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Dowel-embedment Properties-Based Finite Solid Element Model for Bolted Connections[1]

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ABSTRACT

Two transversely isotropic plasticity-based models for wood, derived from the standard compression properties and the embedment properties were investigated for suitability of application for bolted connections. It was found that the conventional connection models involving the compression properties were incapable of simulating the real behaviour of the connections because the compression properties provided too stiff foundation to represent embedding behaviour of wood under the bolt. However, wood foundation-based connection model that was newly developed using the bolt embedment properties showed good agreement with the actual behaviour of bolted connections.

Keywords : dowel, embedment property, finite element model, bolt connection

1. INTRODUCTION

For bolted wood connections, most of numerical models have been developed using finite element (FE) method (Patton-Mallory 1996; Moses 2000; Kharouf 2001; Chen *et al*. 2003). In general, the key procedure in the FE model development is to define material parameters that are suitable for simulating wood response against the bolt embedment as closely as possible.

To date, for the FE material model for wood a conventional method has been to employ the wood material properties which were evaluated through the standard uniaxial compression tests (Patton-Mallory 1996; Moses 2000; Kharouf 2001). However, with wood, which is non-homogenous and porous material, application of the conventional method for bolted connection model has been questioned because the behaviour of bolt embedment on wood can not be explained by simply wood compression properties. In other words, the wood compressive behaviour in general compression and in dowel embedding is quite different. It is well known that the cause of this difference is mainly due to localized wood crushing failure at a contact area between wood and bolt. It has been demanding that a model should be accounting for wood crushing behaviour in FE analysis of the bolted connection. Recently, wood foundation approach that introduced the crushing behaviour into 3D FE model of dowel-type wood connection has been proposed (Hong *et al*. 2010).

In this study, therefore, by applying the two meth-

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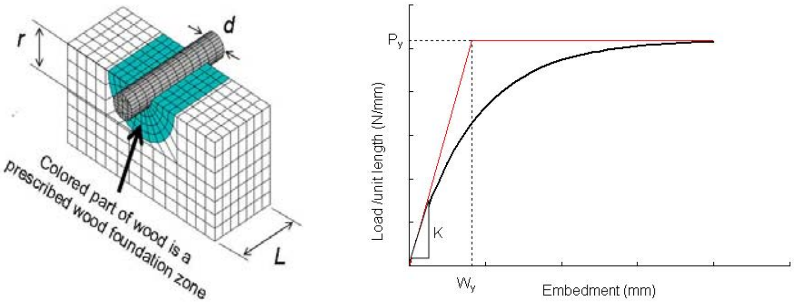

Fig. 1. Bolt embedment test model with wood foundation (left) and definitions of requisite parameters in the load per unit length-embedment curve (right).

ods for 3D FE analysis of the bolted connections the suitability and characteristics of the conventional method and the wood foundation method were investigated.

2. MATERIALS and METHODS

2.1. Anisotropic Plasticity-based Material Model for Wood

Anisotropic plasticity with bilinear stress-strain relations were assumed in three orthogonal directions of compression, tension and shear. Based on each directional compressive constitutive relationship, the same bilinear stress-strain relationships were assumed in tension. These assumptions reduced the number of major material parameters to be four that included initial modulus and yield stress (or strain) in longitudinal and transverse directions respectively.

Upon these assumptions, two different methods were used to determine the initial moduli and yield stresses; one is the conventional method that uses uniaxial compression tests. The other is the wood foundation method that uses bolt embedment tests.

2.1.1. Conventional Method

In the conventional method ASTM D 143 parallel and perpendicular to grain compression tests were performed to determine the initial moduli and the yield points that were defined through bilinear curve fitting to the experimental stress-strain curves. The tangent modulus was taken as 0.01 times the initial modulus, and a break point of the bilinear curve was chosen as a yield point. Other parameters including shear parameters and Poisson’s ratios were estimated from values in Wood Handbook (FPL 1999). This method follows a common procedure to develop a wood material model as found in existing FE bolted connection models (Patton-Mallory 1996; Moses 2000; Kharouf 2001).

