Abstract—This paper reports numerical investigation of tropical hardwood which is obviously an orthotropic material. The characteristic of material is unique and complex to correspond the stiffness degradation under compression load which is difficult to determine a proportional deformation level. Usually, it can be found to be in linear configuration. Numerical plasticity model has been taken into account for proportional limit stresses level in order to meet nonlinear stress-strain relationship. The nonlinear elastic-plastic stage can be defined by development of material stiffness in relation to the hardward strength relies upon grain orientation. Simulation under non-linear Finite Element Model (FEM) necessarily provides a parametric study in order to present validation between the numerical and experimental works. Based on the result of validation, it can be found that crystalline plasticity model predicted well load-deformations to agree the experimental work. Furthermore, this work has already been used to calibrate lateral carrying load capacity of traditional (non-engineered) timber frame structures under seismic excitation. This parallel study has been done to determine seismic performance as well as to examine failures mode of the typical structures and its components as a subject to be concerned.

Index Terms — Orthotopic-timber; geometric non-linearity; user-defined plasticity model; FEM

I. INTRODUCTION

In general, the objective of study was to evaluate the performance of non-engineered low rise structures in developing country; Indonesia. The structures concerned are vernacular; traditional timber frame, masonry monumental, and relatively modern of either confined or unconfined masonry structures. In particularly, the timber frame structure was found to be structures resists to collapse during the seismic event [1-3]. There are many different type of timber structures found in Indonesia [4, 5] with different characteristic of structural system. However, the seismic capacity of the structures were limited to be investigated [6].

Although, timber materials may be described as being with an old fashion or traditional, however, it is still favourable for framing material for many years. It has not yet been replaced for housing structure up to now. In general, the traditional structure, shown in Fig. 1 was usually made of timber material. It was considered as a successor to sustainable traditional natural building materials. The reasons why timber material is used which can be relegated as follows: availability, cheap material, strength, workability, capable of adapting to several new techniques, compatibility with fabrication method, etc., [7].

In modern timber structure, material development used to be greatly based on wood technologies with new techniques were adopted for prefabrication methods, composite reconstruction and connection methods to improve the performance of structural applications. Glulam (laminated timber) is excellent technique which the expressions of the use of timber technology for building construction [7] was well defined. Typical composite wood product is key to taking over sawn timber. The improvement of lower grades of material that originated from old grown forests can be improved in a very effective manner with more homogenous structural member product. Nevertheless, swan timber and composite Glulam are orthotropic material [9]. Relevant to the investigation, studies relates the timber materials can be found in [10-17].

To obtain the material property of timber, several tests used to be conducted such as compressive tests either of parallel or perpendicular to the grain, bending test, etc. Under static pressure, loading monotonically is given gradually from 0 - 40 MPa up to maximum of 260 MPa, the compressive and bending strengths can be taken from the test specimen with cross-section of (50mm x 50mm), the length of 200mm and 760mm, respectively. Or monotonic load also can be given by load rate of 0.02kN/sec or up to maximum 260 MPa of static load. Then, it necessarily to have validation under parametric study to confirm further numerical simulation of the actual structure. On one hand, material model procedure may essentially be adopted for typical small strain deformation problems which can be associated with plasticity model for solid material [18-21]. On the other hand, to evaluate the seismic performance of the structures, commonly, that is equally to find lateral
load-displacement capacity level associated with geometric non-linearity \[22\] of the most for solid material and structure. Typically, pushover analysis \[23\] as one of prominence performance base design procedure suits to large deformation of structural cases. This can be used to predict the structural behaviour under e.g.: seismic and dynamic wind load.

II. GEOMETRIC NON-LINEARITY AND ARC-LENGTH (RIKS METHOD)

A. Geometric Non-Linearity

Error! Reference source not found.(a) shows single DOF developed in \[22\] is a typical problem relevant to a "shallow truss theory". Pythagoras’s theorem valid to deal with the strain, \[I\] developed in the bar/frame. Stiffness of component structure considered based on the structural member of area, A and Young’s modulus, E. When a load, P is subjected to the structure, it provides a displacement, w. By assuming of \[I\] is sufficiently small, N is force in the member, lateral equilibrium of the structure developed as \[22\]:

\[
P = N \sin \theta = \frac{N(z + w)}{l} \approx \frac{N(z + w)}{l} \quad (1)
\]

\[
\varepsilon = \sqrt{(z + w)^2 + l^2 - z^2 - l^2} = \left[ \frac{z}{l} \right] \left[ \frac{w}{l} \right] + \frac{1}{2} \left[ \frac{w}{l} \right]^2 \quad (2)
\]

\[
N = E \varepsilon = E A \left[ \frac{z}{l} \right] \left[ \frac{w}{l} \right] + \frac{1}{2} \left[ \frac{w}{l} \right]^2 \quad (3)
\]

