PREDICTING LOAD DEFLECTION RESPONSE OF WOOD I-JOISTS WITH FLANGE NOTCH

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Abstract:

Canada's 400 million hectares of land area are covered with forest, which is 43.6 percentage of its total land area. Through a sustainable forest management this huge forestry resources can be utilized without creating any impact to the global environment. Construction of civil infrastructure with timber is a viable option for utilizing this huge resource. Timber I-joist is an engineered building construction element produced from solid timber and Oriented Strand Board (OSB) as flange and web, respectively. Timber I-joists are commonly used in building construction due to easiness of passing the service conduits and ducts through openings in the OSB web of I-joists and the passageway for service conduits and ducts usually made without considering the structural integrity of the system. This research study investigated the ultimate capacity of wood I-joists in the presence of flange cut. A total of 100 specimens were tested with various sizes and locations of openings in the flange. 10 specimens were tested as control beams with no openings. The I-joists were tested with four points bending test in two different span lengths of 3.66 m (12 feet) and 6.10 m (20 feet) to evaluate the load carrying capacity of I-joist. Based on the test results, linear and non-linear regression models were developed for load-deflection response of each series of I-joists and Akaike Information Criterion (AIC) has been calculated to determine the best fit model. It is found that the linear models are well fitted for predicting the load capacity of I-joists for structural analysis.

1 INTRODUCTION

Composite wood I-joists are widely used as floor and roof joists in the construction of commercial and residential buildings in Europe and North America. Commonly these I-joists are made with timber or laminated veneer lumber (LVL) as flange material in combination with Oriented Strand Board (OSB) or Ply-wood as web materials. These structurally engineered wood I-joists are cheaper, lighter weight, stronger, and more efficient compared to the solid sawn lumber beams. According to the manufacturer design guideline (American-Wood-Council 1999), (WIJMA 2008), flange cut OSB webbed I-joists are strictly prohibited to use in construction sites. Cuts and notches in the flange of I-joist are commonly made during construction to facilitate the electro-mechanical systems of the buildings. The effect of flange notches on the strength properties (e.g. load carrying capacity, moment capacity, and shear strength) of wood I-joists is not fully understood and current design specifications (Canadian-Standard-Association 2010) for building construction do not provide any design guideline for I-joists with flange cut and notches(Canadian-Standard-Association 2010). Very few research studies on OSB webbed timber I-joists with flange cut and notch have been conducted (Hindman and Loferski 2008). The prime objective of this research paper is to compare the load capacity and stiffness of single flange cut I-joists with those of an uncut I-joist (control specimen). In the current research study, an experimental work was carried out on OSB webbed timber I-joists with flange notches or cuts at different locations along the length as well as two different sizes of flange cuts. A total of 80 I-joist specimens with flange notched and 20 uncut (control) I-joists were tested in this experimental study to investigate the strength reduction and failure pattern of I-joists with flange notches.

Timber I-joists are very commonly used in building construction due to their easiness of passing the service conduits and ducts through the openings of OSB web of I-joists. However, due to its common uses as a building material, service or utility constructors are careless when cutting openings at the web I-joists and sometimes they cut the flanges unintentionally or without considering the structural integrity to accommodate the service conduits and ducts. As a result the main constructor must replace or retrofit the flange cut I-joists both of which may affect the project cost, time schedule and safety of the project.

Most of the previous research studies were carried out on the wood I-joists with web holes rather than with flange notch or cut. An experimental study and finite element modelling was conducted by Zhu et al. (2005) and they found that stress concentrations occur around the web opening. They also observed that fractures were formed in tension zones around the opening of the OSB web and the cracks developed towards the beam flanges in a direction roughly at 450 to the beam axis. Pirzada et al. (2008) conducted their study predicting the strength of wood I-joists with web holes by applying fracture mechanics based on the Finite Area Method (FAM). (Afzal et al. 2006 also conducted an experimental study to evaluate the I-joist strength with web holes (Afzal et al. 2006). Later on Morrissey et al. (2009) conducted an experimental and analytical investigation with excess web openings. Finite-element analyses of all test configurations were conducted to understand the effects of web openings (circular and square) on the stiffness, stress distributions around openings, and ultimate failure mechanisms. They observed that square web openings are more critical than the circular web openings for load carrying capacity due to the occurrence of stress concentration at the corner of the square opening. The load carrying capacity of I-joists with circular web openings was 45% lower than that of the control I-joists, whereas for I-joists with square openings, it was 53% lower than that of the control I-joists.

