Reliability of Multi story CLT Shear Wall Structure Considering Connection Uncertainty

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Abstract

Compare to concrete or steel material, timber construction contributes much less carbon footprint and having less self-weight. The use of timber as material construction has not been widely used in several seismic region countries due to the questioning of its seismic resistance. Researches has shown that the main element of CLT shear wall to resist lateral loading is its connection. To have a confidence of CLT shear wall application, uncertainty in shear wall connection need to be considered during the design stage. This study proposes a framework to design CLT shear wall structure considering uncertainty in its connections. This study consists of three parts. The first part is to build a nonlinear link element that could represent CLT hysteresis connection behavior under seismic. It requires calibrating numerical model to comply experimental result. Second stage is to build a numerical model of the CLT wall structure. Beside structure modelling, method to evaluate model subjected to seismic will also be defined. In this case, NTHA (Nonlinear Time History Analysis) will be carried out. Third part is integrating the numerical model into reliability assessment method. For this purpose, M-IS (Multisphere Importance Sampling) used to evaluate the reliability index. Proposed framework has purpose to give design framework of CLT subjected to seismic loading while account connection uncertainty.

Keywords: CLT, Reliability, User Defined Material, Nonlinear Time History Analysis

1. Introduction

Timber is sought as a potential construction material since it possesses relatively small carbon footprint compared to peer structural material such as concrete and steel. Utilization of timber as material construction has not been familiar especially under seismic region due to the questioning of its seismic resistance and reliability. Despite advantage of less carbon footprint and self-weight posed by timber element, strength and energy dissipation capability of timber structure is far less than concrete or steel material structure. In last decade, numerous of study has explored the use of timber element in form of CLT (Cross Laminated Timber) as shear wall or slab in a structure [1-2]. Ratio between self-weight and its lateral load resistance has been an interest in several study. Researches has shown that the main element of CLT shear wall to resist lateral loading is its connection [3-4] as shown in Figure 1.

Lateral seismic energy solely dissipated by CLT connection while CLT will act in linear manner although plasticity has taken place in connection. To accurately model CLT connection configuration and dissipation mechanism is a challenging task in FEM (Finite Element Model). Most researcher simplify connection configuration as nonlinear link connection in FEM. Although this has simplified quite much of connection design stage, CLT has lot of connection configuration variants as shown in Figure 2. Different configuration will impose different nonlinear hysteresis behavior especially in its slipping and degradation behavior.

For this various connection type, flexible hysteresis nonlinear model is required to cope much variants of connection in FEM. Ideal hysteresis model for CLT connection should have parameters that could control range of bond slip and degradation behavior. Aside from hysteresis behavior, study from Verdet et al. [5] point out that stiffness connection from CLT posed a high value of cov (coefficient of variation). To have a confidence of CLT shear wall application subjected to seismic load,

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Figure 1. CLT as shear wall construction

(a) Hold down connection.

(b) Horizontal shear connection.

Figure 2. Various CLT connections.
method to assess failure probability of structure subjected to seismic load.

2 Proposed Modified Saws Hysteresis Model

As explained earlier, ideal hysteresis model for CLT design require to have parameter that able to control wide range of slipping and degradation behavior. Initially, CLT hysteresis model has been widely proposed by several study such as Saw and pinching4 model [2]. However, some hysteresis model like Saws model have negative stiffness curve during its hysteresis regulation. This negative stiffness gives convergence problem when nonlinear time history analysis is performed. For this reason, this study chooses to modify and improve Saws model so that it can be used for dynamic analysis without convergence problem and some improvement in degradation behavior are made. The reason for this study to pick Saws model is based on its original simple degradation behavior and small number of parameters that could control slipping and hysteresis degradation behavior.

![Hysteresis Parameter](image)

(a) Hysteresis Parameter.

![Hysteresis Regulation](image)

(b) Hysteresis Regulation.

Figure 3. Modified Saws model.

