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## TIMBER I-JOISTS WITH WEB OPENINGS: REINFORCEMENT, CAPACITY PREDICTION AND SENSITIVITY ANALYSIS

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### ABSTRACT

Timber I-joists are a popular product in light-frame wood construction in North America. The design with timber I-joists, however, has not yet achieved the same level of refinement compared to reinforced concrete or steel structures. One of the reasons is that timber I-joists have higher variability in their material properties than more homogeneous building materials. Additionally, although very commonly applied in practice, engineers and practitioners have limited knowledge and guidance for I-joists with web opening. As a result, in many cases the design of timber I-joists based on manufacturer's specifications lead to very conservative solutions. The present research predicts the capacity of unreinforced and reinforced timber I-joists with openings from experimental results. A total of 100 unreinforced and 100 reinforced I-joists with opening were tested under four point loading. The capacity of the I-joists with opening was predicted from regression analysis. A sensitivity analysis was performed for the predicted equations using Meta-model of Optimal Prognosis (MOP) to evaluate the contribution of each parameter on the model responses. The research demonstrates that the reinforcement technique was efficient for I-joists with openings and the proposed equations were very accurate to predict the I-joists capacity.

Keywords: I-Joists, Web, Opening, Capacity, Reinforcement, sensitivity analysis.

### 1. INTRODUCTION

Wooden I-joists are prefabricated engineering wood products which are popular in light frame construction as floor and roof elements because of their high strength and stiffness, low weight, dimensional stability and low cost in comparison to solid timber (AFPA 1999). During construction, openings are common to the webs of I-joists for passage of service ducts, plumbing and wiring. However, the presence of the web openings leads to reductions in stiffness and capacity. The current edition of the Canadian Standard for Engineering Design in Wood (CSA086 2014) provides no guidance for such openings in I-joists and the National Design Specification for Wood Construction in the US (NDS 2015) recommends manufacturer specifications for I-joists with openings.

Previous research evaluated the failure mode and capacity reduction of wood I-joists with web openings. Morris et al. (1995) summarized three failure modes as web fracture, web buckling, and de-bonding of web-flange adhesive joint. Fergus (1979) studied the effect of circular openings on moment-governed 7.3m long I-joists and shear-governed 2.4m long I-joists and found no significant change in stiffness with a web removal of up to 70% of total height. On the contrary, Maley (1987) and Wang and Cheng (1995) reported that openings reduced stiffness and shear capacity. Wang and Cheng (1995) investigated 2.8m to 3.6m long I-joists with rectangular web openings of 33% to 100% web height placed at a distance of 0.5m to 1.0m from the support and observed that the shear strength

was reduced up to 79% when the opening height was equal to the height of web. No significant change occurred for opening heights of 33% of web height. Afzal et al. (2006) performed tests on wood I-joists with circular and square openings. The I-joists were 302mm and 406mm deep and the opening size was varied up to 100% of web height. While the opening size-to-web depth and the span-to-depth ratio both affected the capacity, the types of opening (circular/square) were found insignificant. Zhu et al. (2005) investigated the failure load of wood I-joists with and without web openings, observed that capacity decreases linearly with opening size, whilst location of opening has little effect on the reduction of capacity. Guan and Zhu (2004) performed finite-element-analyses (FEA) to predict the behavior of wood I-joists with openings where the opening sizes were varied from one-quarter to three-quarter to the height of the I-joists. They observed that the predicted capacity for I-joist with circular openings was 20% higher than the I-joists with rectangular openings. Islam et al. (2015) investigated the capacity of I-joists with flange notches and found that the capacity reduced up to 80% compared to without any notches.

Previous studies used several techniques to increase the flexural and shear capacity of timber beams such as: (a) attaching metal, (b) solid timber, (c) EWP plates, and (d) Fiber-Reinforced-Polymer (FRP) sheets either by mechanical means or adhesive bonding (Franke et al. 2015). Morrissey et al. (2009) investigated reinforced I-joists with steel angles attached to both sides of the web and the flange above and below the openings. They obtained an increase in capacity up to 39%. Polocoser et al. (2013) reinforced wood I-joists around the openings with U-shaped LSL, OSB patches and OSB collars. Some of the tested reinforced specimens regained the capacity of the original joists and among the three different techniques, the OSB collar was found to be most effective.