2 TESTING OF TIMBER I-JOISTS WITH A SINGLE FLANGE CUT

Two different span lengths of I-joists were tested; 3.65m and 6.1m. These joists were produced by an I-joist manufacturer (AcuTruss Industries Limited) in Kelowna, Canada. The I-joists were produced with a 9.5mm thick OSB web and 38mm by 63mm lumber flanges as shown in Fig. 1. Test set-up and specimen dimensions were selected by strictly following the provisions of ASTM D 5055 (ASTM-2013) and Wood I Joist Manufacturer guideline (WIJMA 2008). The test setup and loading diagram are shown in Fig. 2.

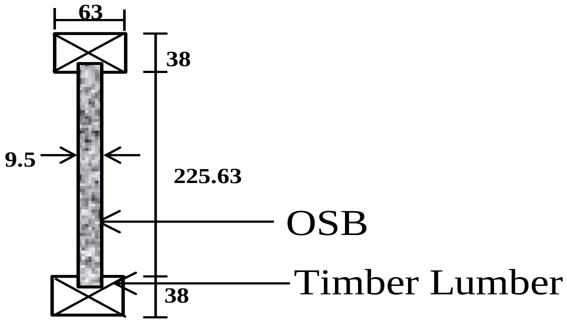

Fig. 1: Cross Section of Tested I-Joists (Dimensions are in mm)

Table 1 represents the different configurations of flange cut I-joists tested including the distance of the cut from the support of the beam (L_n), span length (L), dimensions of the flange cut ($b \times d$), and number of samples. The locations of the flange notch were selected as per the most common scenarios experienced by the I-joist installation and manufacturing industry. I-joist manufacturing industry usually faces the notch related problems within 600 mm (2 ft) from the end support due to the presence of floor drains of sewer and sanitary pipes and conduits. The load and deflections were measured continuously during the entire test. The deflections were measured in two different methods; an extensometer was used to measure the deflection of I-joists at the mid span up to a certain limit (usually the maximum measurement limit of the extensometer) and image processing analysis was used beyond that certain limit until the failure occurred. Considering the large length of the specimen, three High Definition (HD) cameras were used to record the entire test of each specimen in three different locations (mid span, one loading point and flange cut) for continuous monitoring of deflection and crack development.

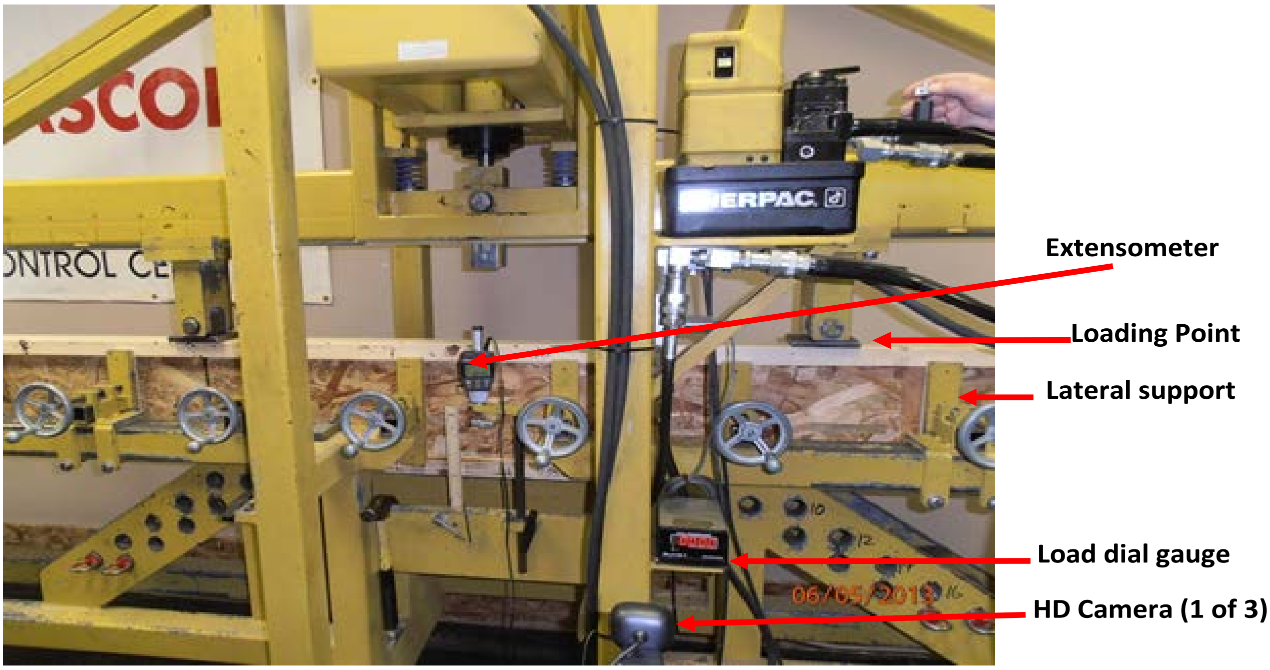

Fig. 2: Test setup for I-joist test with four point loading.