2.1.2. Wood Foundation Method

Wood foundation method is a new technique for constructing a 3D FE wood material model of dowel-type wood connection that is able to account for wood crushing behaviour around a dowel (FPL, 1999). This method employs bolt embedment test instead of compression test, in order to determine the material parameters of wood in the wood foundation zone. Fig. 1 shows the concept of 3D FE wood foundation model. The material parameters determined through bolt embedment tests constitute wood foundation material model which applies only

Table 1. Material parameters of three-dimensional finite element models for wood and wood foundation

Material parameters *	For wood material model	For wood foundation material model
Elastic modulus: L (MPa)	16900	760
Elastic modulus: R = T (MPa)	830	110
Elastic shear modulus: RL = LT (MPa)	760	130
Elastic shear modulus: RT (MPa)	76	41
Poisson's ratios: RL, LT, RT	0.018, 0.37, 0.38	0.05, 0.37, 0.38
Compressive, tensile yield stress: L, R (= T) (MPa)	44.3, 4.5	27.9, 5.0
Compressive, tensile tangent modulus: L, R (= T) (MPa)	169, 8.3	7.6, 1.1
Shear yield stress: RL (= LT), RT (MPa)	4.6, 0.46	2.7, 1.5
Shear tangent modulus: RL (= LT), RT (MPa)	7.6, 0.76	1.3, 0.41

* L = longitudinal, R = radial and T = tangential direction

for a prescribed wood foundation zone. Definitions of wood foundation material parameters are illustrated as follows.

- Radius of wood foundation, r:

  $r = M \cdot d$ (mm) ·· Eq. 1

- Initial modulus of wood foundation , E_{WF}:

  $E_{WF\,i} = \alpha_i \cdot K_i = \alpha_i \cdot \left(P_y / W_y\right)_i$ (MPa) ··················· Eq. 2

- Yield strain of wood foundation, ε_{WF}:

  $\varepsilon_{WF\,i} = \dfrac{\left(W_y / d\right)_i}{\beta_i}$ (mm/mm) ······························ Eq. 3

Where,

i= parallel to grain (//) or perpendicular to grain (⊥) direction

d= diameter of bolt (mm)

M= multiplier to determine the size of wood foundation

L= length of wood block (mm)

P_y= load per unit length at a breaking point of bilinear load-embedment curve (N/mm)

W_y= yield deformation in the load/unit length-embedment curve (mm)

α_i= calibration factor for the wood foundation modulus

β_i= calibration factor for the wood foundation yield strain

In this study, 12.7-mm diameter bolt and Douglas fir (*Pseudotsuga menziesii*) were involved. For this material combination, Hong *et al*. (2010) estimated the linear relationships between multiplier (M) and calibration factors (α_i and β_i), as given in equation (4) and (5). Eventually, using the relationships, for a specific multiplier and the load-embedment data the corresponding wood foundation material model can be established through the same procedures as the conventional method.

- *M-factors* linear relationships for Douglas fir

  Parallel to grain

  $\alpha_{//} = 0.10 \cdot M + 1.29$ and $\beta_{//} = 0.79 \cdot M + 0.41$ ·· Eq. 4

  Perpendicular to grain

  $\alpha_{\perp} = 0.04 \cdot M + 0.67$ and $\beta_{\perp} = 0.23 \cdot M + 1.08$ ···· Eq. 5

2.1.3. Three-dimensional Finite Element Material Models

Wood material parameters and wood foundation material parameters given in Table 1 were determined through ASTM D 143-Compression test

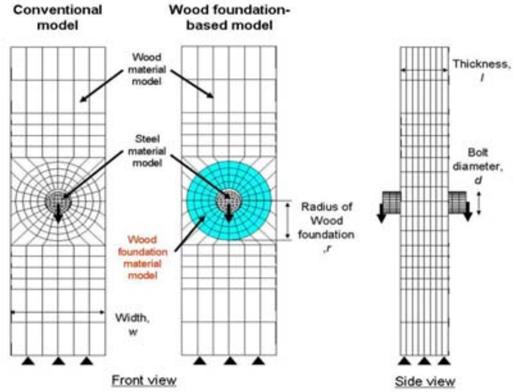

Fig. 2. Bolted connection model which is analogous to full-hole embedment test; the conventional model (left in front view) and the wood foundation-based model (right in front view).