## 2. EXPERIMENT

### 2.1 Objective

Placing web openings in I-joists is common practice that can lead to significant reduction in stiffness and capacity which – if not appropriately considered in design – may cause excessive deflections and premature failure of the element and possibly the structure. Practitioners, however, are not provided with sufficient design guidance that captures the reduction in capacity and stiffness of I-joists with web openings. The objectives of this research are to investigate the impacts of: i) reinforcing I-joists with web openings with OSB collars on the failure modes, capacity and stiffness on I-joists with web openings; ii) predict the capacity of I-joists with opening with sensitivity analysis.

### 2.2 Materials and Methods

All wood I-joists' specimens for experiment were prepared at the facility of AcuTruss Industries Ltd., Canada. The specifications were chosen from the NASCOR NJH12 I-joist series (Nascor 2010). Flanges were made of LVL from SPF No2, webs were made from OSB manufactured to meet the requirements of the Performance Standard for Wood-Based Structural-Use Panels (PS2 2010) and CSA-O325 (2012). The height of the specimens was 302mm, the flange width and height were 63.5mm and 38mm, respectively, and the thickness of the web was 9.5 mm, see Figure 1. The material for the subsequent retrofit was OSB from the I-joist fabrication. I-joists with two different span lengths of 3.66m (12ft) and 6.10m (20ft) were tested. They were categorized into five series (series A to E) of specimens. Ten beams from each series of a total of 100 specimens were tested. Series A was the control beam without any openings. Series B and C had an opening of diameter (D) equal to the height of the web (212.7mm). The distance of the opening from the edge ( $L_e$ ) in series B was 305mm for both 12ft and 20ft specimens, while in series C opening were located at 610mm and 915mm for 12ft and 20ft specimens, respectively. In series D and E, the diameter of the opening was 152.4mm and 101.6mm respectively and the opening was located 305mm from the edge. The size and location of the openings are described in Figure 1 and Table 1.

I-joists with the same dimensions and openings as series B to E were reinforced with OSB collars to investigate the impact of the retrofit on capacity and stiffness. Five more series (series F to J) of specimens with the same span length of 3.66m (12ft) and 6.10m (20ft) were tested after being reinforced around the opening with an OSB collar. Collars were located on only one side of the web and consisted of two layers, each layer composed of 9.5mm (3/8inch) OSB. The first layer was arranged around the opening and glued directly onto the web. The second layer was glued on top of the first collar. The reinforcement length ( $L_r$ ) of the OSB collar on each side of the opening was kept equal to the diameter of the opening (series F to I). Only for series J, the collar (reinforcement) length was doubled to evaluate the capacity improvement due to OSB collar length. The details of the reinforced I-joists are given in Figure 2 and Table 1. A total of 100 reinforced specimens were tested with ten replicates in each test series.

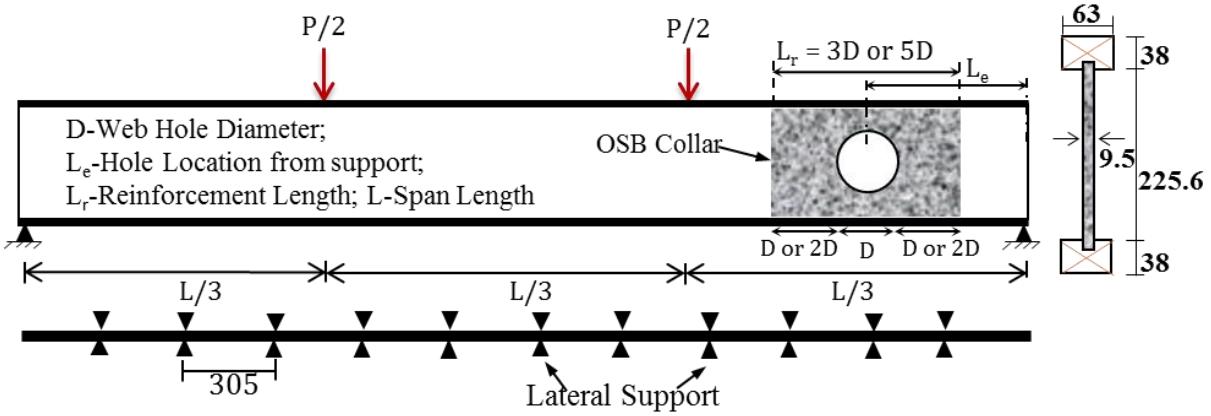


Figure 1: Schematic of I-Joists with web opening and retrofitting (left), cross section (right).

