

# A finite element analysis of bearing resistance of timber loaded through a steel plate

**Citation for published version (APA):**

Awaludin, A., Hayashikawa, T., & Leijten, A. J. M. (2012). A finite element analysis of bearing resistance of timber loaded through a steel plate. *Civil Engineering Dimension*, 14(1), 1-6.

**Document status and date:**

Published: 01/01/2012

**Document Version:**

Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

**Please check the document version of this publication:**

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
- The final author version and the galley proof are versions of the publication after peer review.
- The final published version features the final layout of the paper including the volume, issue and page numbers.

[Link to publication](#)

**General rights**

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license above, please follow below link for the End User Agreement:

[www.tue.nl/taverne](http://www.tue.nl/taverne)

**Take down policy**

If you believe that this document breaches copyright please contact us at:

[openaccess@tue.nl](mailto:openaccess@tue.nl)

providing details and we will investigate your claim.

# A Finite Element Analysis of Bearing Resistance of Timber Loaded through a Steel Plate

Awaludin, A.<sup>1)</sup>, Hirai, T.<sup>2)</sup>, Hayashikawa, T.<sup>3)</sup>, and Leijten, A.J.M.<sup>4)</sup>

**Abstract:** Decrease projected length of bolts due to bending deformation in timber joints compresses the steel washers onto timber member and increases lateral resistance of the joints. As this lateral strength increase primarily depend on bearing characteristics of timber beneath the steel washers, a finite element analysis was performed to predict their bearing-embedment behavior. A 3-D finite element model consisting of 8-node solid and contact pair elements was developed using ANSYS assuming an anisotropic plasticity model for timber and an elastic-perfectly plastic model for the washers. Material constants for both steel washer and timber member were obtained from previous test data. The results of the analysis were in good agreement with the experimental load-embedment curves as well as the analytical curves obtained in a previous study based on a rigid-body-spring-model. The same approach was also used to evaluate the effective bearing length (under uniform compression) of a 50 mm depth timber block partially compressed.

**Keywords:** Bearing resistance, contact condition, effective bearing length, finite element model, partial compression.

## Introduction

The mechanical behavior of bolted timber joints beyond the elastic limit is obviously affected by the development of axial forces in bolts as a result of bending deformation of the bolts. The axial force development has a positive effect on the (ultimate) lateral resistance, ductility and hysteretic response [1-3]. Some studies have considered this axial force in their numerical models [4-6]. Linear and non-linear spring elements were used in those numerical models and its behavior was determined based on the load-embedment curves of timber beneath steel washers or steel side plate. The embedment resistance of timber under steel washers should be considered in an appropriate design method of bolted timber joints with steel washers or side plates.

An attempt to analyze numerically the bearing resistance of steel washers on timber members using rigid-body-spring-model (RBSM) was previously presented by Hirai et al [7]. In their analysis a steel washer was assumed to consist of discrete rigid plate elements connected to adjacent elements with springs and supported on foundation springs at their centers of gravity. The foundation springs were determined by considering an effective foundation area for partial bearing under rigid bodies [7], which varied upon loading configuration [8-10]. They ignored shear contribution of deformed timber fibers as Winkler-type foundation springs were used in their numerical model. In this study the load-embedment curve of the steel washer on timber was simulated using the ANSYS v.10 [11] based on a 3-D finite element model consisting of 8-node solid and contact pair elements. The same technique was used to study the effective bearing length of timber member under partial bearing just like contact joints between columns and sills.

## Finite Element Modeling

The experimental model shown in Fig. 1, which was adopted from the work of Hirai et al [7], was used in this finite element analysis. The timber species used in the above work was *Picea jezoensis*. The specimens had an average moisture content of 13.1% and air-dry specific gravity of 0.41. Both steel washer and timber member had a pre-drilled hole of 13 mm diameter and were discretized using 8-node solid elements as shown in Fig. 2.