and ASTM D 5764-Half hole embedment test with dry Douglas fir, conditioned to moisture content of 15% and 12.7-mm diameter bolt. Using 25-mm width × 25-mm thickness × 100-mm length prismatic wood specimens the compression tests were conducted in longitudinal, radial and tangential direction with 45 repetitions respectively. Then, the data in radial and tangential directions were averaged to represent the perpendicular to grain properties.

For the wood foundation material model the half-hole bolt embedment tests were conducted with fifteen 100-mm width × 38-mm thickness × 50-mm height Douglas fir wood blocks in parallel and perpendicular to grain directions. Then, with the multiplier (*M*) of 1.8, which was the maximum value to be the radius of cylindrical wood foundation (1.8 × *d*) admissible to the width of the wood block (*W*) of 4 × *d*, all requisite parameters for the wood foundation material were established.

For both of the material models the parameters in shear were estimated using theoretical relationships with the principal properties, which was studied by Saliklis *et al*. (2003). Poisson's ratios were also estimated using the values in the Wood Handbook (Pope *et al*. 1995).

For bolt an elasto-perfectly plastic model was assumed with the yield stress of 310 MPa, modulus of 200 GPa and Poisson's ratio of 0.3.

2.2. Bolted Connection Models

Fig. 2 shows a three-dimensional finite element models for full-hole embedment tests which is analogous to a bolted connection model with a member thickness/bolt diameter (*l/d*) ratio of 2. The model without a wood foundation was a conventional model that employed only the wood material model. In the wood foundation-based model, the wood foundation material model was assigned to a cylindrical wood foundation with a diameter of 1.8 × *d* (the coloured part of wood around a bolt).

All three-dimensional finite element models in this study were developed using the finite element analysis (FEA) software package, ANSYS. A three-dimensional eight-noded, quadrilateral isoparametric brick element that has three degrees of freedom at each node (SOLID45 from ANSYS) was employed to embody the connection. Contact interactions between wood and bolt were modelled using surface-to-surface contact elements with frictional coefficient of 0.7 (CONTA174 and TARGE170 from ANSYS).

The protruding of the bolt from the wood member was set to 9.5 mm which was identical to the configuration of Patton-Mallory's model (1996). The bolt-hole diameter was 1.6 mm larger than the bolt diameter. The displacement-controlled compression loading was applied on both end surfaces of the bolt. All nodes on the bottom end surface of the wood member were fixed.

Using a parametric modelling technique bolted connection models with *l/d* ratio of 5 and 7 were also studied. Ratio of edge distance to bolt diameter (*e/d*) was fixed to be seven.

