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NONLINEAR MODELLING OF NAILED WOOD SHEAR CONNECTIONS WITH A LOW-STRENGTH MATERIAL IN BETWEEN WOOD ELEMENTS

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ABSTRACT: The behaviour of nailed wood shear connections with a layer of low-strength material in between two wood elements with different strengths is assessed using a nonlinear model. One example application for such a connection is the use of a layer of insulation between the studs and sheathing in a light frame wood shear wall, in order to mitigate thermal bridging. The layer of insulation, which will not provide any significant lateral resistance or stiffness itself, may affect the lateral strength and stiffness of the joint. A numerical model was developed using the nonlinear structural analysis software OpenSees and it includes the strength and stiffness of all of the shear wall connection elements, including the stud, sheathing, insulation, and nail. This model is compared to a series of sheathing-to-stud interface tests, which considered varying thicknesses of styrofoam insulation between 3 mm and 38 mm in between the sheathing and the stud. The model was capable of predicting the strength of the connections well, but underestimated the stiffness.

1. Introduction

The most popular building method for low-density commercial and residential structures in North America is light-frame wood construction. Light-frame construction is lightweight, sustainable, and relatively easy to construct. The primary structural components of such a structure include the external and internal walls, floors, and roof, which all consist of evenly-spaced lumber sections held together and to sheathing panels by common nails. These nailed connections are loaded primarily in shear. There are some design cases, where it may be desirable to include a different, low strength material in between wood elements in a nailed shear connection. One particular example is the inclusion of a layer of insulation between the vertical studs and sheathing (plywood or oriented strand board) in an exterior wall.

Typically, in exterior light frame wood walls, insulation is provided between the studs; however, the studs themselves may form a thermal bridge, reducing the effective insulation value of the entire wall since the studs break up the insulation. To reduce thermal bridging, an additional layer of rigid insulation (expanded polystyrene, EPS, or extruded polystyrene, XPS) may be added between the exterior face of the studs and the inside of the exterior sheathing. The inclusion of such a layer of insulation may reduce the strength and stiffness of the individual nailed connections between the sheathing and the studs; however, the magnitude of this reduction has not been previously studied in detail. Such an additional layer of insulation can currently be found in all-in-one sheathing products such as the Zip-System (Huber, 2012). This system provides improved thermal performance and provides the added benefit of reduced construction time.

Aune and Patton Mallory (1986) developed empirical equations to estimate the shear strength of nailed wood connections, based on the yield model originally developed by Johansen (1949), under various conditions including where a layer of insulation was sandwiched between two wood members with identical strength. Their study suggested an exponentially decaying relationship between the ultimate load and intermediate insulation thickness, but was only valid for connections where both wood members had the same strength. The same relationship would not be applicable to light frame walls in which the two layers of wood (lumber and panel product) have significantly different strengths and properties.

Numerous finite element models of nailed connections have been previously developed. Ni (1997) developed a 2-dimensional model, which consisted of a line of nodes representing the nail, with springs to represent the embedment properties of member materials. More recent models developed by Xu and Dolan (2009) and Hong & Barrett (2010) have included 3-dimensional behaviour and have captured additional mechanical effects such as the effect of wood pre-compression around the nail due to nail driving. None of these analytical models of nailed connections have been used to simulate a nailed connection with an intermediate layer of material in between the two wood layers.

The current study has developed a new model of a nailed connection based on Ni's (1997) model that has been adapted to simulate the behaviour of nailed wood connections with a different intermediate material between the two wood elements. This model is then used to simulate the behaviour of experimentally tested joints representing light frame shear wall nailed connections, which include an intermediate layer of insulation between a stud oriented strand board (OSB) sheathing. The model and test also included the case where the sheathing were placed directly on the stud.

