



CROSS LAMINATED TIMBER WALLS WITH OPENINGS: IN-PLANE STIFFNESS PREDICTION AND SENSITIVITY ANALYSIS

Md Shahnewaz
PhD Candidate, UBC, Canada

M. Shahria Alam
Associate Professor, UBC, Canada

Thomas Tannert
Assistant Professor, UBC, Canada

Marjan Popovski
Principal Scientist, FPInnovations, Canada

ABSTRACT

Cross-laminated timber (CLT) is gaining popularity in residential and non-residential applications in the North American construction market. An accurate quantification of in-plane stiffness of the CLT walls with openings is required to design a CLT structure subjected to lateral loads. Nevertheless, till today, no general approach is available for the design of CLT-members loaded in plane and there are no standardized methods for determining the stiffness of CLT shearwalls in the respective material design standards: the CSA O86 in Canada, and the NDS in the US. This study aims to quantify the stiffness of CLT walls with openings under in-plane loading. A finite element (FE) model of CLT walls was developed modelling wood as orthotropic elastic material and the glue-lines between layers using non-linear contact elements. The FE model was verified from test results of CLT panels under in-plane loading. A parametric study was performed to evaluate the change in stiffness of CLT walls with the variation of opening size and shape. A simplified equation to predict the in-plane stiffness of CLT walls with openings was proposed. Subsequently, a sensitivity analysis was performed using Meta-model of Optimal Prognosis (MOP) to evaluate the contribution of each parameter on the model response.

Keywords: Cross-laminated timber (CLT), stiffness, opening, finite element, and sensitivity analysis.

1. INTRODUCTION

Cross-laminated timber (CLT) is an engineered wood product categorized as “mass” timber. The use of CLT is increasingly gaining popularity because of its many benefits when compared to either light-frame wood construction or concrete and steel construction. The cross lamination provides dimensional stability, strength and rigidity. CLT has a low carbon footprint due to low embodied greenhouse gas emissions and carbon storage capacity of wood. The good thermal insulation and a fairly good behaviour in case of fire are added benefits. Furthermore, it is a clean product to work with resulting in less waste and dust produced on site which is better in terms of health and safety. CLT panels consist of several layers of boards stacked crosswise and glued together. A CLT element has usually an uneven number of layers of boards glued orthogonally to form a solid panel. Pre-cut wall and floor panels are assembled on the construction site using various types of screws and steel connectors to form the structural system.

To design CLT shear walls, understanding of the mechanical properties of CLT panels and connectors connecting them is needed. Several studies have been carried out and some analytical equations to predict the mechanical properties of CLT panels loaded in plane are proposed. E.g., Blass and Fellmoser (2004) developed a method for the design of CLT panels under in-plane loading based on the composite theory. The composition factors (k-factors) account for the strength and stiffness of CLT panels in various directions, based on single layer properties. Moosbrugger et al. (2006) proposed a model based on the regular periodic internal geometric structure of the CLT

wall element, considering uniform shear loading on wall boundaries. They defined the complex internal structure of CLT elements with a unit cell called Representative Volume Element (RVE). The RVE extends over the whole plate thickness and is sub-divided into Representative Volume Sub-Elements (RVSE). Bogensperger et al. (2007) experimentally investigated the in-plane behavior of CLT panels and verified their results with FE analyses. The effective shear modulus was calculated and a deviation of the shear modulus of up to 26% was reported comparing tests results and FE analyses. Bogensperger et al. (2007) also performed FE analysis and further verified the studies by Moosbrugger et al. (2006). Their FE model accurately predicted the effective shear of CLT panels. Finally, Flaig and Blass (2012) developed another method for shear design of CLT beams loaded in plane and proposed equations for shear stress and stiffness and verified them with test results. Few of these studies, however, addresses openings in CLT walls.

Openings for doors and windows are very common in the CLT wall panels. The areas around an opening experience stress concentrations that can reduce in-plane stiffness and load bearing capacity of the panel. Moosbrugger et al. (2006) performed FE analyses as an attempt to quantify the stiffness of a CLT panel with a quadratic opening at the center. They estimated the reduced stiffness by taking the ratio of the effective wall area (A_{wall}) to total area (A_{total}) where, $A_{wall} = A_{total} - A_{opening}$. However, the results from this estimate overestimated the reduced stiffness when compared to the test results. Dujic et al. (2007) experimentally investigated the behavior of CLT wall panels with different opening locations. Four cyclic tests were performed. It was observed that for a wall with an opening equal to 30% of the wall area, the strength of the wall did not change. However, the stiffness was reduced by about 50%. A FE parametric study was conducted to determine the influence of the size and layout of openings on the strength and the stiffness of CLT walls. Equation (1) was proposed to calculate the reduced stiffness of the CLT wall panels:

$$[1] \quad K_{opening} = K_{full} \frac{r}{2-r}$$

where, $K_{opening}$ is the stiffness of CLT walls with opening, and r is the panel area ratio given in Equation 2.