<sup>1</sup> Department of Civil and Environmental Engineering, Universitas Gadjah Mada, Jl. Grafika No. 2, UGM campus, Yogyakarta, 55281, INDONESIA.  
E-mails: ali@tsipil.ugm.ac.id

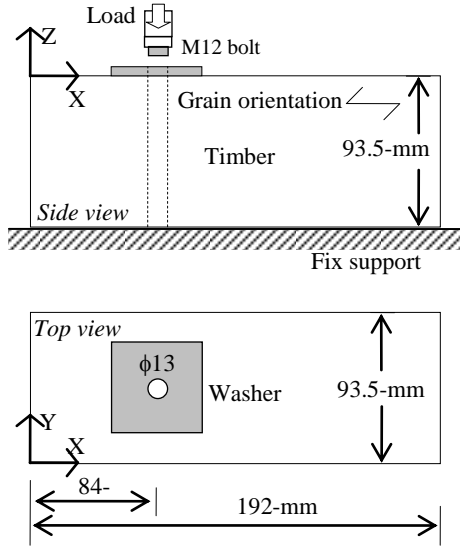
<sup>2</sup> Research Faculty of Agriculture, Hokkaido University, Kita 9 Nishi 9, Kita-ku, Sapporo 060-8589, JAPAN.

<sup>3</sup> Research Faculty of Engineering, Hokkaido University, Kita 13 Nishi 8, Kita-ku, Sapporo 060-8628, JAPAN.

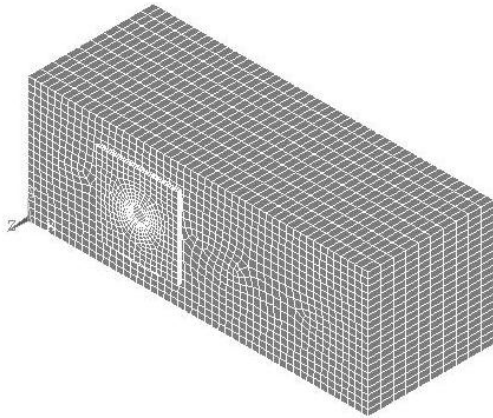
<sup>4</sup> Department of Architecture, Building and Planning, Eindhoven University of Technology, Den Dolech 2, P.O. Box 513, VRT 9.23, 5600 MB Eindhoven, THE NETHERLANDS.

**Note:** Discussion is expected before June, 1<sup>st</sup> 2012, and will be published in the "Civil Engineering Dimension" volume 14, number 2, September 2012.

Received 11 August 2011; revised 30 December 2011; accepted 18 January 2012.



**Figure 1.** Bearing Test Model of Timber Member Under Steel Washer [7]



**Figure 2.** A 3-D Finite Element Model for Timber Bearing Under Steel Washer in ref. 7

The axial force perpendicular to the timber grain was facilitated by applying uniform nodal force to nodes at the presence of M12 bolt head around the bolt-hole of the washer. A flexible surface-to-surface contact model was implemented via contact pair of CONTA174 and TARGE170 elements provided by the finite element codes ANSYS v.10 [11]. The normal and sliding contact stiffness was automatically calculated based on the material properties of the underlying elements and was updated on each step of the computation. In this analysis, the static frictional coefficient between the steel washer and the timber member was roughly assumed as 0.3 [6].

A bilinear stress-strain relationship was assumed for each anisotropic axis of timber. An apparent yield stress and tangent modulus are required for each stress-strain relationship. Therefore, 18 additional constants are needed in addition to the 9 normally required for orthotropic elastic material. These

constants are summarized in Table 1 [12].  $E_x, E_y, E_z$  are moduli of elasticity in three material axes;  $G_{xy}, G_{yz}, G_{xz}$  are shear moduli;  $E_t$  is tangent modulus;  $G_t$  is tangent shear modulus;  $\sigma_{\pm}$  is yield stress in tension or compression;  $\tau$  is shear stress and  $\nu$  is Poisson's ratio. It was further assumed that the maximum stress criterion was used so that at each load increment the three normal stresses and shear stresses are independently compared against critical values; little or no interaction between these stresses exists [13].