Table 1: Summary of test series and test results

| I-Joist               | Series ID          | $L$  | $D$  | $L_e$ | $L_r$   | $k$   |      | $F_{exp}$ |      |      |
|-----------------------|--------------------|------|------|-------|---------|-------|------|-----------|------|------|
|                       |                    | mm   | mm   | mm    | mm      | N/mm  | COV  | kN        | COV  |      |
| Control               | 12-A               | 3650 | -    | -     | -       | 1220  | 17   | 40.5      | 30.4 |      |
|                       | 20-A               | 6100 | -    | -     | -       | 310   | 10   | 28.9      | 14.3 |      |
| I-Joists with Opening | 12-B               | 3650 | 213  | 305   | -       | 1000  | 10   | 18.3      | 11.7 |      |
|                       | 12-C               | 3650 | 213  | 610   | -       | 1035  | 10   | 17.1      | 9.72 |      |
|                       | 12-D               | 3650 | 150  | 305   | -       | 1080  | 14   | 27.5      | 9.5  |      |
|                       | 12-E               | 3650 | 100  | 305   | -       | 1165  | 16   | 36.5      | 18.9 |      |
|                       | 20-B               | 6100 | 213  | 305   | -       | 364   | 12   | 20.7      | 13.1 |      |
| I-Joists with Opening | 20-C               | 6100 | 213  | 914   | -       | 315   | 14   | 20.1      | 13.1 |      |
|                       | 20-D               | 6100 | 150  | 305   | -       | 345   | 11   | 27.9      | 15.2 |      |
|                       | 20-E               | 6100 | 100  | 305   | -       | 305   | 9    | 26.3      | 24.8 |      |
|                       | Reinforced I-Joist | 12-F | 3650 | 213   | 305     | D+D+D | 1045 | 13        | 21.9 | 13.4 |
|                       |                    | 12-G | 3650 | 213   | 610     | D+D+D | 1085 | 8         | 20.5 | 9.7  |
| 12-H                  |                    | 3650 | 150  | 305   | D+D+D   | 1115  | 9    | 35.2      | 13.9 |      |
| 12-I                  |                    | 3650 | 100  | 305   | D+D+D   | 1180  | 14   | 40.7      | 24.1 |      |
| 12-J                  |                    | 3650 | 100  | 305   | 2D+D+2D | 1240  | 15   | 45.9      | 24.7 |      |
| 20-F                  |                    | 6100 | 213  | 305   | D+D+D   | 310   | 12   | 21.1      | 13   |      |
| 20-G                  |                    | 6100 | 213  | 914   | D+D+D   | 310   | 8    | 22.2      | 10.6 |      |
| 20-H                  |                    | 6100 | 150  | 305   | D+D+D   | 305   | 9    | 30.5      | 16.8 |      |
| 20-I                  |                    | 6100 | 100  | 305   | D+D+D   | 320   | 15   | 29.2      | 9.9  |      |
| 20-J                  |                    | 6100 | 100  | 305   | 2D+D+2D | 315   | 11   | 26.7      | 15.1 |      |