Equation 2 is relevant to non-linear problem. Variation of arbitrary value of z and w governed of differential scheme, except \(z = 0\). Relation between the load, P and displacement, w is given as follows:

\[
P = \frac{EA}{l} \left( \frac{z^2}{2} + \frac{3}{2} w^2 + \frac{1}{2} w^3 \right) \quad (4)
\]

Tangent stiffness matrix take over the role once small change of load or displacement are taken into account, it can be defined as \[22\]:

\[
K_i = \frac{\partial P}{\partial w} = \frac{(z + w)}{l} \frac{\partial N}{\partial w} + \frac{N}{l} \quad ;
\]

\[
K_i = \frac{EA}{l} \left( \frac{z^2}{2} + \frac{3}{2} \frac{w^2}{l^2} + \frac{1}{2} \frac{w^3}{l^2} \right) + \frac{N}{l} \quad (5)
\]

B. Arc-Length (Riks Method)

Non-linear geometry used to be taken into account by using Newton-Raphson approximation to find convergence solution during iteration process. Theoretically, Fig. 3 be

According to the virtual work principle, the total internal work correspond to the unknown force must be equal to the external force which can be of integrated arbitrary virtual displacement (small or large) with the body force and surface force.

Fig. 2 Typical non-linear geometric problem of (a). One (1) degree of freedom (DOF) \[22\], (b). Six (6) DOF on traditional timber frame with spring stiffness, Ks represented to be the original strength stiffness of structure \[24\].

The first yield force predicted to correspond displacement designated which is projected into the convergence points at the equilibrium path (curve). Further iteration, based on the changed of stiffness; degradation, the angle of tangent stiffness is change. Updated force-displacement proportionally plots another convergence point at the equilibrium path of arc-curve. Iterations leads the portion of load-displacement to be generated to maintain the equilibrium path under the stiffness development. It clearly shows that the iteration of predictor and corrector method provides solution in relation to predict the structural behavior.

In the FEM, the incremental procedures is developed by assembling of "geometric stiffness matrix" which is associated with an updating of either local or global coordinate system on structural geometry in conjunction to the displacement matrix. The aim is to control the iteration in simulation for numerical solution of such complex non-linear problems. The complex path of load-displacement development into the range of elasto-plastic or into the post critical range \[25\-27\] traced by using Riks method \[28\]. Proportional load \[25\] can be written as a standard equilibrium equation as follows:

\[
\lambda P - F(x) = 0 \quad (6)
\]
Fig. 3 Reproduced typical arc-length (a) Orthogonality method and (b) (Riks, 1972; 1979; Wempner, 1971) method for non-linear FEM analysis. [25-27]. (c) Sample arbitrary traditional Newton-Raphson simulation using Mat-lab for proportion of stiffness of $k = 11.859 / (u+1)^2$ and load of $F=10$.

Initial solution was introduced traditionally by using Newton incremental iteration in [25] as follow:

$$K(i) \Delta u = \lambda P - F(x_i)$$

$$x_{i+1} = x_i + \Delta u$$

(7-8)

The result of simulation to provide proportional load generated by the sufficiently of material/structure stiffness can be seen in Error! Reference source not found.. In which the used of basic elastic orthotropic for similar case was not predicted properly of the proportional load-deformation or the stress elastic-plastic condition.