**Table 1.** Material Constants for Timber used in the Finite Element Model [12]

$E_x$	4,720 MPa	$G_{txz}$	9.5 MPa
$E_y$	378 MPa	$\sigma_{\pm x}$	18 MPa
$E_z$	236 MPa	$\sigma_{\pm y}$	3.72 MPa
$G_{xy}$	337 MPa	$\sigma_{\pm z}$	3.72 MPa
$G_{yz}$	33.7 MPa	$\tau_{xy}$	4.08 MPa
$G_{xz}$	317 MPa	$\tau_{yz}$	0.93 MPa
$E_{txx}$	140 MPa	$\tau_{xz}$	3.09 MPa
$E_{txy}$	11 MPa	$\nu_{xy}$	0.37
$E_{txz}$	7 MPa	$\nu_{yz}$	0.47
$G_{txy}$	10 MPa	$\nu_{z\pm}$	0.42
$G_{tyw}$	1 MPa		

The yield stresses in three material axes are not independent to each others, but they must satisfy the consistency equation described as

$$\frac{\sigma_{tx} - \sigma_{cx}}{\sigma_{tx}\sigma_{cx}} + \frac{\sigma_{ty} - \sigma_{cy}}{\sigma_{ty}\sigma_{cy}} + \frac{\sigma_{tz} - \sigma_{cz}}{\sigma_{tz}\sigma_{cz}} = 0 \quad (1)$$

where  $\sigma_{tx}$  and  $\sigma_{cx}$  refer to x-direction yield stress in tension and compression, respectively.

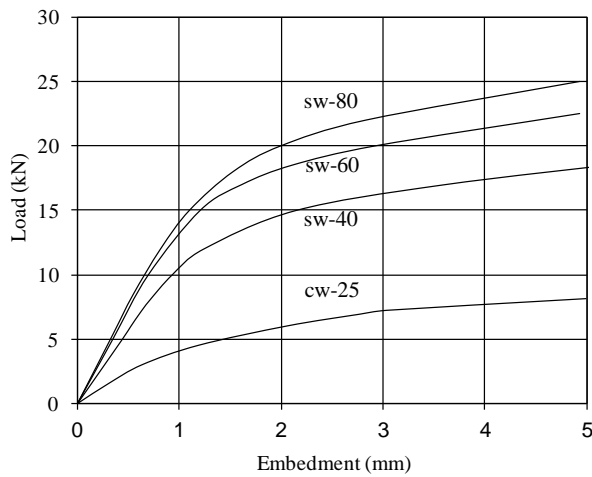
The washer was modeled as elastic-perfectly plastic and its material properties obtained from direct tests [7] were:  $E = 195$  GPa;  $\sigma_{yield} = 308.7$  MPa;  $\nu = 0.3$ .

## Results and Discussions

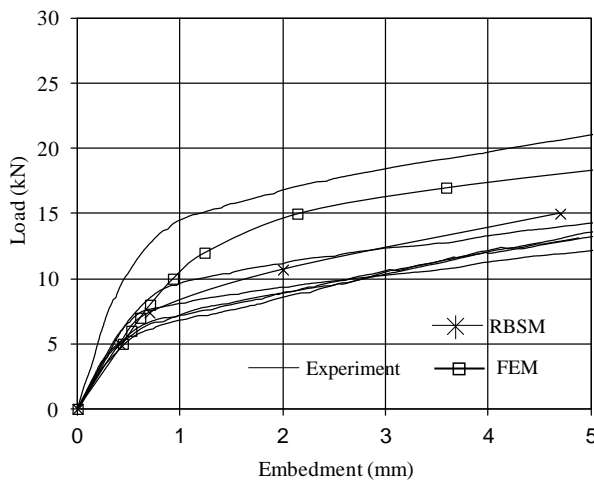
Figure 3 shows the load-embedment curves up to 5 mm embedment of the FEM analysis for three square steel washers of 40x40 mm (sw-40), 60x60 mm (sw-60) and 80x80 mm (sw-80) and a circular washer of 25 mm diameter (cw-25). All washers have thickness equals to 4.3 mm. The FEM curves clearly indicate that bearing load increases with washer dimension and the circular washer cw-25, which has the smallest surface (contact) area among the four kinds of considered washers, yields the lowest bearing load at a same embedment.