$$[2] \quad r = \frac{H \sum L_i}{H \sum L_i + \sum A_i}$$

where, H is the height of wall, $\sum L_i$ is the summation of length of full height wall segments (excluding length of openings from total length), and $\sum A_i$ is the summation of openings area.

Accurate quantification of the in-plane stiffness of the shear-walls is required to design a CLT structure subjected to lateral loads. Nevertheless, till today, no general approach is available for the design of CLT-members loaded in plane. In fact, the strength and the stiffness properties reported in different technical approvals for verification of in plane resistance of CLT walls vary significantly (Flaig and Blass 2012). In addition, there are no standardized methods for determining the stiffness and resistance of CLT shearwalls in the respective material design standards: the CSA O86 (2014) in Canada, and the NDS (2015) in the US. The objectives of this research are to calculate the in-plane stiffness of CLT walls with the variation of size and shape.

2. NEW MODEL FOR STRENGTH AND STIFFNESS OF CLT WALLS WITH OPENINGS

2.1 Experiments

Two sets of experiments were used for model calibration. The first set consisted of four point bending tests on CLT panels was performed at FPInnovations, Canada. Three series of CLT panels (2 replicates of each type) were tested with a span length of 3.5m, 5.9m, and 8.4m, see Figure 1. The specimens were 1.2m high and laterally supported. The 5-ply boards with a thickness of 175mm were from Canadian S-P-F and manufactured at NORDIC. The deformation under quasi-static monotonic loading was measured at mid span by LVDT which allowed calculating the in-plane stiffness. The second set of tests consisted of quasi-static monotonic tests on CLT walls at FPInnovations, Vancouver, Canada (Popovski et al. 2010). The CLT panels were 3-ply with 2.3m x 2.3m panel size and thickness of 94mm made of European spruce and manufactured at KLH. Several types of connectors (hold-downs and steel brackets) and fasteners (annular ring nails, spiral nails, screws, and timber rivets) were used for the connections.

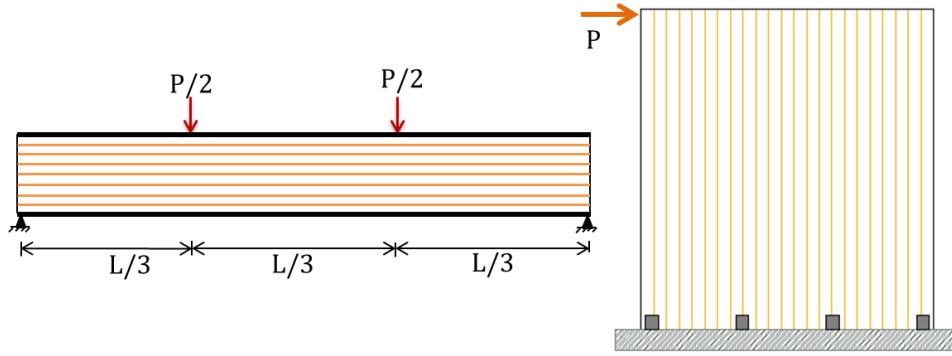


Figure 1: CLT beam (left) and wall (right) test configurations.

2.2 FE Model Development

A 3D FE model of CLT panel was developed in ANSYS (Figure 2). The CLT panel was modelled using 20-node SOLID186 element where each node has three degrees of freedom. Elastic material properties were assigned in each orthogonal direction of the lamella as provided by the manufacturers' specifications. The glue line in between panels was modelled using contact elements (Conta_174 and Targe_170). Test results showed a very stiff glue-line, therefore, a friction coefficient of 1.0 was used. The connection between the CLT wall and floor was modelled using linear COMBIN14 spring elements. The stiffness properties for the connections were taken from previous research (Schneider 2015). The FE model was validated using the load-deformation curves from the test results, see Figure 3. The elastic stiffness from the FE analysis closely matched with the experimental results.