Table 3. Modified Saws model parameters.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_0$</td>
<td>Yielding force</td>
</tr>
<tr>
<td>$F_1$</td>
<td>Force when drastic degradation occur</td>
</tr>
<tr>
<td>$F_2$</td>
<td>Force during slippage at zero displacement</td>
</tr>
<tr>
<td>$\delta_{\text{limit}}$</td>
<td>Limit displacement when drastic degradation occur at next loop</td>
</tr>
<tr>
<td>$S$</td>
<td>General stiffness of connection</td>
</tr>
<tr>
<td>$R$</td>
<td>Slope to create smooth transition for backbone curve</td>
</tr>
<tr>
<td>$R_{\text{slipping}}$</td>
<td>Backbone slope after ultimate force attained</td>
</tr>
<tr>
<td>$R_1$</td>
<td>Unloading slope</td>
</tr>
<tr>
<td>$R_2$</td>
<td>Slipping slope</td>
</tr>
<tr>
<td>$R_3$</td>
<td>Reloading slope after drastic degradation occurrence</td>
</tr>
<tr>
<td>$\alpha$ and $\beta$</td>
<td>Degradation parameter for reloading slope, used in Eq.3</td>
</tr>
</tbody>
</table>

Table 1. Modified Saws model parameters.

Regulation and parameter of modified Saws model in this study is illustrated in Figure 3. In total there will be 10 parameters to control hysteresis behavior of proposed modified Saws hysteresis model as shown in Table 1. Detail regulation of how hysteresis works will be further explained as listed below:

- Hysteresis begin with path arrow 1 as shown in Figure 3(b), this loading path will follow Eq. 1 in defining force-displacement relation.
- Unloading as shown in Figure 3(b) path arrow 2 will simply follow $R_2S_0$. Unloading stiffness in proposed model will keep the same in entire process. Unloading will be taken place until displacement reach slippage $R_2S_0$ slope.
- Reloading as shown in arrow path 4 in Figure 3(b) follow Eq. 2 and taken place when slope between two point in which current displacement and $\beta$ formed a line with slope of $K_p$ in Eq.2. $\delta_{\text{limit}}$ defined as last loop unloading displacement as shown in Figure 3(a).
- When reloading keep increase as shown in path arrow 5 in Figure 3(b) until its displacement cross $R_2S_0$ line illustrated in Figure 3(a), Eq.1 will be used to govern again the hysteresis line. However, $F_0$ will be reduced to be $F_0'$ following Eq.3. $\delta_{\text{limit}}$ defined as maximum displacement has been reach during cyclic loading. Need to be noted that at each loading direction, this $F_0$ value could be different depend on maximum displacement at both directions.

For several connection configurations, drastic drop of stiffness could occur. This characteristic is modeled in proposed hysteresis. Whenever displacement has pass through $\delta_{\text{limit}}$, next loop reloading stiffness will be $R_2S_0$.

$$F = sgn(\delta) (F_0 + R_2 S_0 |\delta|) \left[ 1 - \exp \left( - \frac{S_0 |\delta|}{F_0} \right) \right]$$ (1)

$$K_p = S_0 \left[ \frac{F_0}{S_0} \right]^\alpha$$ (2)

$$F' = F_0 + R_2 S_0 (\delta_{\text{max}} - \delta_0)$$ (3)

To validate the ability of proposed method in mimicking real experiment hysteresis, Section 2.1 and 2.2 will demonstrate ability of proposed hysteresis model. Explained hysteresis behavior will be constructed in ABAQUS FE software utilizing UMAT (User defined material). Section 2.1 demonstrate proposed hysteresis curve in mimicking cyclic loading experiment on hold down and bracket connection. While Section 2.2 shows experiment of CLT wall under cyclic loading.

2.1 Connection Cyclic Loading

In this section, two type of connections in which hold down and angle bracket connection will be modeled using proposed hysteresis rule in ABAQUS FEM. In this part, experimental data will be taken from reference [2]. Two type of connection is subjected to cyclic loading following ASTM-CURTEE protocol. Complete experiment setup and detail of connection could be found in reference [2].

Figure 4 shows the hysteresis comparison for (a) hold down connection and (b) bracket shear connection. Top side shows experiment hysteresis curve together with original Saws model, while bottom side shows proposed modified Saws model. Big improvement of numerical hysteresis model is shown on angle bracket connection. Proposed hysteresis model could well mimic sudden drop
degradation from CLT connection as shown in Figure 4(b).