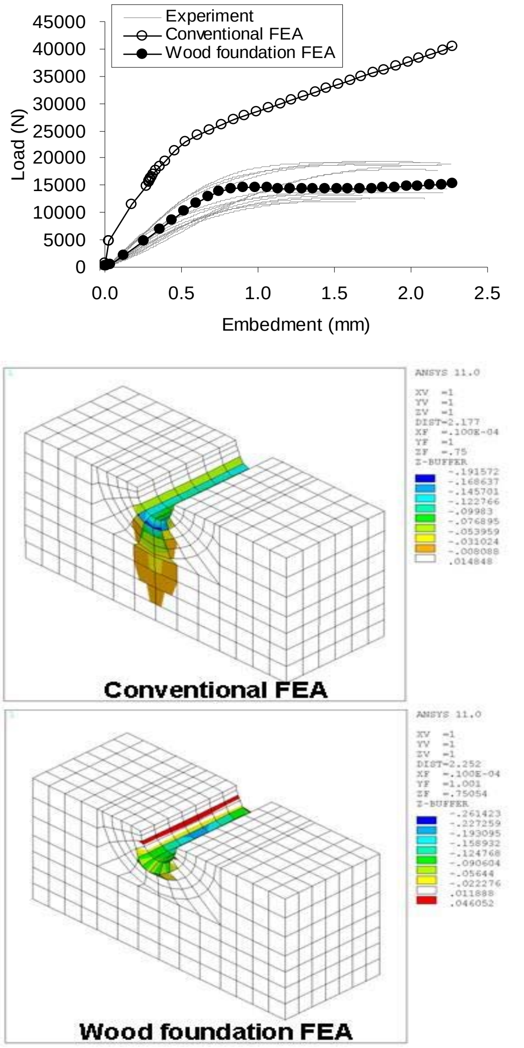

Fig. 3. Predicted load-embedment curves and contours of vertical plastic strain in parallel to grain direction.

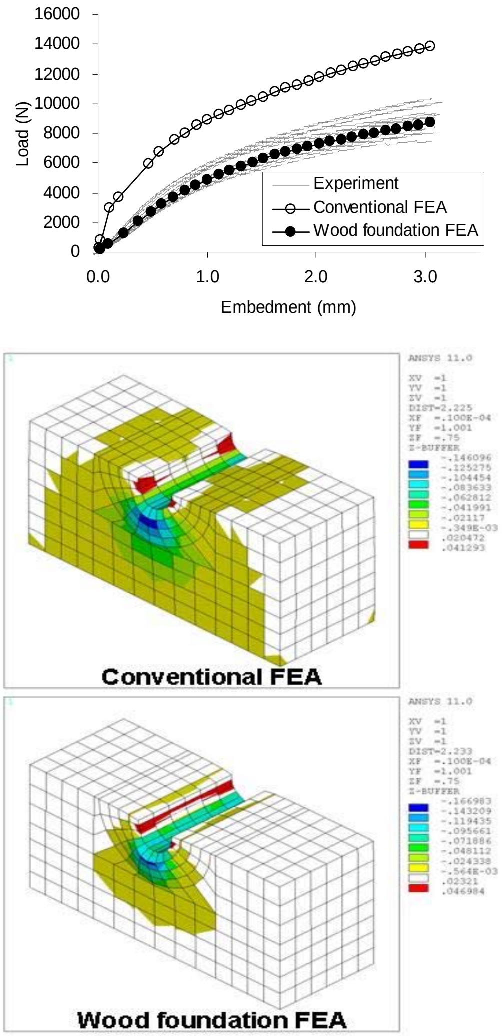

Fig. 4. Predicted load-embedment curves and contours of vertical plastic strain in perpendicular to grain direction.

3. RESULTS and DISCUSSION

3.1. Bolt Embedment Test

3.1.1. Half-hole Embedment Test

As shown in Fig. 3 and 4, prediction of the conventional model overestimated the experimental load-embedment results. This implies that the material parameters used in the conventional models were too stiff foundation under the bolt. Compared to the real deformation, the simulated permanent (or plastic) deformations were also unrealistically spread in the conventional models.