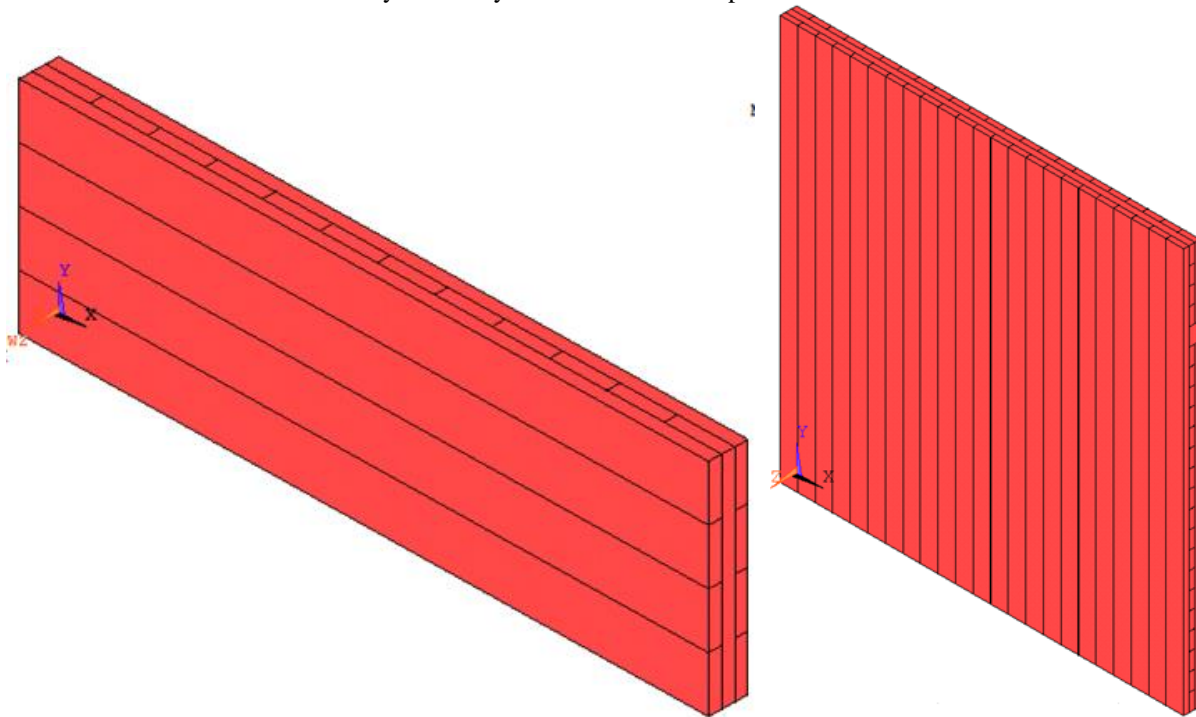


Figure 2: FE models of CLT beam (left) and wall (right).

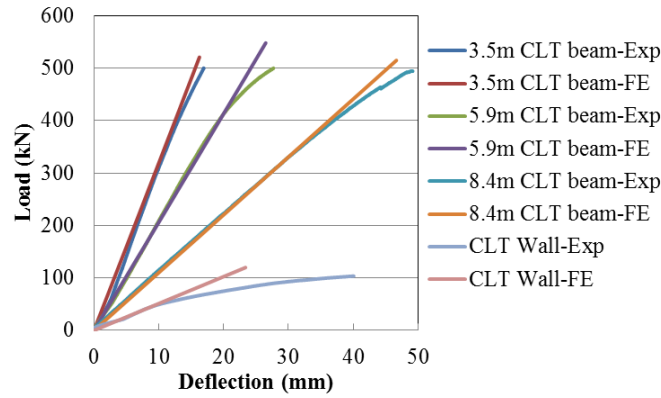


Figure 3: Experimental vs FE load-deflection curves.

2.4 CLT walls with openings

Subsequently, a parametric numerical study was performed with variation of the size and shape of openings. The stiffness reduction of CLT walls with different number, size, and shape of openings was investigated. Typical openings like, a window and/or a door as seen in Figure 4 were considered. A maximum of up to half of the total wall area was removed in the FE analysis. It was found that with a removal of half of the wall area the stiffness of the wall reduced more than 60%. As seen Figure 5(a), the stiffness reduction is non-linear with respect to wall area reduction.