Based on the Schmid law, typically slipping rate of slip system in the rate dependent of crystalline solid is determined by resolving the shear stress which is typical hardening rule. User-defined procedure of typical crystalline material has been used by providing material Jacobian matrix $\frac{d\lambda}{d\sigma}$. Firstly, the code used to update the stress and solution dependent state variable to their value at the end of increment. Secondly, the code is a constitutive model to be required for an iterative Newton Raphson solution. Elastic and inelastic deformation respectively developed by embedded lattice and crystalline slip to generate dislocation motion. The total deformation is $F=F+FP$, where $F$ is stretching and rotation of the lattice and $FP$ is plastic strain material to an intermediate reference configuration under lattice orientation. The rate of change of FP relates to the slipping rate, $(F^E)$ in the slip system (8), the formulation given;

$$\dot{F}P F = \sum_{u} x^{(u)} S^{(u)} m^{(u)}$$

(10)

where $S^{(u)}$ = slip direction vector, $m^{(u)}$ = normal to slip plane, $E^{(u)} = F^E S^{(u)}$ is lying along the slip direction of the system and $m^{(u)} = F^E m^{(u)}$ is reciprocal base vector.

C. Plasticity Model Approach into the Orthotropic Properties

Timber is associated with anisotropic or orthotropic material. Pulp is one of sophisticated wood-based material (fibers). It consists of structural and chemical composition which is fiber dimension and chemical (a lignocellulosic fibrous material) [29]. Under high pressure, temperature and high impact during homogenization, the cellulose are isolated to be the fibrils as nanocellulose, or microfibrillated cellulose (MFC). That is nanofibrils with lateral dimensions of 5–20 nanometers and longitudinal dimension 10–nanometers to several micrometers. The nanocellulose is giving rise to highly crystalline and rigid nanoparticles (nanowhiskers) which are shorter (100s to 1000 nanometers) than the nanofibrils and it is known as nanocrystalline cellulose (NCC) [30].

It could be associated with crystalline material which is embedded on its lattice which is potentially to perform elastic and rotation deformation [31]. The inelastic deformation can be provided by typical crystalline slip in which dislocation motion flows through the crystalline lattice. To establish plasticity model of material, it is required to provide consistency of yield condition, hardening stages and flow rule.

By using material user-defined (UMAT subroutine) in Abaqus for Crystal plasticity [32], simple modification on mechanical properties has been done to evaluate timber material in plastic condition. Non-linear geometry and classical Newton-Raphson are involved in this subroutine along with numerical forward scheme approximation. In particularly, contribution will significantly be useful for the case of small deformation problem such as compressive shortening test in which the used of basic elastic orthotropic for similar case was not predicted properly of the proportional load-deformation or the stress elastic-plastic condition.
to all vectors in the slip plane.

Schmid’s law equals the slipping rate \( f^n \) in any particular slip system assumed to be dependent on the current stress, \( \bar{\sigma} \), so-called the Schmid stress, \( \left( \bar{T} \right)^{\text{Sch}} \). The use of thermodynamic stress conjugate to the slip formulated as:

\[
\tau^{(a)} = m^{(a)} \frac{\sigma_0}{\rho} \alpha S^{(a)}(\rho)
\]

Rate of change of Schmid stress;

\[
\tau^{(a)} = m^{(a)} \left( \sigma + \alpha (1; D) - D' \sigma + \alpha D' \right) S^{(a)}(\rho)
\]

and hardening rule of rate-dependent for crystalline material is

\[
\dot{\gamma}^{(a)} = \frac{(h^{(a)} f^{(a)} - \bar{\sigma}^{(a)})}{\dot{\gamma}^{(a)}}
\]

where \( \bar{\sigma}^{(a)} \) = reference strain rate on slip system, \( \dot{\gamma}^{(a)} \) = current strength and \( f^{(a)} \) = non-dimensional factor. Strain hardening characterized by the evaluation of the stress through the incremental hardening

\[
\dot{\gamma}^{(a)} = \sum \dot{\gamma}^{(a)}(\rho)
\]

relation; \( \dot{\gamma}^{(a)} \) = slip hardening moduli (the sum ranges over all activated slip system).

After Pirece, Asaro, Needleman [33-35], the hardening was formulated as:

\[
h_{\text{an}} = b(y) \text{sech}^2 \left( \frac{h_0 y}{h_0} \right)
\]