Basically, wood is not a scalable material. It is,

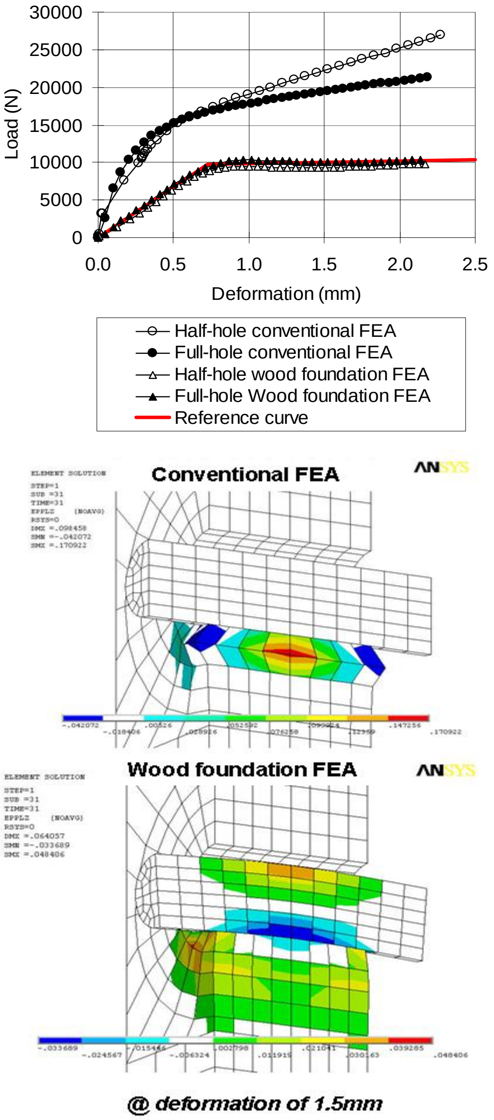

Fig. 5. Comparison of full-hole and half-hole embedment simulation; load-deformation curves (left) and contours of vertical plastic strain (right). Plastic bending in bolt should not occur in l/d=2 bolted connection.

therefore, obvious that the material parameters determined from uniaxial compression tests can not represent properly embedding behaviour of wood, which is governed by microscopic behaviour of wood fibres. This is also supported by the fact that the calculation of European yield connection model (EYM) adopts dowel embedding strength rather than modulus of elasticity or compression strength.

3.1.2. Full-hole Embedment Test

Patton-Mallory's bolted connection test (1996) had an analogous configuration of the standard test method for full-hole dowel-embedment strength given in the EN 383 (European Standards) or ASTM D 5764-97a. These standard embedment test methods specify the dimensions of the wood block, so that the bending deformation of the dowel should be minimized during the testing. Patton-Mallory's test configuration with *l/d* = 2 and *e/d* = 7 corresponded to the full-hole embedment test. For this configuration of the connection, she reported that no significant permanent (or plastic) bending of the bolt was observed, and the load-deformation curve from the bolted connection test was slightly stiffer than the curve from the half-hole embedment test. These characteristics distinctive between the full- and half-hole tests were also observed by Pope *et al.* (1995), who compared the bolt embedding strengths obtained from the EN 383 full-hole test and the ASTM half-hole test.

As shown in Fig. 5, the wood foundation-based model represented the distinctive characteristics successfully. Note that the reference curve in Fig. 5 is the average bilinear curve which fits to the experimental data of the parallel to grain half-hole embedment tests and is scaled down to the curve corresponding to 25.4-mm (= 2 × *d*) embedment length, from the original 38-mm length (*L* in Fig. 1). The simulated half-hole embedment curves were also reduced corresponding to the 2 × *d* embedment length.

The conventional model, however, did not simulate the characteristics. Compared to the reference curve, all simulated curves of the conventional model were unacceptably over-predicted. More importantly, the simulated deformation showed plastic hinge formation in the middle of bolt that did not agree with Patton-Mallory's observation (1996).

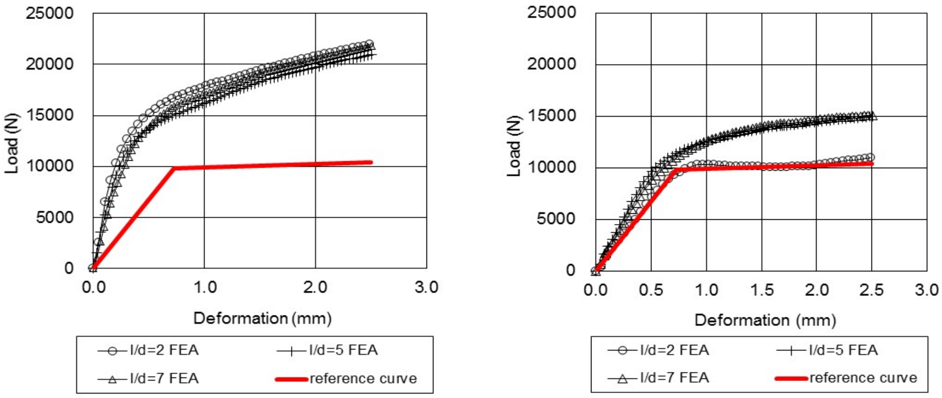

Fig. 6. Comparison of the predicted load-deformation curves of 12.7-mm bolted connection with l/d = 2, 5 and 7; The conventional models (left) and the wood foundation-based models (right).