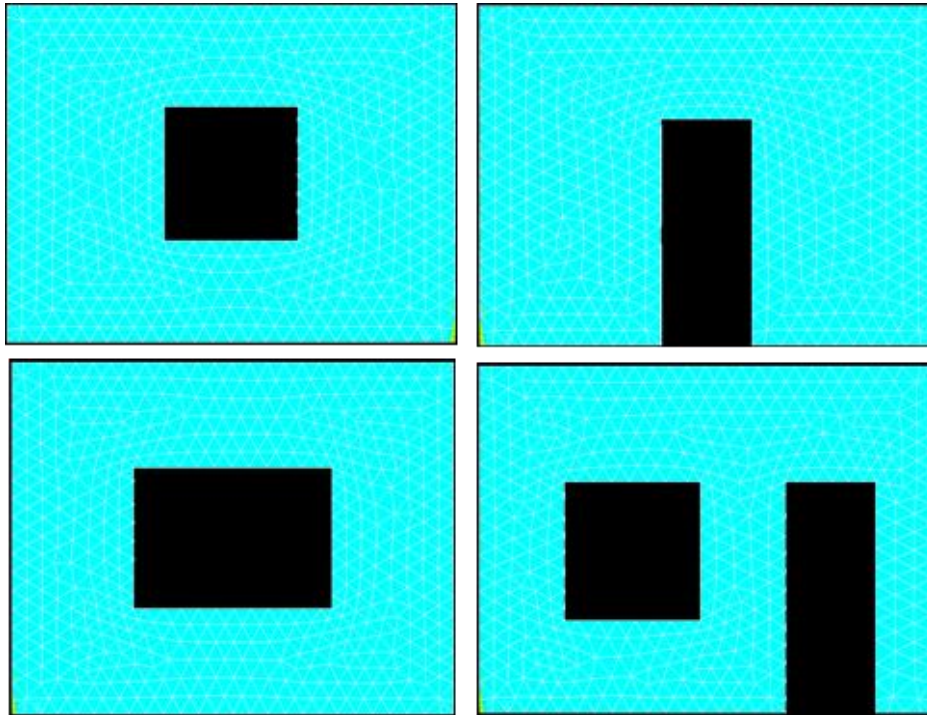


Figure 4: Typical openings in CLT Walls.

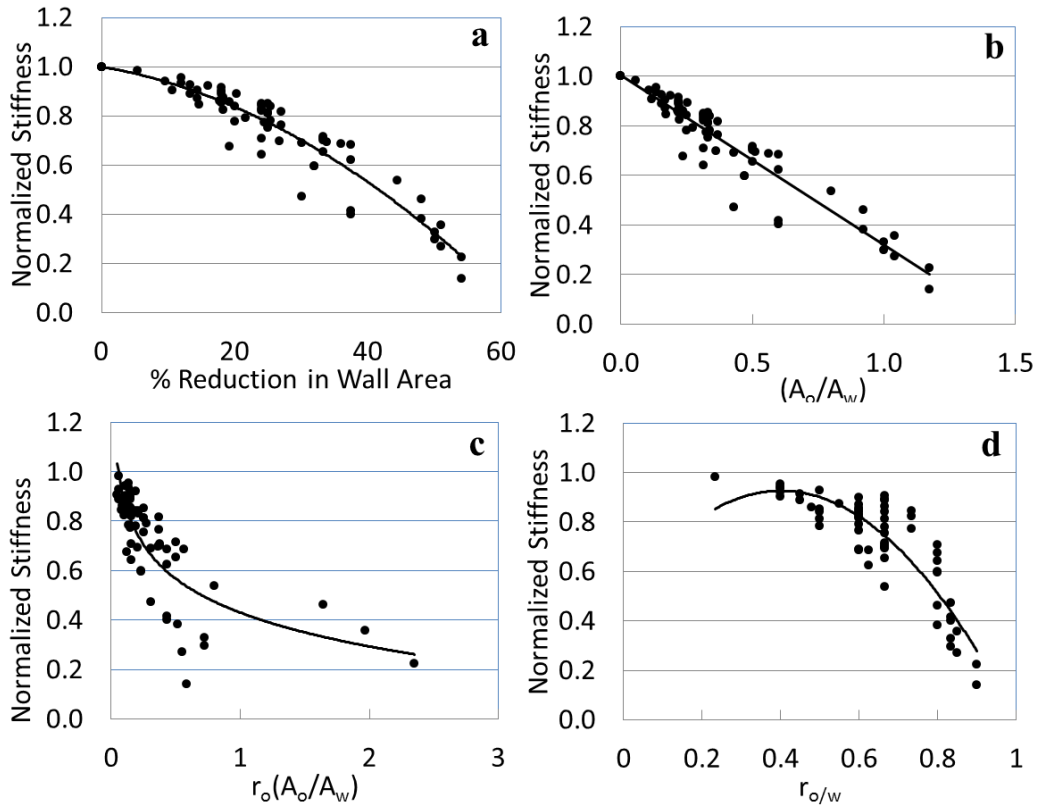


Figure 5: Effect of opening on CLT wall stiffness.