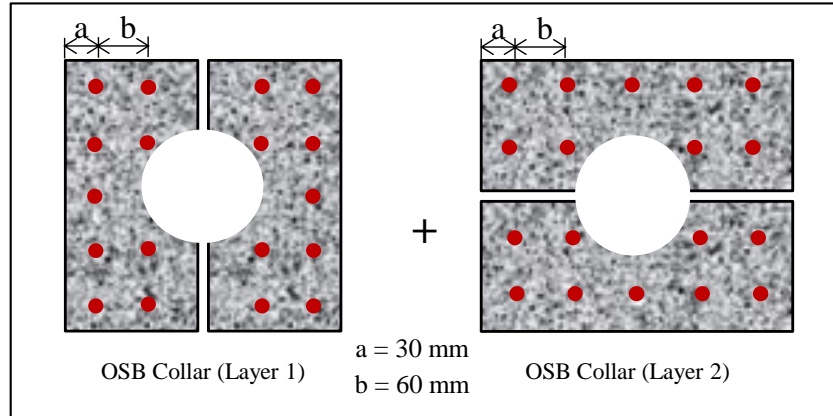


Figure 2: Retrofit of I-joists with two OSB ply in collar system

The specimens were tested as simply supported beams in four-point bending according to ASTM D5055 (2013). The loads were applied by a hydraulic actuator with a loading rate of 4mm/min. Hollow structural section (HSS) rectangular tubes were placed vertically on both sides of the flanges along the length of I-Joists at a spacing of 305mm to ensure concentric loading and to prevent lateral buckling (see Figure 1). The joist deflections were measured by placing an extensometer at mid-span. The stiffness was calculated for the range of 10% to 40% of capacity according to EN 26891 (CEN 1991) Three cameras, focused at the mid-span, at the location of opening and at the loading point, were installed to monitor the crack pattern and failure of the specimens.

### 2.3 Results

The load-deflection all specimens were linear up to failure. The average capacities and stiffness for all test series as well as the corresponding coefficient of variations (COV) are summarized in Table 1.

Series A represents the control beams without any opening. The 12ft I-joists failed in either shear at support or flexure at mid-span. The failure was initiated mostly by the presence of knots in the flanges or due to de-bonding of the OSB webs. In the case of 20ft I-joists, all the specimens failed in flexure at mid-span and there was no shear failure in any of the 20ft specimens. The presence of an opening changed the failure mode and capacity of the I-joists. Series B specimens featured an opening equal to the height of the web and located 305mm from the leading edge. All 12ft and most 20ft series B I-joists failed in shear at the opening, the exceptions being specimen 20-B9 which failed in shear right next to the opening and specimen 20-B10 which experienced flexural failure at mid-span. In both specimens failure was initiated at a knot. Series C featured the same opening size as series B but located at 610mm and 915mm from the support for 12ft and 20ft I-joists, respectively. All specimens of series C failed in shear at the location of the opening. All specimens of series D (openings 66% the height of the web and located 305mm from the support) failed in shear, with failure starting diagonally at the opening by cracking of OSB followed by web-flange joint de-bonding and finally diagonal splitting of the flange. Half of the 12ft specimens of Series E (openings about 50% of the web height, also located at 305mm from the support) failed in shear diagonally along the opening similar to series D. The failure patterns of the 20ft I-joists were similar to the control series A with all specimens failing in flexure close to mid span and capacity was similar to the control beams.

The opening in each I-joist of series F through I were reinforced by attaching an ( $L_r = D$ ) OSB collar around the opening. This collar prevented abrupt failure at the location of the opening. The majority of specimens still failed in shear diagonally which was followed by de-bonding of web-flange joint. The OSB collar de-bonded at the end of the failure process. In two series F specimens (20-F2 and 20-F10), the OSB collar prevented the shear failure and instead induced a flexural failure. In series G, all 12ft I-joists and all but two 20ft specimens failed in shear diagonally at opening. The exceptions failed in flexure at mid-span. Compared to unreinforced series B the capacity of both 12ft F and G series specimens was found to be 19% higher. Most 12ft and all 20ft specimens from series H failed in flexure, similar to control I-joists series A, and compared to unreinforced series D, their capacity increased 27% and 13% 12ft/20ft, respectively. Likewise, in series I the reinforcement collar efficiently prevented failure at the opening and the failure of the both 12ft and 20ft I-joists was in flexure. Compared to unreinforced series E, average capacity improved by 4% and 13%, respectively, for 12ft and 20ft reinforced I-joists. In series J, the length of the

OSB collar on each side of the opening was doubled compared to series I to  $L_r = 2D$ . Most of the 12ft and all of the 20ft reinforced I-joists failed similar to the control specimens either in flexure at mid-span or in shear at the loading point. The capacity of the 12ft and 20ft I-joists increased 17% and 8%, respectively, compared to unreinforced series E and even 14% and 5% compared to the control series.