That is typical self-hardening and \( h_{\text{an}} = q h(y') \) as latent hardening and \( q = \) constant. Bassani and Wu [36] modified the stages of hardening crystalline materials depend on the shear strain, \( y_{(c)} \) all slip system which is described in the formulation:

\[
h_{\text{an}} = \left( h_0 - h_3 \right) \text{sech}^2 \left( \frac{h_0 y}{h_0} \right) + h_3 G(y/\beta)
\]

where \( \alpha \neq \beta \) and \( h_{\text{an}} = q h_{\text{an}}; \) \( h_0 \) = initial hardening moduli, \( y_{(c)} \) = yield stress equals the initial value of current strength \( b \) \( \alpha ) \). \( \alpha \) \( \tau^\alpha \) = stage I stress (large plastic flow initiates), \( y_{(c)} \) = Tyr5ulu cumulative shear strain on all slip systems;

\[
y = \sum \int_0^{t_0} \left| \dot{\gamma}^{(a)} \right| dt
\]

\( \text{h}_x \) = hardening modulus introduced within the stage I, \( q = \) constant, \( G = \) function of interactive cross-hardening,

\[
G(y/\beta) = 1 + \sum_{\beta \neq \alpha} f_{\beta \omega} \tanh \left( \frac{y_{\alpha}}{\gamma_0} \right)
\]

amount of slip after which the interaction between slip system reaches the peak hardening of each component, \( f_{\beta \omega} \) represents the magnitude of strength of particular slip interaction. Detail of crystalline plasticity can be found in [31, 34-41].

User-definite material for timber given in Abaqus, e.g.: PROPS(1) - PROPS(9) are the ELASTIC card (DEVAR) orthotropic in Abaqus that is provided in Table 3. Parametric study was given into the simulation to provide values relevant for the timber properties developed, shown in Table 1.

### III. RESULT AND DISCUSSION

The result of study shows that the used of typical crystalline plasticity model to predict the strength of orthotropic material is relatively feasible. Although, only elastic modulus of compressive test along the grain available, simulation can be taken into account by using parametric study.

By changing the parameters such as Poisson’s ratios, it provides significant prediction relates to the test cases under taken. For the case of small deformation problems shown in Error! Reference source not found. and Error! Reference source not found. (a-b), it is very sensitive development in which small change of the parameter will provide different numerical results. In this case, the material/structure (micro-model) is likely to behave in ductile manner. On the other hand, the result of numerical for bending test is becomes relatively easier to be found with or without plasticity material model involved, shown in Error! Reference source not found. and Error! Reference source not found. (c). It is typically of large deformation problem (tensile test) in which the structure is relatively behave in brittle manner or more likely of typical tensile strength test for timber material.

<table>
<thead>
<tr>
<th>Wood Type</th>
<th>Bangkirai</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Notation</th>
<th>Elastic (MPa)</th>
<th>Notation</th>
<th>Poisson’s Ratios</th>
</tr>
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<tbody>
<tr>
<td>a</td>
<td>E</td>
<td>s</td>
<td>( \nu_{L}(\nu_{L}) )</td>
</tr>
<tr>
<td>b = 1.1 a</td>
<td>E_1</td>
<td>t</td>
<td>( \nu_{R}(\nu_{R}) )</td>
</tr>
<tr>
<td>c</td>
<td>E_t/E_1</td>
<td>u</td>
<td>( \nu_{R}(\nu_{R}) )</td>
</tr>
<tr>
<td>d</td>
<td>E_t</td>
<td>v</td>
<td>( \nu_{R}(\nu_{R}) )</td>
</tr>
<tr>
<td>e</td>
<td>E_w/E_1</td>
<td>w</td>
<td>( \nu_{R}(\nu_{R}) )</td>
</tr>
<tr>
<td>f</td>
<td>E_w</td>
<td>x</td>
<td>( \nu_{R}(\nu_{R}) )</td>
</tr>
<tr>
<td>g</td>
<td>G_{K1}/E_1</td>
<td>y</td>
<td>( (1-x-y-v-u-wt) )</td>
</tr>
<tr>
<td>h = bg</td>
<td>G_{K1}</td>
<td>( \nu_{R}(\nu_{R}) )</td>
<td>2901.94</td>
</tr>
<tr>
<td>i</td>
<td>G_{K1}/E_1</td>
<td>m</td>
<td>( L=1 )</td>
</tr>
<tr>
<td>j = bi</td>
<td>G_{K1}</td>
<td>n</td>
<td>( T=2 )</td>
</tr>
<tr>
<td>k</td>
<td>G_{K1}/E_1</td>
<td>r</td>
<td>( R=3 )</td>
</tr>
<tr>
<td>l = bk</td>
<td>G_{K1}</td>
<td>( \nu_{R}(\nu_{R}) )</td>
<td>3130.23</td>
</tr>
</tbody>
</table>

In crystal plasticity model, basically, lattice properties; distortion and rotation of typical crystal deformation provides reliable prediction of the grain to grain interaction due to the sensitivity of self-hardening without involving kinematic effect (no Bauschinger effect). It allows to provide less sensitivity of element size in FEM analysis. The flow of stresses are still maintain properly without providing fine mesh generation.