2.5 Proposed equation

The objective of the research was to propose an analytical model to calculate the in-plane stiffness of CLT walls with openings. From the FE analysis, it was found that the ratio of opening to wall area, A_o/A_w , the aspect ratio of opening, r_o , and the aspect ratio of opening to wall, $r_{o/w}$ affect the reduction in wall stiffness (Figure 5). Therefore, these parameters are considered, see Equation 3. The equation was accurate in predicting stiffness of CLT walls with opening when compared to a previously proposed model by Dujic et al. (2007), see Figure 6.

$$[3] \quad K_{opening} = K_{full} \left[1 - \frac{r_{o/w} \left(\frac{A_o}{A_w} \right)}{\sqrt{r_{o/w} + r_o \left(\frac{A_o}{A_w} \right)}} \right]$$

where, K_o and K_w are the stiffness of walls with and without opening, respectively; A_o and A_w are the area of walls with and without opening, respectively; r_o is the aspect ratio of opening (smaller to larger dimension); and $r_{o/w}$ is the maximum aspect ratio of opening to wall dimension (max of l_o/L or h_o/H , where, L and H is the wall length and height, respectively, and l_o and h_o is the opening length and height, respectively).

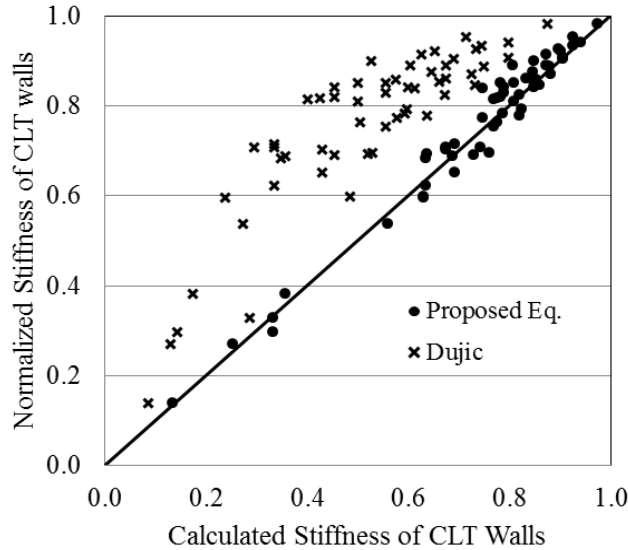


Figure 6: FE vs calculated stiffness of CLT wall.

3. SENSITIVITY ANALYSIS

3.1 Methods

A sensitivity analysis quantifies the uncertainty in the output of a model qualitatively or quantitatively, to different sources of variation in the input of a model. In addition, it also analyzes the contribution of each input variable to the model response. In this research, a sensitivity analysis was performed in the commercial software package optiSLang (Most and Will 2008). The design of experiments (DOE) for random sampling for sensitivity analysis utilizes Advanced Latin Hypercube Sampling (ALHS) technique. ALHS is effective to represent the non-linearity of the model in a reduced space. Meta-models were used to represent the model responses of surrogate functions in terms of the model inputs. A surrogate model is often advantageous due to the inherent complexity of many engineering problems to approximate the problem and to solve other design configurations in a smooth sub-domain (Sacks et al. 1989, Simpson et al. 2001). However, most meta-models i.e., Moving Least Square (MLS) approximation, Kriging or Neural Networks requires a high number of samples to represent high-dimensional problems with sufficient accuracy. To overcome these limitations, the Meta-model of Optimal Prognosis (MOP) approach was developed for the optimal filter meta-model configurations (Most and Will 2008). By doing this, a surrogate model of the original physical problem can be used to perform various possible design configurations without computing any further analyses. To develop an automatic approach requires defining a measure for the characterization of the approximation quality. The MOP uses the generalized coefficient of determination (*CoD*) which results for the special case of pure polynomial regression. The *CoD* assesses the approximation quality of a polynomial regression by measuring the relative amount of variation explained by the approximation as follows:

$$[4] \quad R^2 = \frac{SS_R}{SS_T} = 1 - \frac{SS_E}{SS_T}; \quad 0 \leq R^2 \leq 1$$

where, SS_T is the equivalent to the total variation, SS_R represents the variation due to the regression, and SS_E quantifies the unexplained variation as follows:

$$[5] \quad SS_T = \sum_{i=1}^N (y_i - \mu_Y)^2, \quad SS_R = \sum_{i=1}^N (\hat{y}_i - \mu_Y)^2, \quad SS_E = \sum_{i=1}^N (y_i - \hat{y}_i)^2$$