### 3. I-JOISTS CAPACITY PREDICTION

A regression analysis was performed using the test results to develop models to predict the capacity of unreinforced and reinforced I-joists with web openings. I-joist span length-to-height ratio ( $L/h$ ) and opening size to web height ratio ( $D/h_w$ ) affect the capacity of I-joist (Afzal et al. 2006) and were considered in the regression model. The proposed equations for unreinforced and reinforced I-joists with web opening are:

$$[1] \quad P_{\text{unreinforced}} = 64.8 - 1.5(L/h) - 54.3\left(\frac{D}{h_w}\right) + 1.9(L/h)\left(\frac{D}{h_w}\right)$$

$$[2] \quad P_{\text{reinforced}} = 105.6 - 3.5(L/h) - 90.8\left(\frac{D}{h_w}\right) + 3.8(L/h)\left(\frac{D}{h_w}\right)$$

where,  $L$  is the I-joist span length (m),  $h$  is the height of I-joists,  $D$  is the size of opening size and  $h_w$  is the height of web. The predictions using these models compared against the test results are illustrated in Figure 3.

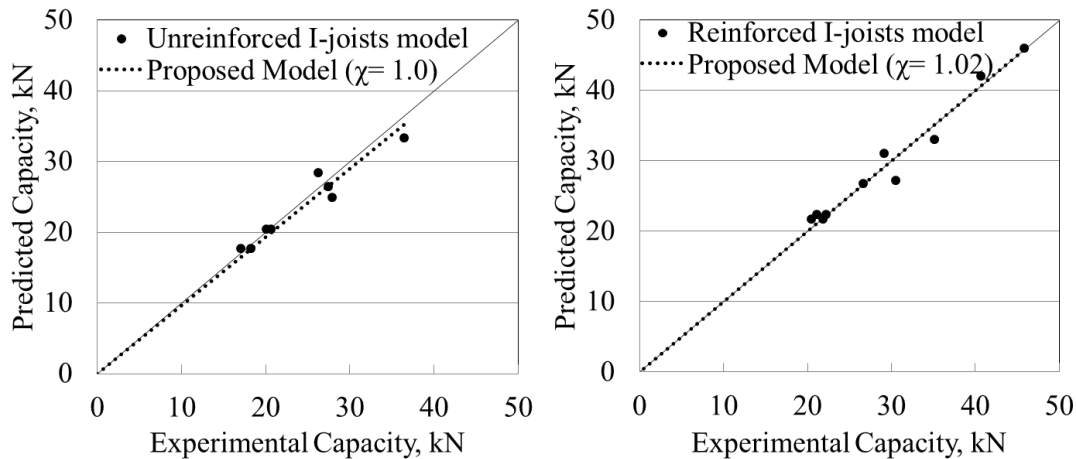


Figure 3: Predicted vs experimental capacity: unreinforced I-joists (left) and reinforced I-joists (right).

## 4. SENSITIVITY ANALYSIS

### 4.1 Methods

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, the sensitivity analyses were performed using the commercially available software package OptiSlang by Dynardo (Most and Will 2008). The design of experiments (DOE) for random sampling for sensitivity analysis utilizes Advanced Latin Hypercube Sampling (ALHS). ALHS is very 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) was

developed (Most and Will 2008), an automatic approach for the optimal filter meta-model configurations. 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 (Montgomery and Runger 2003) as follows:

$$[3] \quad R^2 = \frac{SS_R}{SS_T} = 1 - \frac{SS_E}{SS_T}; \quad 0 \leq R^2 \leq 1$$

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:

$$[4] \quad SS_T = \sum_{i=1}^N (y_i - \mu_Y)^2, \quad SS_R = \sum_{i=1}^N (\hat{y}_i - \mu_{\hat{Y}})^2, \quad SS_E = \sum_{i=1}^N (y_i - \hat{y}_i)^2$$

However, in order to penalize the over-fitting, Montgomery and Runger (2003) also introduced the adjusted Coefficient of Determination as in Equation 5.

$$[5] \quad R_{adj}^2 = 1 - \frac{N-1}{N-p} (1 - R^2)$$

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) defined as in Equation 6.

$$[6] \quad CoP = \left( \frac{\mathbf{E} \left[ Y_{Test} \hat{Y}_{Test} \right]}{\sigma_{Y_{Test}} \sigma_{\hat{Y}_{Test}}} \right)^2; \quad 0 \leq CoP \leq 1$$

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 7.

$$[7] \quad CoI_{Y, X_i} = R_{Y, X}^2 - R_{Y, X: i}^2$$

Where,  $R_{Y, X}^2$  is the *CoD* of the full model including all terms of the variables in  $X$  and  $R_{Y, X: i}^2$  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 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 4. The parameters setting for the sensitivity analysis is given in Table 2.