Figure 4, 5 and 6 show the load-embedment curves of the FEM analysis as well as the curves from the experiments and those given by Hirai et al [7] (marked as RBSM) for the steel washers sw-40, sw-60 and sw-80. Some test data at early stage of

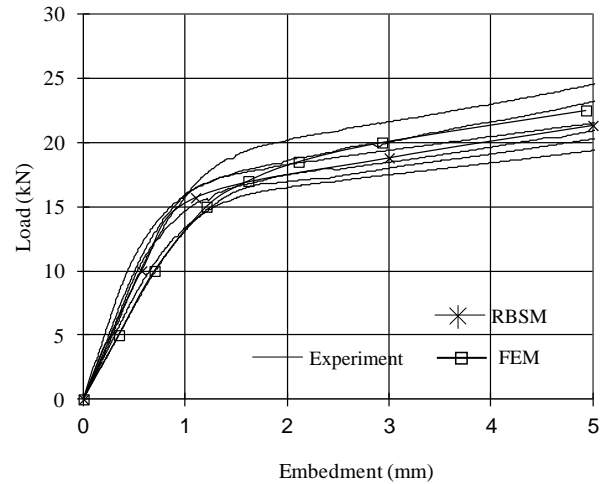
loading was removed from the experimental curves as they generally produce initial slip with no bearing load. As a result, comparison between experimental and predicted load-embedment curves at initial loading becomes more convenience. The predicted curves given by FEM and RBSM analyses are in good agreement with experimental data especially with steel washer sw-60 and sw-80. FEM curve differed from the RBSM curve only for the steel washer sw-40 (see Fig. 4), where a notable variation was also observed among the load-embedment curves of the experimental results. Further investigation is required for specimens with steel washer sw-40 including more experimental data as to clarify this discrepancy.



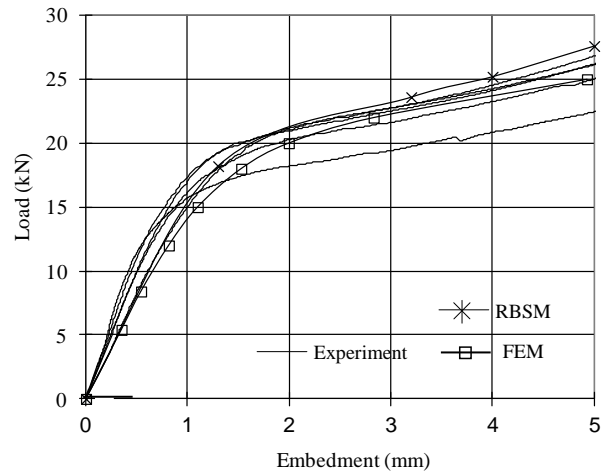
**Figure 3.** FEM Predicted Load-Embedment Curves for four Kinds of Steel Washer (sw-40, square washer 40x40 mm; sw-60x60, square washer 60x60 mm; sw-80, square washer 80x80 mm; and cw-25, circular washer 25 mm diameter)



**Figure 4.** Experimental and Predicted Load-Embedment Curves, Washer sw-40



**Figure 5.** Experimental and Predicted Load-Embedment Curves, Washer sw-60



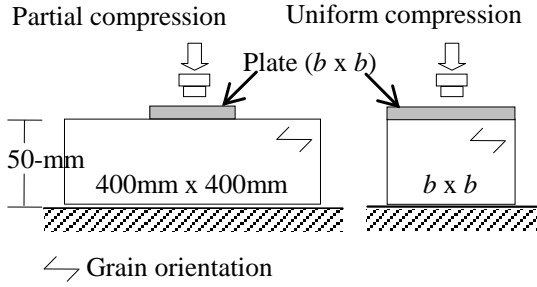
**Figure 6.** Experimental and Predicted Load-Embedment Curves, Washer sw-80

## Numerical Simulation

Some numerical simulations were conducted using the FEM model developed above.