However, in order to penalize the over-fitting, Montgomery and Runger (2003) also introduced the adjusted Coefficient of Determination, see Equation 6:

$$[6] \quad R_{adj}^2 = 1 - \frac{N-1}{N-p} (1 - R^2)$$

where, N is the number of sample points and p is the number of regression co-efficient. The quality of an approximation was evaluated in terms of the prognosis quality by using an additional test data set. The agreement between this real test data and the meta-model estimates is measured by the coefficient of prognosis, CoP (Most and Will 2008) as defined in Equation 7:

$$[7] \quad CoP = \left(\frac{\mathbf{E} \left[\frac{Y_{Test} \cdot \hat{Y}_{Test}}{\sigma_{Y_{Test}} \sigma_{\hat{Y}_{Test}}} \right] \right)^2; \quad 0 \leq CoP \leq 1$$

An optimal metamodel can be searched with a defined CoP . Each meta-model is investigated for all possible significance by varying the significance quantile from 99% to a given minimal value. A polynomial regression is developed thereafter and the coefficients of importance (CoI) are calculated for each variable following Equation 8.

$$[8] \quad CoI_{Y, X_i} = R_{Y, X}^2 - R_{Y, X \setminus i}^2$$

Where, $R_{Y, X}^2$ is the CoD of the full model including all terms of the variables in X and $R_{Y, X \setminus i}^2$ is the CoD of the reduced model, where all linear, quadratic and interactions terms belonging to X_i are removed from the polynomial basis. The threshold CoI_{min} is varied from 1% to a given value. Based on the CoI of each variable the meta-model is built up and the coefficient of prognosis is computed. The optimal meta-model is chosen from the maximum CoP configuration. The training data set is used for the construction of meta-model, while the test data set is used for the calculation of the CoP . On the contrary, a merge data set from training and test data is used for the correlations for the significance filter and the regression for the importance filters. However, if no additional test data set is available, the initial data set is split into training and test data in a way that each data set the response ranges are represented with maximum conformity to the entire data set. The sensitivity analysis in optiSLang involves following steps:

- 1) A solver chain was created in optiSLang for the sensitivity analysis.
- 2) The range of the input parameters and their types (i.e., deterministic and/or stochastic) were defined.
- 3) ALHS sampling technique was used for DOE and total 1,000 samples were created randomly with the defined input parameters range.
- 4) An input file created for the proposed equation which link to the ALHS for sampling.
- 5) Python script was used as a solver and calculates the output.
- 6) The solver chain was run for n times (1000 times) to generate all output.
- 7) The MOP was created to quantify the contribution of each parameter on the proposed model.

The algorithm for the sensitivity analysis is presented in Figure 7. The parameters for the sensitivity analysis are given in Table 1.

Table 1: Parameters for Sensitivity analysis in optiSLang

Sampling method	ALHS
Number of samples	1,000
Meta-models	Polynomial, Clasic MLS, Interpolating MLS
Solver	Python script
Sample splitting ratio	50%
Number of steps	10
CoI limit	0-5%
Rank criteria	CoD_{adj}
Parameters (range):	
$A_o/A_w(x_1)$	0.05-1.2
$r_o/w(x_2)$	0.1-0.8
$r_o(x_3)$	0.3-2.0