| 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 <sub>adj</sub>                        |
| Parameters (range):    |   |
| $L/h(x_1)$             | 4.0-25.0                                  |
| $D/h_w(x_2)$           | 0.1-1.0                                   |

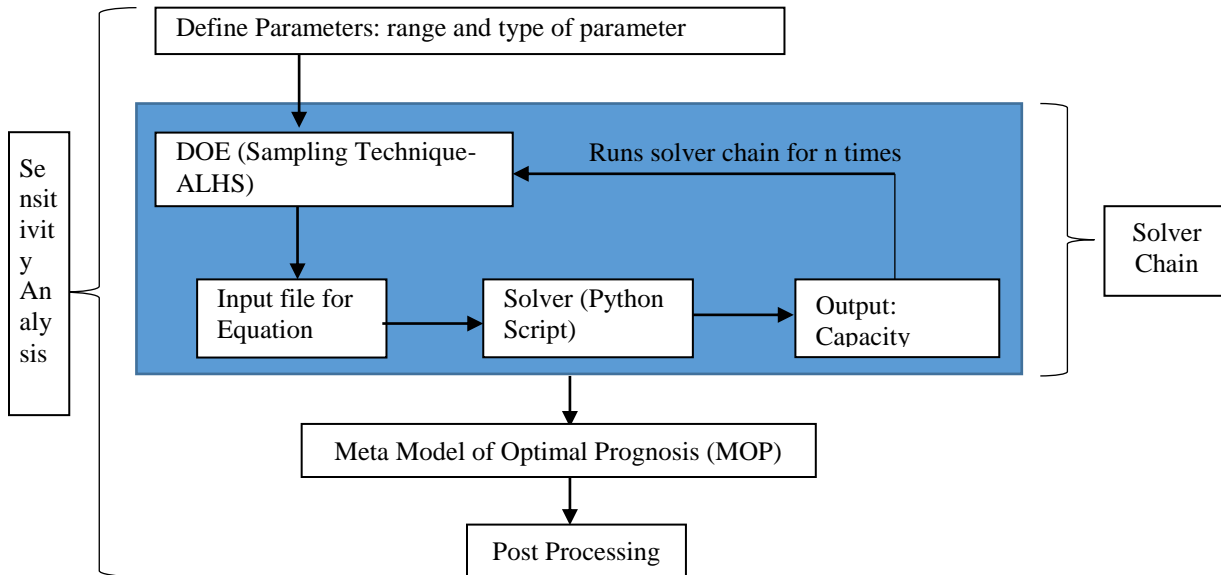


Figure 4: Algorithm for sensitivity Analysis in Optislang

## 4.2 Results

The impact of each input parameter on the output along with the models three dimensional space is illustrated in Figures 5 and 6 showing the MLS approximation of the unreinforced and reinforced I-joist's capacity with respect to the model input parameters  $L/h(x_1)$  and  $D/h_w(x_2)$ . The MLS approximation exhibited the variation of the output in the predicted model space. A smooth surface of the output (see Figure 5 and 6) indicated a good approximation of the proposed model. By 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  $L/h(x_1)$  and  $D/h_w(x_2)$  influenced I-joists capacity significantly, where,  $D/h_w(x_2)$  showed higher impact compared to  $L/h(x_1)$ .