### *Rigid Body Assumption*

If steel plates have enough thickness, they can practically be regarded as rigid bodies that introduce uniform embedment on timber members. Precise information about dimensional proportions of the plates that ensure the quasi-rigid behavior, however, has not been available. In this study, therefore, the effect of width/thickness ratio was simulated first. Figure 7 shows a 50 mm depth timber block under two different loading conditions, partial and uniform compression.



**Figure 7.** Timber Block Model for the Evaluation of Rigid Body Assumption ( $b$ : plate width)

In the block with a partial compression, the block dimension in grain direction or perpendicular is 400 mm, while in the block with a uniform compression the block dimension is exactly the same as the dimension of the steel plate. In both loading conditions, the steel plate thickness is made constant, 10 mm, while the plate width ( $b$ ) is defined according to the selected width-over-thickness ratio. And the load is assumed as uniform nodal forces within an area of M12 bolt head (15 mm by 15 mm) at the center of the plate.

An ideal rigid plate has a uniform embedment, which means the plate rigidity ratio,  $r$ , expressed by Eq. (2) equals to zero.

$$r = \frac{(\delta_{\max} - \delta_{\min})}{\delta_c} \times 100\% \quad (2)$$

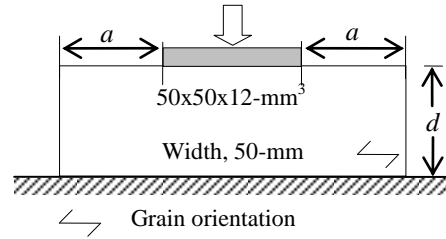
In Eq. (2),  $\delta_{\max}$  and  $\delta_{\min}$  is, respectively, maximum and minimum embedment of the plate and  $\delta_c$  is embedment of the center of the plate. Our finite element analysis results indicate that  $r$  is less than 5% when plate width-over-thickness ratio is not higher than 6 under partial compression or 9 under uniform compression, respectively. Blocks under partial compression introduce bending by lateral forces distributed along the block edges. Therefore, thicker plates are required to attain the same level of  $r$  which is calculated for the case of the uniform compression.

*Effective Length under Partial Bearing*

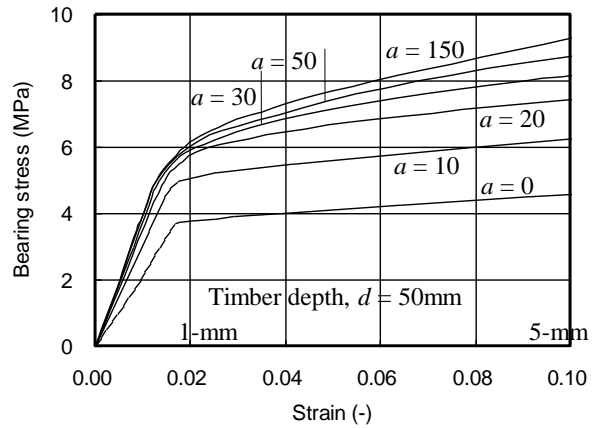
Under partial bearing the effective bearing length, which corresponded to the bearing length with uniform compression, was simulated assuming the load transmission through a rigid body. The effective bearing length has been proposed in many previous studies [7, 14] to evaluate the ultimate effective (equivalent) partial compressive strength. The effective bearing length was simulated using the same technique. In this study, a block loaded as shown in Fig. 8 was considered. The block dimension and loading arrangement is adhered to ASTM D143 [15]

and the plate can be assumed as rigid body (width-over-thickness ratio equals to 4.2).