2. Experimental Test Specimens

A total of eighty-four nailed shear connection specimens were constructed and tested for this study. The test setup of a typical specimen, which includes an intermediate layer of insulation, is shown in Fig 1. The force is applied as direct shear to two identical nailed shear connections, one on each side of the stud element. The specimen consists of a segment of 38x140 mm (2"x6") SPF (spruce-pine-fir) No. 2 grade framing, with two layers of oriented strand board (OSB) sheathing with a thickness of 15.9 mm (5/8"), and a layer of rigid extruded polystyrene (XPS) insulation of variable thickness between 3 mm and 38 mm. Each specimen has two separate nailed connections, one on each side of the stud to eliminate loading eccentricity and allow each connection to be loaded in pure shear.

Two different nail sizes were used: 10d (76 mm long, diameter of 3.66 mm), and 16d (89 mm long, diameter of 4.06 mm). Specimens with the smaller 10d nails represent typical sheathing to framing connections in shear walls. The 16d nails are larger than those typically used in shear walls, and were tested to determine the effect of nail size on the performance of the overall connection. The smaller 8d nails were not tested because the 8d nails would not be able to accommodate a significant insulation thickness without compromising nail penetration into the stud.

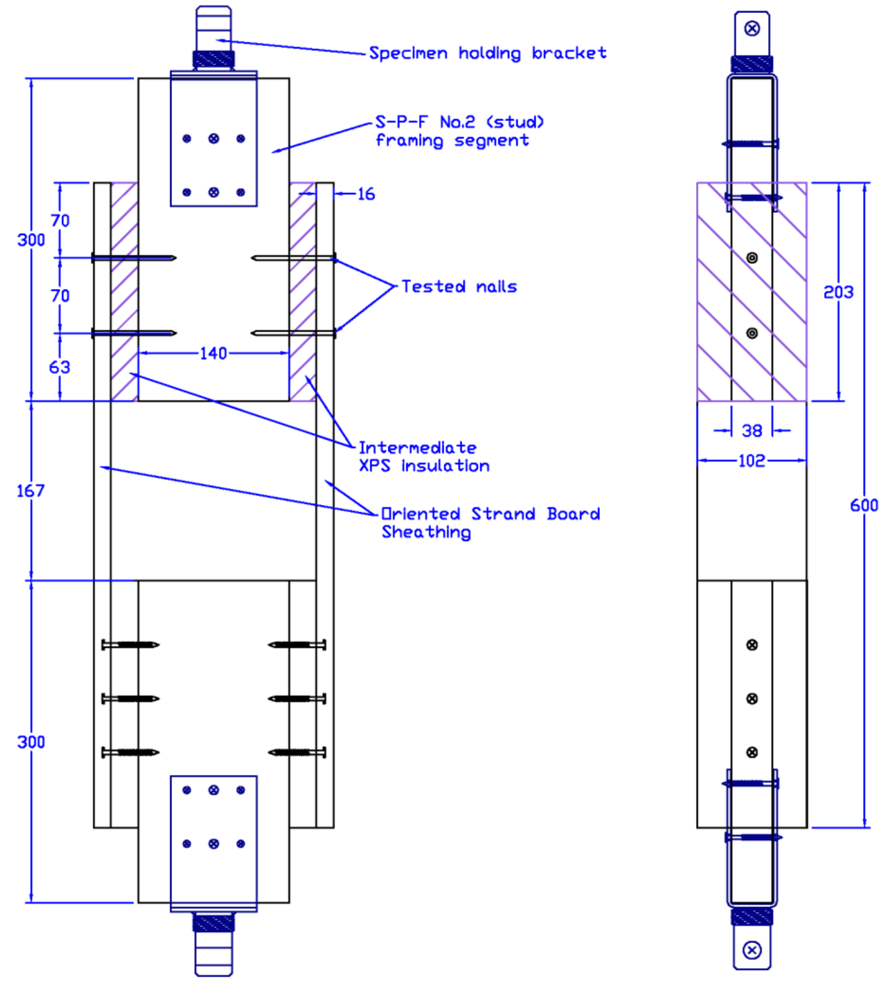

Fig. 1 - Experimental test specimen

Table 1 presents a testing matrix of all of the tests that were conducted. For each combination shown in the table, six identical specimens were tested.