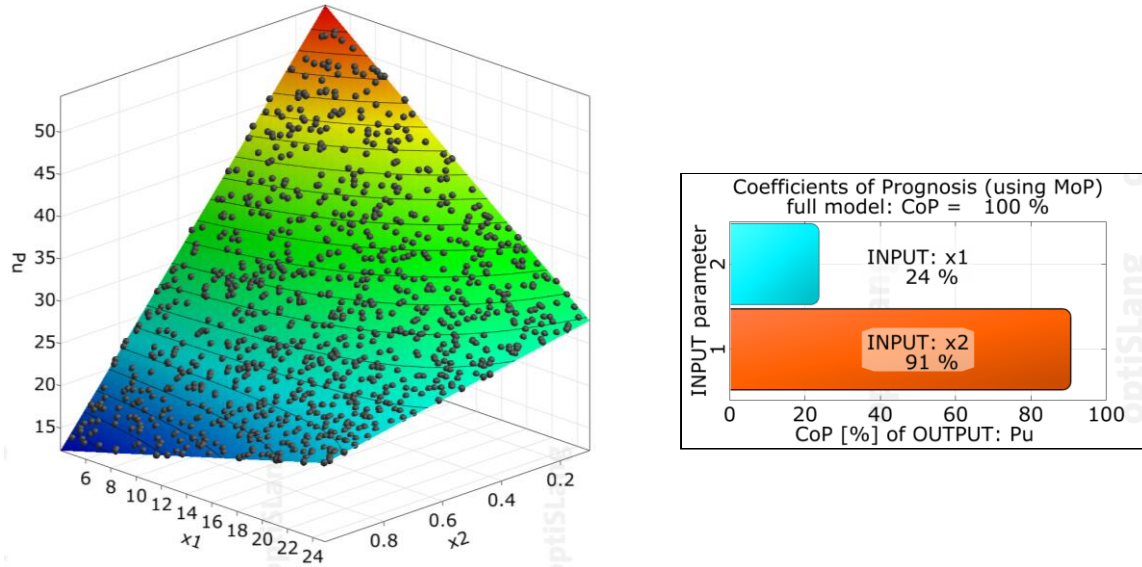


Figure 5: MLS approximation of the unreinforced capacity,  $P_u$  with respect to the two input parameters,  $L/h$  ( $x_1$ ) and  $D/h_w$  ( $x_2$ ) (left) and CoP values of each parameter (right).

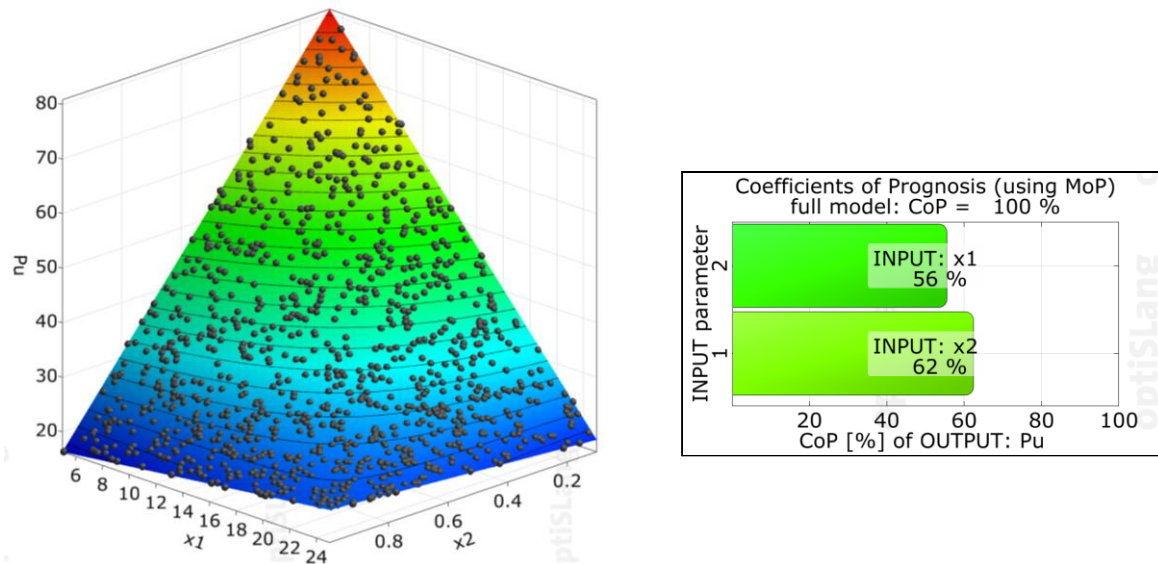


Figure 6: MLS approximation of the reinforced capacity,  $P_u$  with respect to the two input parameters,  $L/h$  ( $x_1$ ) and  $D/h_w$  ( $x_2$ ) (left) and CoP values of each parameter (right).

## 5. CONCLUSION

The experimental and analytical investigation on 12ft and 20ft wood I-joists with web openings (unreinforced and reinforced) allows the following conclusions to be drawn:

1. An opening had more impact on smaller span beams. Most of the 12ft test specimens with openings showed premature shear failures at the location of the opening. The capacity of 12ft I-joists was reduced up to 54%, while for 20ft I-joists, the capacity was reduced only up to 21%.
2. In the case of 20ft I-joists, presence of openings about half of the web height did not have any effect on longer span beams. The statistical analyses confirmed these findings.