Table 1: Specimen Details of I-Joist Testing

Specimen Code	Span (mm)	Notch Size, (b x d) (mm)	Notch Distance, (L_n) (mm)	No. of Samples	Span (mm)	Specimen Code
12-A--	3650 (12ft)	-	-	10+10	6100 (20ft)	20-A--
12-F--	3650 (12ft)	100x100	305	10+10	6100 (20ft)	20-K--
12-G--	3650 (12ft)	100x100	455	10+10	6100 (20ft)	20-L--
12-H--	3650 (12ft)	100x100	610	10+10	6100 (20ft)	20-M--
12-I--	3650 (12ft)	100x150	455	10+10	6100 (20ft)	20-N--

The average peak load and stiffness were determined to evaluate the delamination of the I-joist performance with flange cut. Stiffness was measured as described by Hindman et al. (Hindman and Loferski 2008), which is defined as the slope of the load deflection curve in the liner elastic region of the curve. All the model fitting analysis was performed with the open source statistical computing program R (version 3.0.2) (R 2013). Along with the generalized goodness of fit tests (R square, adjusted R square, SSE, and RMSE) of regression models, a parsimony index, Akaike Information Criterion (AIC), was also determined for each linear and non-linear model. AIC values of linear and non-linear models were compared to each other and ΔAIC was measured as shown in Equation 4 (Burnham and Anderson 2004). ΔAIC gives an indication of information loss between the fitted linear model and non-linear model. AIC was determined as described in Equation 1 as suggested by Bozdogan H. (1987). The first term of the equation AIC represents the badness of fit and the second term represents the complexity or the penalty due to the increased reliability of the first term (Bozdogan 1987). All values of goodness of fit indices are listed in **Table 3**.

$$\mathrm{AIC} = -2\log(\hat{\theta}_k) + kn \qquad (1)$$

$$\Delta\mathrm{AIC} = \mathrm{AIC}_i - \mathrm{AIC}_{\min} \qquad (2)$$

$\hat{\theta}_k$ = likelihood; n= number of free parameters (for linear model, y=ax; n=1 and for non-linear model, $y=ax^2+bx$; n= 2); k=2

3 RESULTS AND DISCUSSIONS

The following section discusses and compares the results from the I-joists experiment. Among the test specimens, series A is the control beams with no opening, series F to I and K to N are the beams with different sizes of flange notch at different locations.

3.1 Load Carrying Capacity

The behaviour of I-joists can be attributed to the load-deflection response as demonstrated in a four point bending test. It was perceptible from the load deflection response of individual tested I-joists that most of the I-joists significantly exhibited the liner elastic behaviour during the entire test duration until failure. However, some I-joists (12-F, 12-G, 12-H, 12-I, and 20-K) also showed a linear relationship at the beginning of the test, which can be attributed to the elastic region of the load deflection response and followed by a nonlinear portion which can be attributed to the inelastic state of the load deflection response of the I-Joists.

The average and coefficient of variation (COV) results of the peak load and stiffness are presented in **Table 2**. For the peak load values, the COV varied from 7.6% to 32.5% and 8.4% to 25.4% for 3.65m span and 6.1m span, respectively. For the stiffness values, the COV varied from 7.6% to 16.43% and 7.2% to 15.1% for 3.65m span and 6.1m span respectively. However, the peak load values varied over a higher range in the presence of large size knots. For instance, knots were present in few samples for the 12-A, 20-A, 20-K and 20-N series I-joists. Hence, a higher COVs were observed for these series, where neglecting those samples could significantly reduce the variations as shown in parenthesis (e.g. COV of peak load for 3.65m span I-joists significantly reduced from 32.5% to 9%).