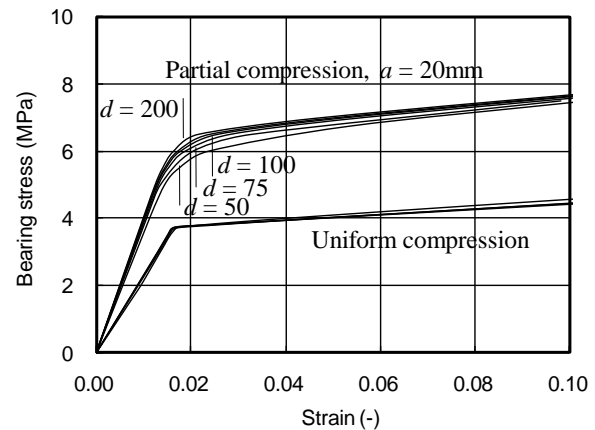
Figure 9(a) shows the analytical bearing stress-strain curves for various margins, while Fig. 9(b) shows the analytical curves obtained from six different depths of the block ( $d$ , 50 mm; 75 mm; 100 mm; 125 mm; 150 mm and 200 mm) under two kinds of loading condition. Here bearing stress is force perpendicular to the timber grain divided by the plate (contact) area, and strain is defined as plate embedment divided by block depth.



**Figure 8.** Model of Block Under Partial Bearing ( $d$ : timber depth;  $a$ : margin)



(a) Various margin



(b) Various depth

**Figure 9.** Analyzed Bearing Stress-Strain Curves ( $d$ : timber depth;  $a$ : margin)

For a compressive strain equals to 2% known as serviceability limit [14] a significant increase of bearing load for 10 mm or 20 mm margin is well observed in Fig. 9(a). But for margin more than 20 mm, the increase comes down. For a very large margin ( $a$  equals to 150 mm), the bearing stress corresponding to 2% of strain is about 1.6 times the bearing stress under uniform compression ( $a$  equals to zero). This suggests that the bearing load can be attained by assuming effective bearing length (under uniform compression) of 80 mm, which is 1.6 times the actual width of the plate (50 mm). This increase of effective bearing length from 50 mm to 80 mm can also be achieved by assuming 1:3 stress dispersion as proposed by a previous study [16]. This stress dispersion means that for a timber depth equals to  $d$ , the effective bearing length can be extended by one third of  $d$  to the left and right sides. However, if the 5 mm embedment is adopted as the limit for thin timber members [17] the slope of stress dispersion changes into 1:2.

From stress-strain curves shown in Fig. 9(b), the influence of timber depth is noticed in the block with partial compression but it is less obvious for the blocks with uniform compression. No influence of timber depth on bearing stress-strain curve of the blocks under uniform compression is confirmed by the experiment of a previous study [14]. In partially compressed blocks, increasing the depth from 50 mm to 125 mm yields a proportional increase at 2% strain. However, increasing the block depth over 125-mm-depth yields a very small increase of the load at a same strain. This increase is about 7% and 10.5%, for depth changing from 50 mm to 125 mm and from 50 mm to 200 mm, respectively. However, for a strain equals to 10%, increasing the depth of the block from 50 mm to 125 mm has no effect as shown in Fig. 9(b).

## Conclusions

In this study a 3-D finite element model was developed using ANSYS to predict the bearing load-embedment curve of a steel washer on a timber member which is necessary to incorporate the development of axial forces into an appropriate design model of laterally loaded bolted joints. A flexible surface-to-surface contact model having static frictional coefficient of 0.3 was included into the FEM to consider the contact condition between the washer and timber. The numerical results showed that the bearing load increases with washer dimension and the predicted load-embedment curves are in good agreement with experimental data. In addition, this study confirms the results of previous studies that a slope of stress dispersion of 1:3 and 1:2 can be practically assumed to evaluate the effective

bearing length of timber under partial compression at 2% and 10% strain, respectively.