Again, proposed hysteresis is try to avoid the use of negative stiffness curve that could cause convergence problem during dynamic analysis. In this case, negative stiffness imposed by hold down connection as shown in Figure 4(a) is not able to be simulated perfectly. However, area of dissipated energy more or less the same as experimental one. Parameter used in modified Saws in this hysteresis could be found in Table 2.

### 2.2 CLT Wall Cyclic Loading

In this section, wall experimental from reference [2] again will be used to test proposed hysteresis model capability in simulating hysteresis curve. Quasi static analysis subjected to cyclic loading analysis will be carried out for this analysis. Experiment setup is illustrated in Figure 5, detail setup and description could be found in reference [2].

![Figure 5. Experimental Setup.](image)

Again, ABAQUS FEM software is utilized for numerical simulation. CLT is modeled as shell with C4R mesh and connection modeled using truss 1D element with hysteresis behavior defined using UMAT with proposed modified saws model. For each connection, vertical and horizontal truss element are applied. Vertical and horizontal modified saws parameter is the same as hold down and bracket angle shear connection in Section 2.1 respectively. Figure 6 shows the comparison between reference and proposed modified saws model. Proposed model could successfully generate more or less the same dissipation energy area as used by reference.

![Figure 6. Comparison of proposed hysteresis model with experimental data and original Saws model.](image)
3. Reliability Assessment.

Beside proposing hysteresis model, uncertainty in connection need to be considered during design stage. This section will demonstrate reliability assessment of CLT structure under seismic ground motion. Same as before, ABAQUS FEM software is utilized since it able to provide user defined material (UMAT) and connection to MATLAB programming language. Dynamic implicit using HHT time integration with alpha value equal to 0.5 is performed. For damping ratio, Rayleigh damping with mass and stiffness constant of 0.65 is applied. Figure 7 shows the illustration and numerical model in ABAQUS software. Structure will be subjected to ground motion as shown in Figure 8. At each story, 5kN/m uniform load is applied to model dead load. Due to complex calculation time, it is assumed that uniform load and number of hold down connection is enough to maintain vertical rocking in linear manner and could be neglected. In that case, only horizontal link is considered as seismic dissipation element. Structure will be subjected to El Centro seismic motion as shown in Figure 8.

This study will utilize M-IS reliability method to assess failure probability of designed structure described above. Detail and complete description of M-IS could be found in reference [6]. In brief, M-IS is an advance version of Radial Based Importance Sampling (RBIS) analysis. Instead of using single sphere to remove unnecessary samples, M-IS deploy several spheres to further wipe out more samples. M-IS does not compromise accuracy of reliability assessment, it has same level accuracy as MCS (Monte Carlo Simulation). However, its efficiency is drastically reduced compare to RBIS or MCS.

Table 3 and 4 list random variables and constant of connection parameters. Before reliability assessment, brief sensitivity analysis is conduct to determine which parameter has significant role in govern structural drift ratio. Table 3 list top five hysteresis parameter that has important contribution on structural drift ratio.
For this reliability analysis, failure will be defined as drift ratio of structure exceed 2.5%. Using M-IS reliability method, failure probability of 0.0086 is obtained as summarized in Table 5. Compared to MCS with 4000 sample size, calculated failure probability using M-IS has acceptable error.

### 4. Conclusion
In this study, modified Saws hysteresis model is proposed. Framework for reliability analysis also introduced using M-IS reliability method. Several brief conclusions are listed below:

- Original Saws model have simple regulation and easy parameter to control hysteresis behavior. However, some part of its hysteresis have negative stiffness curve path that easily lead to convergence problem during dynamic time integration analysis. Proposed hysteresis model improved original Saws model by removing negative stiffness region and introducing sudden abrupt stiffness that commonly encounter on several bracket connection behaviors.
- In seismic region, time history analysis is time consuming analysis. To perform accurate reliability assessment yet not sacrificing much time is challenging task. M-IS in this study consume 1719 sample size. M-IS is radial based reliability assessment where smaller failure probability will utilize less sample size evaluation since large density of samples will be wiped out. However, in this study case, failure probability of 0.0159 is not small enough to demonstrate M-IS capability. Although it consumes lot of sample size, its accuracy compared to MCS is identical.

### References