Table 2: Test Results of the I-Joist with flange cut at different location

Specimen Code	Avg. Max. Load (N)	COV %	Avg. Stiffness (N/m)	COV %	Specimen Code	Avg. Max. Load (N)	COV %	Avg. Stiffness (N/m)	COV %
12-A	990.72 (1157.70)	32.5 (9.0)	33.64	7.6	20-A	685.79 (748.93)	25.4 (16.5)	8.56	15.1
12-F	486.50	9.5	28.46	10.6	20-K	384.13 (395.09)	14.4 (11.6)	6.66	8.0
12-G	284.37	10.9	22.61	16.4	20-L	301.54	8.4	6.24	7.2
12-H	199.07	7.6	20.71	12.2	20-M	208.96	14.2	6.25	16.7
12-I	176.79	21.9	18.24	10.3	20-N	170.27 (176.79)	15.3 (9.6)	5.77	11.4

3.2 Load Prediction Model

It was perceptible from the load deflection response of individual tested I-joists that most of the I-joists significantly exhibited the liner elastic behaviour during the entire test duration until failure. However, some I-joists (12-F, 12-G, 12-H, 12-I, and 20-K) also showed a linear relationship at the beginning of the test, which can be attributed to the elastic region of the load deflection response and followed by a nonlinear portion which can be attributed to the inelastic state of the load deflection response of the I-Joists. To predict the load deflection response of flange cut I-joists, two types of regression models (linear and non-linear) have been developed to represent the load-deflection responses of each type of specimen based on the experimental results as shown in **Fig. 3**. The R^2 values for linear regression analysis vary from 0.9698 to 0.9850 and 0.9520 to 0.9940 for 3.65m and 6.1m I-joists, respectively.

However, the R^2 values for non-linear regression analysis vary from 0.9746 to 0.990 and 0.9580 to 0.9944 for 3.65m and 6.1m I-joists, respectively.

From **Table 3**, it is obvious that the linear models are the best fitted model for the 12-A, 20-A, 20-L, 20-M and 20-N, I-joist series as the AIC values are lower for the linear models than those of the non-linear models. The percent loss of information (%ΔAIC) for these five series, is very low (<1.0%). Moreover, the R square, adjusted R square, SSE, and RMSE values of linear and non-linear models of these five series are very close to each other. For Series 12-H and 12-I the percent loss of information between the fitted linear and non-linear models is less than 2.0%, which is within the threshold limit of the best fitness of the model (ΔAIC≈10.0). However, for I-joist series 12-F, 12-G and 20-K, the percent loss of information between the linear and non-linear models is more than 3.0% which is beyond the threshold limit of the best fitness of the model (ΔAIC>10.0). Hence, from above discussion, it can be suggested that use of linear models instead of non-linear models for any structural analysis is more efficient to avoid the complexity of the analysis procedure.