Table 1 – Testing Matrix

Tests with 10d nails			**Tests with 16d nails**		
Insulation	**Nail Penetration into Stud**		**Insulation**	**Nail Penetration into Stud**	
	(mm)	**Nail diameters**		**(mm)**	**Nail diameters**
0 mm (0")	60.3	16.5	0 mm (0")	73.0	18.0
3.2 mm (1/8")	57.2	15.6	6.4 mm (1/4")	66.7	16.4
6.4 mm (1/4")	54.0	14.7	12.7 mm (1/2")	60.3	14.9
9.5 mm (3/8")	50.8	13.9	19.1 mm (3/4")	54.0	13.3
12.7 mm (1/2")	47.6	13.0	25.4 mm (1")	47.6	11.7
15.9 mm (5/8")	44.5	12.1	38.1 mm (1.5")	34.9	8.6
19.1 mm (3/4")	41.3	11.3			
25.4 mm (1")	34.9	9.5			

The test matrix included two control tests (one for each nail size) with no insulation in between the stud and sheathing. For the 10d nails, eight insulation thicknesses from zero to 25.4 mm (1"), incremented at 3.2 mm (1/8") were tested, with the exception of 7/8". For the 16d nails, six insulation thicknesses from zero to 38.1 mm (1.5"), incremented at 6.4 mm (1/4") were tested, with the exception of 1.25". All of the 10d nail specimens satisfy the limits on nail penetration as set out by the Canadian Standard for Engineering Design in Wood, CSA-O86-14, which states that nail penetration must be at least six nail diameters (CSA, 2014).

The shear displacements of the nailed connections were directly measured using two string potentiometers, one for each side of the connection. A displacement rate of 2.5 mm/min was used in conformance with ASTM D1761 (ASTM, 2012).

3. Experimental Results

Load data was averaged between the six identical specimens for each test and divided by four to obtain the behaviour of an individual nail. The displacement data from the two string potentiometers was also averaged. Fig. 2a and 2b show the shear load-slip response for specimens with 10d, and 16d nails, respectively. These results show that, for both nail sizes, an increasing thickness of intermediate insulation results in a decreasing connection capacity and stiffness.