In fact, the over-prediction of the simulated load-deformation curves in the conventional model has been a major problem in FE analysis for bolted connections. It is due to its inability to simulate localized wood crushing behaviour. This problem can be found in the 2-D FE models also (Kharouf 2001; Chen *et al*. 2003). The over-prediction and the plastic bending of bolt were attributed to the highly stiff foundation under the bolt. This justified the introduction of wood foundation in the wood foundation-based model.

3.2. Bolted Connections Model with *l/d*=2, 5 and 7

For bolted connections with *l/d* = 5 and 7, both models revealed the plastic hinge formation in the middle of the bolt also as the case of the conventional bolted connection model with *l/d* = 2. This resulted that as shown in Fig. 6, the conventional models produced almost the same load-deformation curves, regardless of the *l/d* ratio; whereas, the wood foundation-based model gave a distinctly different load-deformation curves of the *l/d* = 5 and 7 connections from the curve of the *l/d* = 2 connection.

In terms of the European yield model (EYM), although there was no side member, under the wood foundation-based model, the yield mode of the *l/d* = 2 connection corresponded to Mode I − *yield governed by crushing of wood fibres in the main member*. For the yielding in the *l/d* = 5 and 7 connections, Mode IV − *yield governed by formation of two plastic hinges in the bolt at each shear plane* − could be assumed, because the yield model for Mode IV is not affected by member thickness. In other words, Mode IV yield occurs regardless of the *l/d* ratio.

The yield modes predicted by the conventional model were only Mode IV for all *l/d* ratios. This could not be true for the *l/d* = 2 connection. However, it was recognized that the wood foundation-based model was able to simulate the yield of

Mode I. This implies that, provided a side member was incorporated into the model, the European yield modes could be predictable using the wood foundation-based model. This may be a good area for further study.

4. CONCLUSION

Wood is not a scalable material in terms of material properties. Therefore, the material properties determined from the standard uniaxial loading test and the bolt embedment test are quite distinct. However, most of existing FE models for bolted connections employed conventionally compression properties for wood material model.

This paper illustrated that the compression properties-based model for wood was not suitable for bolted connection models and newly developed model, wood foundation model could overcome the limitations of the conventional method.

REFERENCES

Chen, C.J., Lee, T.L., Jeng, D.S. 2003. Finite element modeling for the mechanical behavior of dowel-type timber joints", Computers & Structures, 81: 2731～2738.

Forest Products Laboratory (FPL). 1999. Wood handbook-Wood as an engineering material. General Technical Report, FPL-GTR-113, 1999.

Hong, J., Barrett, D. 2010. Three-Dimensional Finite-Element Modeling of Nailed Connections in Wood. Journal of Structural Engineering, ASCE, 136(6): 715～722.

Kharouf, N. 2001. Post-elastic behaviour of bolted connections in wood. Ph.D dissertation, Department of Civil Engineering and Applied Mechanics, McGill University, Montreal, QC, Canada.

Moses, D.M. 2000. Constitutive and analytical models for structural composite lumber with applications to bolted connections. Ph.D dissertation, Department of Civil Engineering, The University of British Columbia, Vancouver, BC, Canada.

Patton-Mallory, M. 1996. The three-dimensional mechanics and failure of single bolt wood connections. Ph.D dissertation, Civil Engineering Department, Colorado State University, Fort Collins, CO, USA.

Pope, D.J., Hilson, B.O. 1995. Embedment testing for bolts: A comparison of the European and American procedures. Journal of the Institute of Wood Science, 13(6): 568～571.

Saliklis, E.P., Urbanik, T.J., Tokyay, B. 2003. Bilinear modelling of cellulosic orthotropic nonlinear materials. Journal of Pulp and Paper Science, 29(12): 407～411.