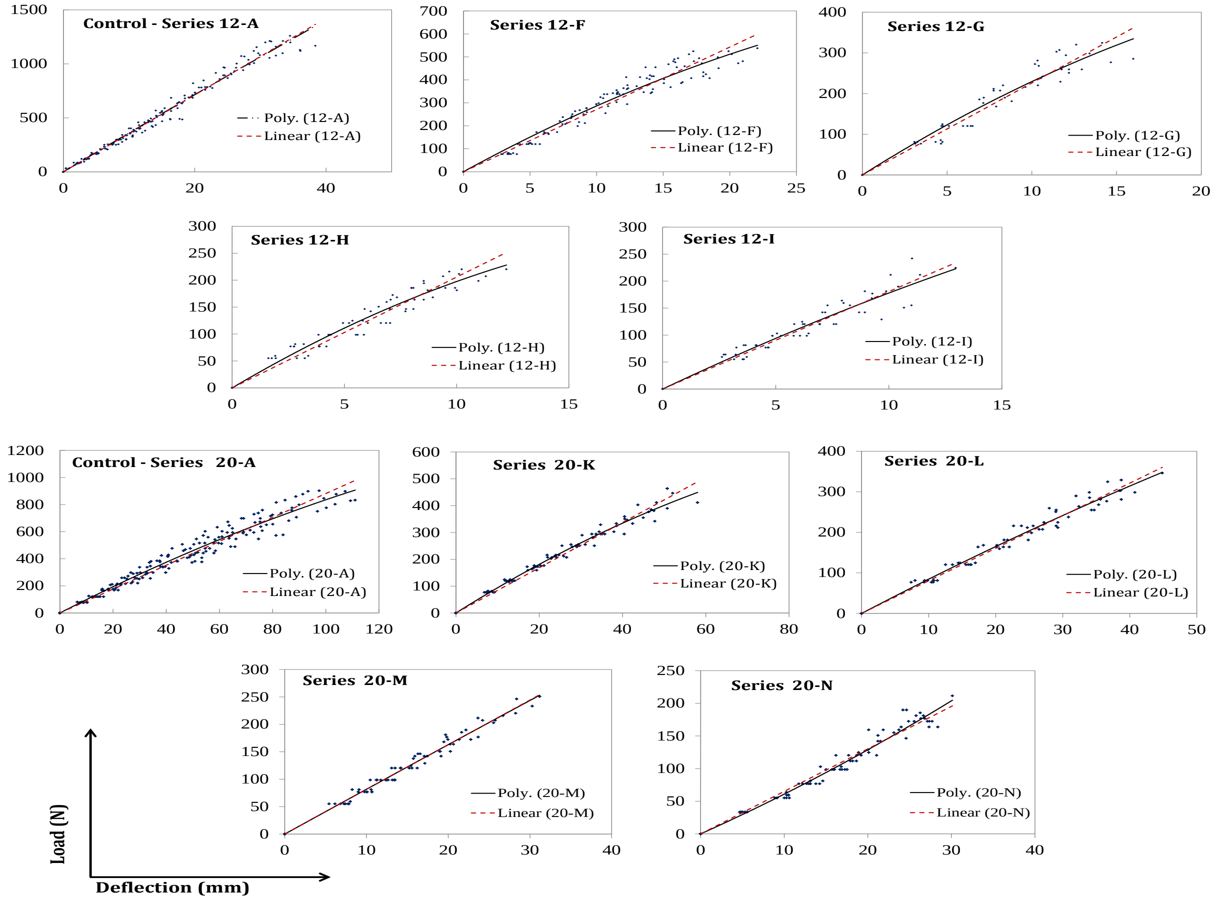

Fig. 3: Load Prediction Models (Linear and Non-linear) for Flange Cut of I-Joists (A-Controls and 12-F, 12-G, 12-H, 12-I, 20-K, 20-L, 20-M, and 20-N with Flange Cut)

Table 3: Comparison of Linear and Non-linear best fit curve of load deflection responses for different I joist series.

		I-joist Series									
		3.65 m Span I-joist					6.10 m Span I-joist				
		12-A	**12-F**	**12-G**	**12-H**	**12-I**	**20-A**	**20-K**	**20-L**	**20-M**	**20-N**
Linear	Model (Y=ax) =>(a)	34.867	27.132	23.168	20.441	17.700	9.204	8.327	8.0305	8.359	6.278
	R^2 Value	0.984	0.985	0.981	0.985	0.970	0.952	0.990	0.994	0.981	0.982
	$R_a{}^2$ Value	0.984	0.985	0.981	0.985	0.969	0.952	0.990	0.994	0.981	0.982
	SSE	545397	169468	38104	18705	26575	874050	47677	15724	25040	20450
	RMSE	58.38	39.80	26.56	16.47	21.05	71.29	23.28	14.99	17.69	15.24
	AIC	1759.5	1096.0	511.44	586.38	539.88	1959.9	807.68	581.66	690.73	733.19
Non-Linear	Model (Y=ax^2+bx) => (a;b)	34.940; -0.0028	33.924; -0.4441	30.244; -0.6405	24.509; -0.4881	21.694; -0.4521	9.714; -0.0077	9.788; -0.0379	8.638; -0.0196	9.228; -0.0428	6.741; -0.0197
	R^2 Value	0.984	0.990	0.988	0.988	0.975	0.958	0.993	0.994	0.982	0.983
	$R_a{}^2$ Value	0.984	0.989	0.987	0.987	0.974	0.958	0.993	0.994	0.981	0.982
	SSE	545371	121869	25116	15511	22347	864509	33779	14707	23695	19932
	RMSE	58.38	33.75	21.57	14.99	19.30	70.90	19.59	14.49	17.21	15.05
	AIC	1761.5	1062.7	490.93	576.46	531.48	1960.0	779.36	578.98	688.31	732.94
(ΔAIC) %		**0.1%**	**3.1%**	**4.2%**	**1.9%**	**1.6%**	**0.0%**	**3.6%**	**0.5%**	**0.4%**	**0.0%**

Note:
R^2 -Co-efficient of determination
$R_a{}^2$ - Adjusted Co-efficient of determination

SSE- Sum of Squares Error
RMSE- Root Mean Square Error

AIC - Akaike Information Criterion

Higher precision was used to show their improved performance for R^2 and adjusted R^2 values

4 CONCLUSION

Based on the experiments performed in this study the following conclusions can be drawn:

- Due to the presence of flange notches in the I-joists, the load carrying capacity decreased up to 80% in comparison with the uncut I-joist with the increasing distance of the notch from the support, which is due to the increasing flexural stresses.
- The stiffness of the I-joists with flange notches is reduced up to 46% and 33% from the stiffness of the control I-joists for 3.65m and 6.1m span length I-joists, respectively.
- The linear regression models are well fitted with the experimental data and it is recommended that researchers and engineers use linear models instead of non-linear models for avoiding the complexity of the structural analysis.

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