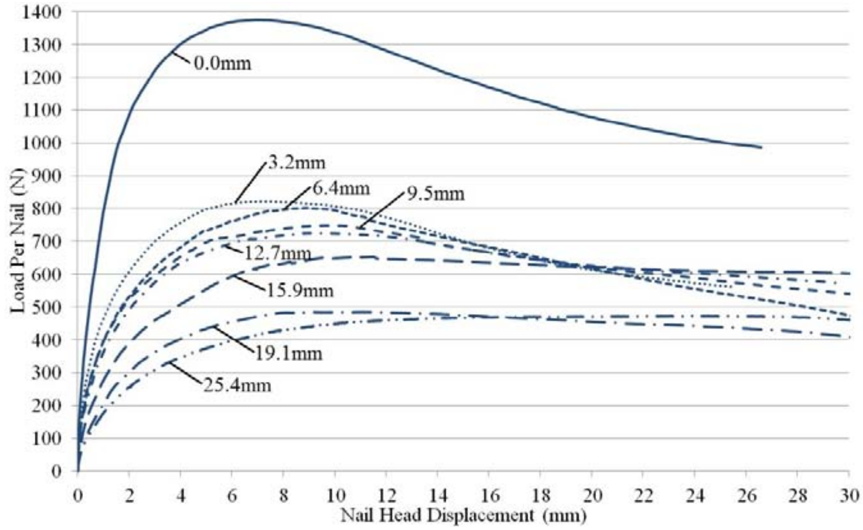

Fig. 2a - Load-slip behaviour for specimens with 10d nails

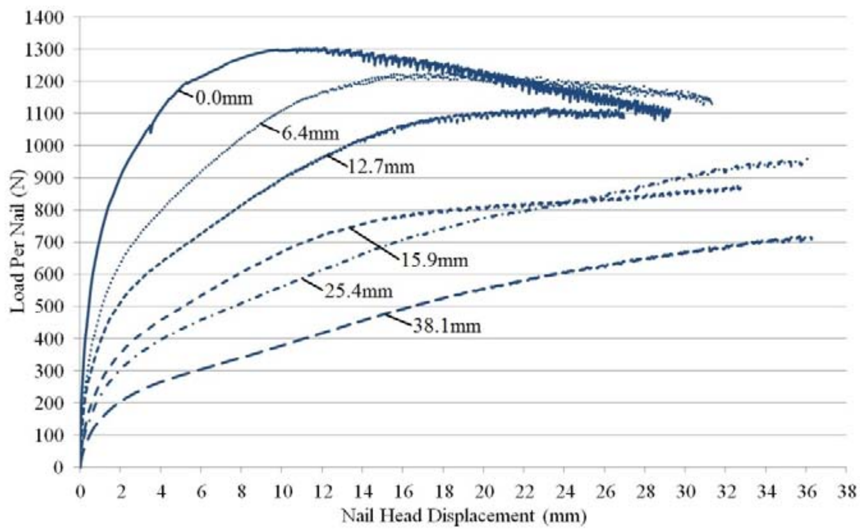

Fig. 2b - Load-slip behaviour for specimens with 16d nails

For both nail sizes, tests without any insulation or with a thin layer of insulation (less than 12.7 mm) had a clearly defined peak load within the test displacement range. In these cases, nails exhibited an S-shaped bend with one bend point in the sheathing and another in the framing. The cases with moderate to large thicknesses of insulation (more than 19.1 mm) exhibited lower initial stiffness and never reached a clearly defined peak load, because the displacement limit of the test setup was encountered before the peak load was reached. The load-slip profiles for these cases are characterized by a gradually increasing load up to the point when the test is terminated. The nails in these tests exhibited predominantly bending at only one point. This failure mode also had a larger amount of nail pull-out from the stud. Specimens with insulation thicknesses between 12.7 and 19.1 mm fell between these two modes, and resulted in a gradual transition between them.

These two different failure modes may be explained by considering the nail to be a simple cantilever with a lever arm of variable length, defined by the thickness of the insulation. For cases with little or no intermediate insulation the lever arm is very short. This increases the applied load required to induce yielding in the nail. In addition, the embedment strength of the sheathing is capable of inducing enough moment at the nail head to bend the nail in the opposite direction, imposing a second yield point in the nail. In this situation, the capacity of the connection is largely governed by the embedment properties of the member materials. For cases with large amounts of intermediate insulation, the lever arm for the cantilever is considerably longer, and the connection therefore requires less applied load to induce nail yielding. In this situation, there is insufficient resistance from the sheathing to induce any reverse bending in the nail, and the capacity of the connection as a whole is largely governed by the bending strength of the nail.

Table 2 shows the peak load for each tested combination, along with the coefficient of variation, for each set of six specimens within each test. There was generally more variation in the control tests without the insulation because these tests rely more on the variability in behaviour of the wood elements than the nail. The table also shows that the shear strength of the connection drops significantly by as much as 65% as the insulation thickness increases up to 25 mm in the 10d connections and by as much as 58% as the insulation thickness increases up to 38 mm in the 16d connections.

The yield strength and secant stiffness (stiffness up to the yield strength) for all experimental tests was calculated using the method developed by Karacabeyli & Ceccotti (1996), and the 5% diameter method (ASTM, 2008). Both methods are shown for sample data in Fig. 3. The yield point is lower than the peak strength, but gives a better indication of when a shear wall will begin to deform inelastically.