## Acknowledgement

This study was carried out when the first author (Awaludin, A) was a post-doctoral research fellow supported by the Japan Society for the Promotion of Science.

## References

1. Awaludin, A., Hirai, T., Hayashikawa, T., Sasaki, Y. and Oikawa, A., Effects of Pretension in Bolts on Hysteretic Response of Moment-carrying Timber Joints, *Journal of Wood Science*, 54, 2008, pp. 114-120.
2. Awaludin, A., Hayashikawa, T., Oikawa, A., Hirai, T., Sasaki, Y., and Leijten, A.J.M, Seismic Properties of Moment-resisting Timber Joints with a Combination of Bolts and Nails, *Civil Engineering Dimension*, 13(1), 2011, pp. 1-5.
3. Awaludin, A., Hirai, T., Sasaki, Y., Hayashikawa, T., Oikawa, A., Beam-to-column Timber Joints with Pretensioned Bolts, *Civil Engineering Dimension*, 13(2), 2011, pp. 59-64.
4. Hirai, T., Nonlinear Load-slip Relationship of Bolted Wood-Joints with Steel Side-Member II: Application of the Generalized Theory of a Beam on an Elastic Foundation, *Mokuzai Gakkaishi*, 29, 1983, pp. 839-844.
5. Schreyer, A.C., *Monotonic and Cyclic Behavior of Slender Dowel-type Fasteners in Wood-steel-wood Connections*. M.A.Sc. Thesis, Department of Wood Science, The University of British Columbia, 2002.
6. Awaludin, A., Hirai, T., Hayashikawa, T., Sasaki, Y., Load-carrying Capacity of Steel-to-timber Joints with a Pretensioned Bolt, *Journal of Wood Science*, 54, 2008, pp. 362-368.
7. Hirai, T., Tsujino, T., Sasaki, Y., Steel Washer on Timber, *Proceedings of World Conference on Timber Engineering*, August 6-10, Portland, 2006. (CD-ROM)
8. Inayama, M., *Theory of Embedment of Timber and its Application*, Ph.D. Thesis, The University of Tokyo, 1991.
9. Kawamoto, N. and Kanaya, N., Elastic Deformation of Wood Subjected to Compression Perpendicular-to-the-grain. Effects of Length and Depth of Specimen, and Effect of Contact Length of Bearing Plate on an Elastic Foundation, *Mokuzai Gakkaishi*, 37, 1991, pp. 16-23.
10. Leijten, A. J. M., Larsen, H. J., Van der Put T. A. C. M., Structural Design for Compression Strength Perpendicular to the Grain of Timber

- Blocks, *Journal of Construction and Building Materials*, 24, 2010, pp. 252-257.
11. Swanson Analysis System Inc., *ANSYS v.10.*, Swanson Analysis System Inc., Houston, Pa, 1996.
  12. Awaludin, A., Toshiro Hayashikawa, T., Hirai, T., Sasaki, Y., Loading Resistance of Bolted Timber Joints beyond their Yield-loads, *Proceedings of the 2nd ASEAN Civil Engineering Conference*, March 11-12, Vientiane, 2010, pp. 148-158.
  13. Moses, D. M., Prion, H. G L., A Three-dimensional Model for Bolted Connection in Wood, *Canadian Journal of Civil Engineering*, 30, 2003, pp. 555-567.
  14. Blass, H. J., and Gortlacher, R., Compression Perpendicular to the Grain, *Proceedings of World Conference on Timber Engineering*, June 14-17, Finland, 2004. (CD-ROM)
  15. *American Society for Testing and Materials: Standard test methods for small clear specimens of timber, ASTM D143*, American Society of Testing and Materials, Philadelphia, 1994.
  16. Madsen, B., Proposal for Including an Updated Design Method for Bearing Stresses in CIB-W18 Structural Design Code, *Proceedings of the 22nd CIB-W18*, Berlin, 1989.
  17. Riberholt, H., *Compression Perpendicular to the Grain of Wood*, COWI-report P-42239-1, 2000.