3. The reinforcement of I-Joists with OSB collars significantly increased the capacity (27% and 20% respectively for 12ft and 20ft I-joists). Furthermore, the capacities of the reinforced I-Joists (series I and J) were found almost equal to the control series capacity.
4. The proposed regression model to predict the capacity of an I-joist with reinforced openings was also sufficiently accurate.
5. The sensitivity analysis using MOP and ALHS sampling technique showed a smooth variation of the proposed model with respect to input parameters.

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## REFERENCES

- Afzal, M. T., Lai, S., Chui, Y. H., and Pirzada, G. 2006. Experimental evaluation of wood I-joists with web holes. *Forest products journal*, 56(10): 26.
- American Forest & Paper Association (AFPA) 1999. Guideline wood I-Joists: Manual for engineered wood construction. American Forest & Paper Association Inc.
- ASTM-D5055-13e1, 2013. Standard Specification for Establishing and Monitoring Structural Capacities of Prefabricated Wood I-Joists. ASTM International, West Conshohocken, PA.
- CSA O86-14, 2014. Engineering design in wood, Canadian Standards Association, Mississauga, Canada.
- CSA-O325, 2012. Construction Sheathing. Canadian Standard Association.
- EN 2689, 1991. European Committee for Standardization CEN. Timber structures - Joints made with mechanical fasteners - General principles for the determination of strength and deformation characteristics. (ISO 6891:1983). CEN, Brussels, Belgium.
- Fergus, D. A. 1979. Effect of web voids and stiffeners on structural performance of composite I-beam. Purdue University, West Lafayette, Indiana, USA.
- Franke, S., Franke, B., Harte, A. M. 2015. Failure modes and reinforcement techniques for timber beams—State of the art. *Construction and Building Materials*, doi:10.1016/j.conbuildmat.2015.06.021.
- Guan, Z. W., and Zhu. E. C. (2004). Non-linear FE modelling of crack behaviour of openings in OSB webbed I-beams. *ASCE J Struct Eng.*, 130(10):1562–9.
- Islam, M. S., Shahnewaz, M., and Alam, M. S. (2015). Structural capacity of timber I-joist with flange notch: Experimental evaluation. *Construction and Building Materials*, 79, 290-300.
- Maley, J. D. 1987. Wood I-joists: a closer look. Proceedings Structures Congress, Building Structures, New York, American Society of Civil Engineers, 221–35.
- Montgomery, D. C., Runger, G. C. (2003). Applied statistics and probability for engineers. John Wiley & Sons.
- Morris, V., Gustafsson, P. J., and Serrano, E. 1995. The shear strength of light-weight beams with and without a hole-A preliminary study. Proc. Work. Mech. Prop. Panel Prod., Watford, U.K: Building Research Establishment.
- Morrissey, G. C., Dinehart, D. W., and Dunn, W.G. 2009. Wood I-Joists with Excessive Web Openings : An Experimental and Analytical Investigation. *J Struct Eng*, 135(6), 655–65.

- Most, T., Will, J. 2008. Metamodel of Optimal Prognosis-an automatic approach for variable reduction and optimal metamodel selection. Proc. Weimarer Optimierungs-und Stochastiktage, 5: 20-21.
- Nascor 2010. Nascor Specifier Guide: NJ, NJH, NJU Series I-Joists.
- NDS 2015. American Forest & Paper Association. (AF&PA). National Design Specification for Wood Construction. Washington, DC: American Wood Council.
- Polocoser, T., Miller, T. H., and Gupta, R. 2013. Evaluation of Remediation Techniques for Circular Holes in the Webs of Wood I-Joists. *Journal of Materials in Civil Engineering*. 25(12), 1898-1909.
- PS2-10, 2010. Performance Standard for Wood-Based Structural-Use Panels. Voluntary Product Standard PS 2-10.
- Sacks, J., Welch, W. J., Mitchell, T. J., Wynn, H. P. 1989. Design and analysis of computer experiments. *Statistical science*, 4(4): 409-423.
- 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.
- Wang, A., and Cheng, J. J. R. 1995. Shear behaviour of OSB wood composite I-beams with web opening. Edmonton, Albarta, Canada.
- Zhu, E. C., Guan, Z. W., Rodd, P. D., Pope, D. J., 2005. Finite element modelling of OSB webbed timber I-beams with interactions between openings. *Advances in Engineering Software*, 36(11): 797-805.