Table 2: Comparison of peak connection shear load and coefficient of variation

10d Nails				**16d Nails**			
Insulation Thickness	**Mean (N)**	**COV**	**% base capacity**	**Insulation Thickness**	**Mean (N)**	**COV**	**% base capacity**
0" (0.0 mm)	1390	0.25	100	0" (0.0 mm)	1318	0.19	100
1/8" (3.2 mm)	829	0.10	60	1/4" (6.4 mm)	1252	0.14	95
1/4" (6.4 mm)	818	0.24	59	1/2" (12.7 mm)	1126	0.19	85
3/8" (9.5 mm)	756	0.07	54	3/4" (19.1 mm)	819	0.19	62
1/2" (12.7 mm)	731	0.12	53	1" (25.4 mm)	776	0.15	59
5/8" (15.9 mm)	689	0.20	50	1.5" (38.1 mm)	556	0.14	42
3/4" (19.1 mm)	490	0.17	35				
1" (25.4 mm)	474	0.26	34				

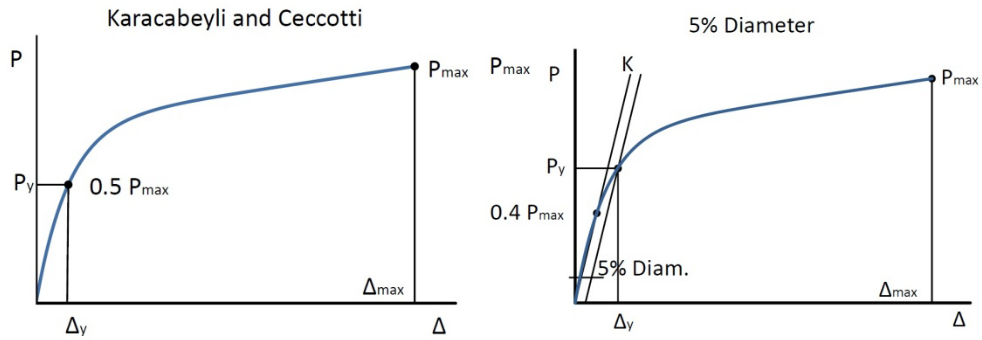

Fig. 3 - Yield point methods explanation (after Munoz et al. 2008)

The decline in connection capacity with respect to the thickness of intermediate insulation (normalized relative to the capacity of the connection without any insulation) is shown in Fig. 4. The plots in Fig. 4 show this strength trend using both the maximum recorded load from Table 2, and the two yield point methods described above. For the 10d nails, there is an immediate loss of strength that occurs as soon as insulation of any thickness is added, relative to the control case. In the case of 10d nails, approximately 20% of the connection capacity is lost for every 10 mm of intermediate insulation, in addition to an immediate loss of about 40%. In the case of 16d nails, there is also a loss of approximately 20% of capacity for every 10 mm of intermediate insulation, however there is no significant immediate loss.