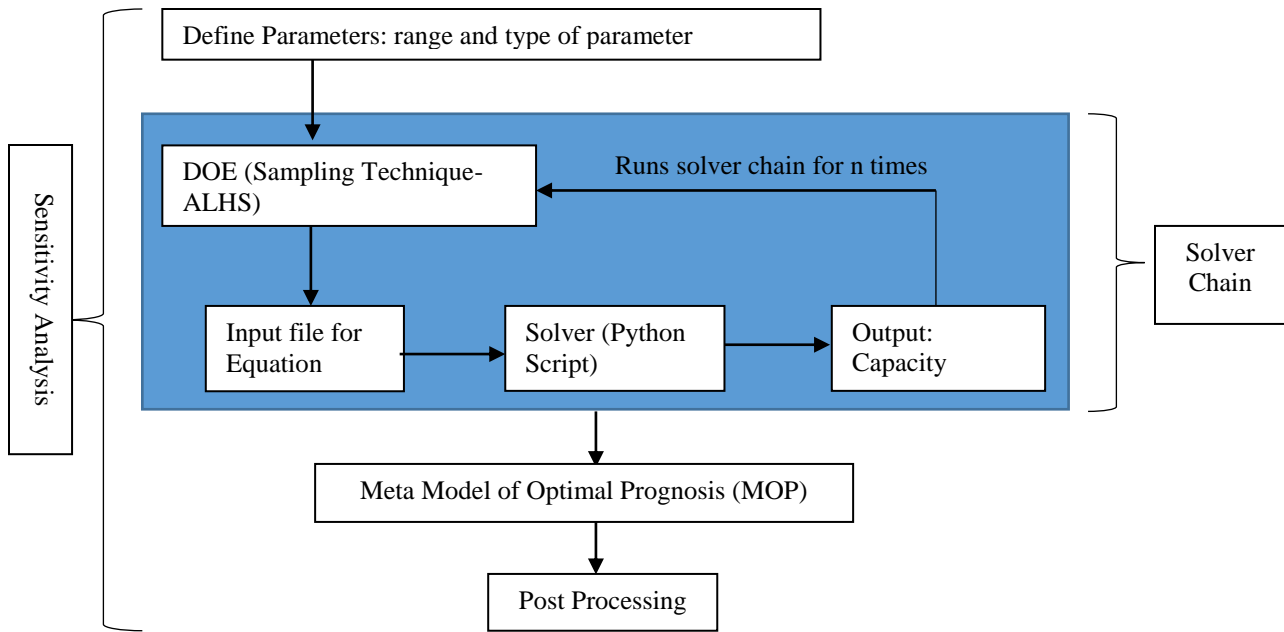


Figure 7: Algorithm for sensitivity Analysis in optiSLang

3.2 Results of Sensitivity Analyses

The impact of each input parameter on the output along with the models three dimensional space is illustrated in Figure 7 showing the MLS approximation of the unreinforced and reinforced I-joist's capacity with respect to the two model input parameters $A_o/A_w(x_1)$ and $r_{o/w}(x_2)$. The MLS approximation exhibited the variation of the output in the predicted model space. A smooth surface of the output (see Figure 8) indicated a good approximation of the proposed model. Using 1,000 samples, a CoP of 100% was achieved for the proposed models which indicated a perfect approximation using MOP. By comparing the CoP value of each parameter, it was found that both parameters $A_o/A_w(x_1)$ and $r_{o/w}(x_2)$ showed the highest influenced on I-joists capacity as compared to $r_o(x_3)$.