Table 2. Defining orthotropic elasticity for Bangkirai Timber based on parameter developed in Table 1.

<table>
<thead>
<tr>
<th>E</th>
<th>G_{11}</th>
<th>G_{12}</th>
<th>G_{13}</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1111</td>
<td>10698.00</td>
<td>s</td>
<td>( \nu_{L}(\nu_{L}) )</td>
</tr>
<tr>
<td>D1122</td>
<td>11767.80</td>
<td>t</td>
<td>( \nu_{R}(\nu_{R}) )</td>
</tr>
<tr>
<td>D2211</td>
<td>7649.07</td>
<td>x</td>
<td>( \nu_{R}(\nu_{R}) )</td>
</tr>
<tr>
<td>D1122</td>
<td>930.45</td>
<td>n</td>
<td>( T=2 )</td>
</tr>
<tr>
<td>D2333</td>
<td>3130.23</td>
<td>m</td>
<td>( L=1 )</td>
</tr>
<tr>
<td>D1111</td>
<td>42</td>
<td>31</td>
<td>12</td>
</tr>
<tr>
<td>D1122</td>
<td>12</td>
<td>31</td>
<td>12</td>
</tr>
<tr>
<td>D2222</td>
<td>31</td>
<td>12</td>
<td>31</td>
</tr>
<tr>
<td>D2333</td>
<td>12</td>
<td>31</td>
<td>12</td>
</tr>
</tbody>
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Table 3 Values of orthotropic material given for Bangkirai Timber based on Table 2 defined as Stiffness Matrix

<p>| | | | | | | |</p>
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<tr>
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<tbody>
<tr>
<td>4</td>
<td>19913.48</td>
<td>25076.23</td>
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<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
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<td>5228.31</td>
<td>2103</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>3</td>
<td>2103</td>
<td>17183.77</td>
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<td>0.00</td>
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<td>0.00</td>
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<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Fig. 5 The result of bending test perpendicular to grain on Bangkirai timber; (a) Numerically proportional load to the elastic stiffness developed (b) Snap-back due to un-proportional load.

Fig. 6 The result of compressive test parallel to grain on Bangkirai timber; (a) experimental, (b) numerical using plasticity model in Abaqus and (c) Validation.

Nevertheless, due to the strength of material structure depends on the characteristic of grain orientation, to develop modelling for different testing such as partial compressive test (perpendicular to grain), bending and tension test, etc., it necessarily to provide sufficient modification on the parameters. However, the advantage can be described that, even though, only elastic modulus of compressive test parallel to grain available, numerical test is still become feasible. Otherwise, experimental test must be conducted to provide appropriate elastic modulus under bending, tension, partial compressive (perpendicular to grain) tests, etc.
IV. CONCLUSION

Simple elastic material models to include non-linear strategy has not yet been predicted load-displacement properly for typical natural material. The difficulty to estimate inelastic condition due to the uniqueness of the microscopic stresses tensor of orthotropic material based on the grain orientations. Crystalline plasticity model takes into account regarding to dual/reciprocal lattice (lattice plane within the element) based on the Miller Index (arrangement of atoms in the crystalline solids) in order to have prediction of nonlinear stress-strain relationship. Validation has been taken into account which the crystalline plasticity model found to agree between the experimental work in Fig. 8 and the numerical in Fig. 5-7 to predict load-deformations. The numerical works has also been used to estimate lateral carrying load capacity of traditional (non-engineered) timber frame structures under earthquake load or typically pushover analysis (load-displacement control).

Fig. 5 The result of bending test perpendicular to grain on Bangkirai timber; (c) Parametric Study using either of elastic-orthotropic or plasticity model and (c) Validation to the experimental result.

Fig. 7 The numerical uniaxial shortening tests result of Bangkirai timber; compressive parallel to grain (a) using plasticity model, (b) elastic-orthotropic, and (c) bending test perpendicular to grain either using elastic-orthotropic or plasticity model.

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