probabilities of exceedance in the hazard curves.

Figure 7a shows that the effectiveness of the system for reducing inter-storey drifts increases for higher deformation levels. Similar trends can be observed for the 6 and 10-storey buildings (Figure 7b and 7c). Much smaller reductions can be observed in the peak floor accelerations. No significant effect can be observed in the case of the 3-storey building, whereas a small reductive effect can be identified for the 6 and 10-storey structures. The difference in the protection effect for inter-storey drifts and floor accelerations may be partially explained by the design procedure. The TIVD system was tuned to the first mode of the structure, which usually provides most of the structure deformation, whereas higher modes effects are related to high floor accelerations. Moreover, the fixed-point expressions for the optimum displacement magnification factor were used to determine the angular frequency and damping ratio of the TIVD devices.

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**Figure 7b** and **Figure 7c** show the results for 6 and 10-storey buildings, respectively. The performances of the protected and unprotected buildings are compared in terms of the mean Structural State Variable for a given level of Intensity Measure. As discussed previously, the numerical model used to represent the structural system is not able to reproduce the response at large displacements. Therefore, a limit of 5% drift was considered for the analysis of the data obtained from the MSA. This limit is consistent with the objective of the study, which intends to assess the effectiveness of the protective measure for reducing inter-storey drifts and floor accelerations at low and moderate demand levels associated with the higher probabilities of exceedance in the hazard curves.

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b) Peak inter-storey drifts and floor accelerations for the protected and unprotected 6-storey buildings

c) Peak inter-storey drifts and floor accelerations for the protected and unprotected 10-storey buildings

Figure 7. Multiple-stripe analyses

5. CONCLUSIONS

This paper studied the feasibility of incorporating inerter-based dampers to reduce inter-storey drifts and floor acceleration demands in low and mid-rise Rocking CLT Walled buildings. The seismic performance of a set of unprotected benchmark buildings was assessed for a wide range of intensity levels. The performance of the structures was examined in terms of peak inter-storey drifts and floor accelerations. Subsequently, a Tuned InerterViscous Damper (TIVD) seismic control system was designed and incorporated to the structures. A numerical model for the inerter component was proposed and validated with theoretical results. The response history analyses were then repeated and the corresponding performance parameters compared with previous results to assess the effectiveness of the protective measure.

Considerable reductions were observed in the drifts demands for the three structures analysed.
Moreover, the efficiency of the protective measure increased with the magnitude of the lateral deformation. Although the inertial masses used in the TIVDs were comparable to the mass of each storey, the actual required mass can be significantly reduced using amplifying mechanisms such as ball-screw or geared wheels systems. In the case of floor accelerations, no significant improvement was observed for the protected structures. This difference may be partially explained by the first-mode tuning design procedure, and the use of optimum displacement magnification factor expressions in the determination of the angular frequency and damping ratio of the TIVD devices. Techniques to tune the protection system to multiple modes may help to further reduce floor accelerations.

6. ACKNOWLEDGMENTS

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