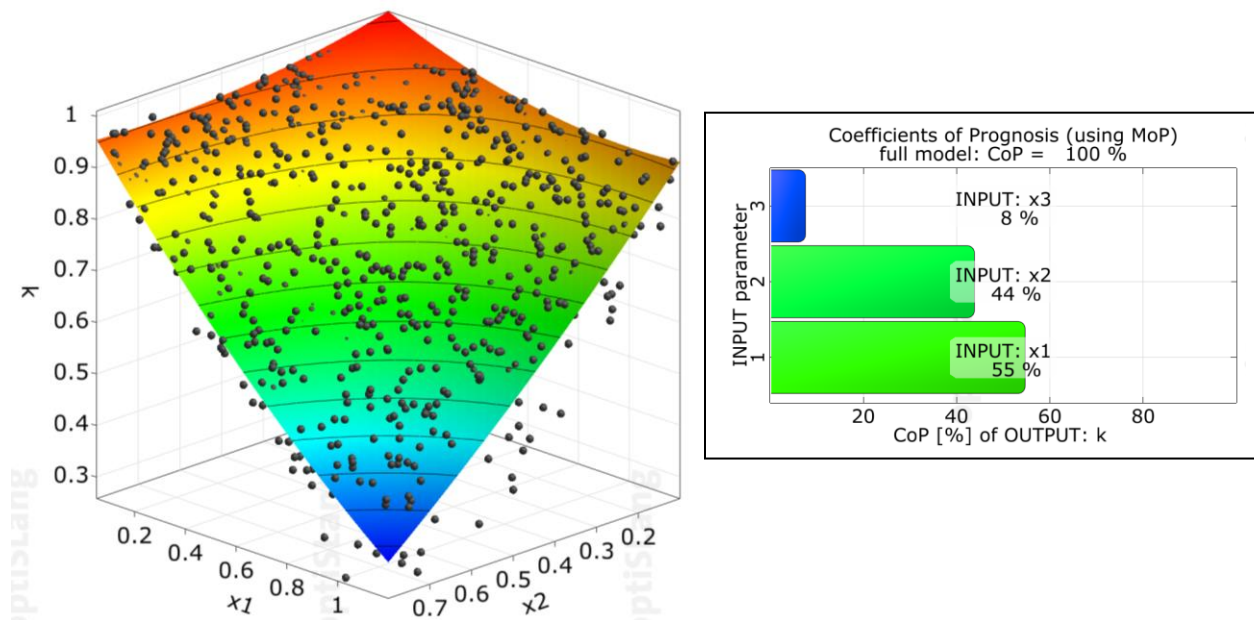


Figure 8: MLS approximation of the unreinforced capacity, P_u with respect to the two input parameters, $A_o/A_w(x_1)$ and $r_{o/w}(x_2)$ (left) and CoP values of each parameter (right).

4. CONCLUSION

FE models were developed that accurately predicted the in-plane behaviour of CLT panels with openings. The effect of opening size and shape on the stiffness of CLT walls was investigated. The experimental, numerical, and analytical investigation on the CLT panels allows the following conclusions to be drawn:

1. The FE model accurately predicted the load-deformation of CLT beams and walls.
2. With the removal of half of the wall area, stiffness was reduced by more 60%.
3. The proposed equation better predicted the reduced stiffness of the CLT walls compared to previous equations.
4. The sensitivity analysis using MOP and ALHS sampling technique showed a smooth variation of the proposed model with respect to input parameters.

ACKNOWLEDGEMENT

The research was supported by the FPInnovations, Canada in collaboration with Softwood Lumber Board (SLB), USA.

REFERENCES

- Blass, H. J., and Fellmoser, P. 2004. Design of solid wood panels with cross layers. *8th World Conference on Timber Engineering*, Lahti, Finland.
- Bogensperger, T., Moosbrugger, T., and Schickhofer, G. 2007. New Test Configuration for CLT-Wall-Elements under Shear Load. CIB W-18, Bled, Slovenia.
- Bogensperger, T., Moosbrugger, T., and Silly, G. 2010. Verification of CLT-plates under loads in plane. *11th World Conference on Timber Engineering*. Riva del Garda, Italy.
- Brandner, R., Bogensperger, T., and Schickhofer, G. 2013. In plane Shear Strength of Cross Laminated Timber (CLT): Test Configuration, Quantification and influencing Parameters. CIB W-18, Vancouver, Canada.
- CSA086-14. (2014). Engineering Design in Wood. Canadian Standards Association, Mississauga, Ontario, Canada
- Dujic, B., Klobcar, S. and Zarnic, R. 2007. Influence of Openings on Shear Capacity of Wooden Walls. CIB W-18. Bled, Slovenia.
- EN 1995. 384. Structural timber. Determination of characteristic values of mechanical properties and density. The British Standards Institution.
- Flaig M, Blass HJ. 2013. Shear strength and shear stiffness of CLT-beams loaded in plane. CIB W18, Vancouver, Canada.
- Jobstl, R. A., BOGENSPERGER, T., and Schickhofer, G. 2008. In-plane Shear Strength of Cross Laminated Timber. CIB W-18. St. Andrews, NB, Canada.
- Montgomery, D. C., Runger, G. C. 2003. *Applied statistics and probability for engineers*. John Wiley & Sons.
- Moosbrugger, T., Guggenberger, W., and Bogensperger, T. 2006. Cross-Laminated Timber Wall Segments under Homogenous Shear with and without Openings. *9th World Conference on Timber Engineering*. Portland, Oregon, USA.
- Most, T., Will, J. 2008. Metamodel of Optimal Prognosis-an automatic approach for variable reduction and optimal metamodel selection. *Weimar Optimization and Stochastic Days 5.0*, Weimar, Germany.
- NDS 2015. American Forest & Paper Association (AF&PA). National Design Specification for Wood Construction. Washington, DC: American Wood Council 2015.

- Popovski M, Schneider J, Schweinsteiger M. 2010. Lateral load resistance of cross laminated wood panels. *11th World Conference on Timber Engineering*. Riva del Garda, Italy.
- Sacks, J., Welch, W. J., Mitchell, T. J., Wynn, H. P. 1989. Design and analysis of computer experiments. *Statistical science*, 4(4): 409-423.
- Schneider J. 2015 Conventional and novel timber steel hybrid connections: testing, performance and assessment. PhD thesis, UBC Vancouver, Canada
- Simpson, T. W., Poplinski, J. D., Koch, P. N., Allen, J. K. 2001. Metamodels for computer-based engineering design: survey and recommendations. *Engineering with computers*, 2001, 17(2): 129-150.