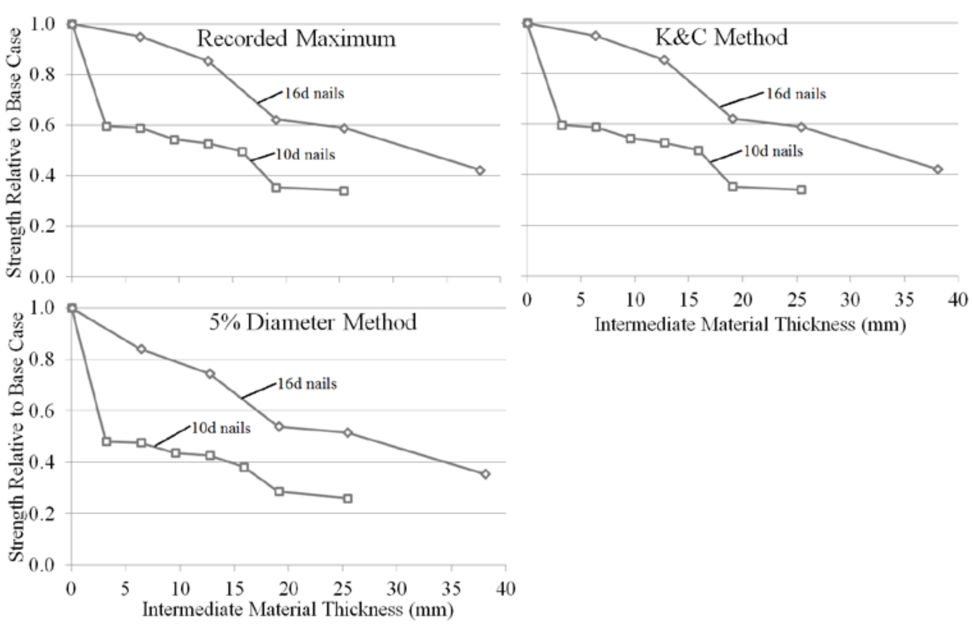

Fig. 4 - Reduction in relative capacity

The decline in connection stiffness with respect to the thickness of intermediate insulation (normalized relative to the stiffness of the connection without any insulation) is shown in Fig. 5. The stiffness is calculated by finding the secant stiffness to the yield point for the two yield point methods described above. The relationship between stiffness and intermediate insulation thickness resembles an exponential decay. For both nail sizes, approximately 50% of the connection stiffness is lost for every 10mm of intermediate insulation.

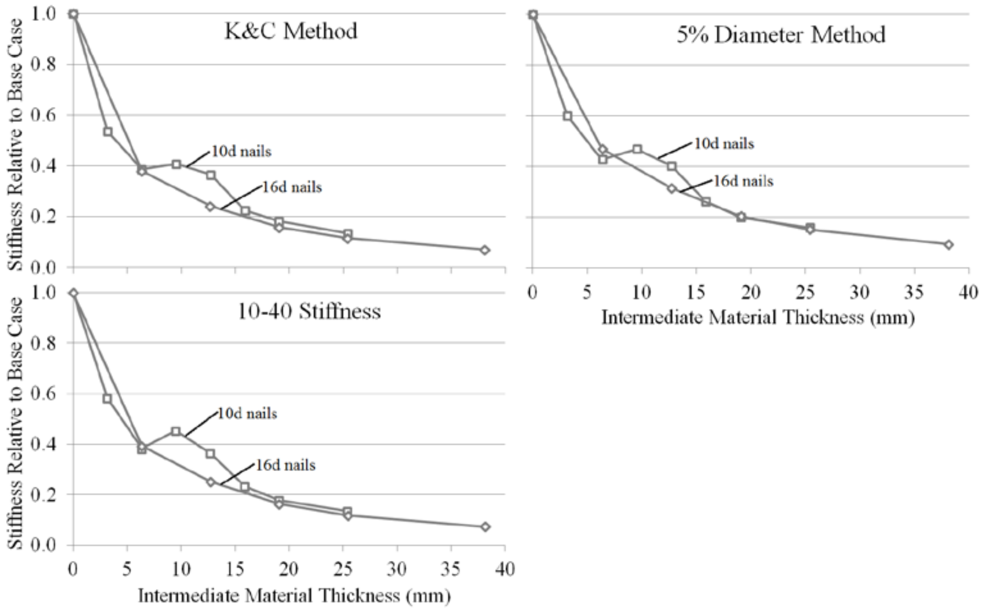

Fig. 5 - Reduction in relative stiffness

4. Analytical Nail Model in OpenSees

A nonlinear model of a nailed connection with an intermediate material between two wood elements was developed using OpenSees (McKenna et al, 2000). A schematic of the model is shown in Fig. 6.

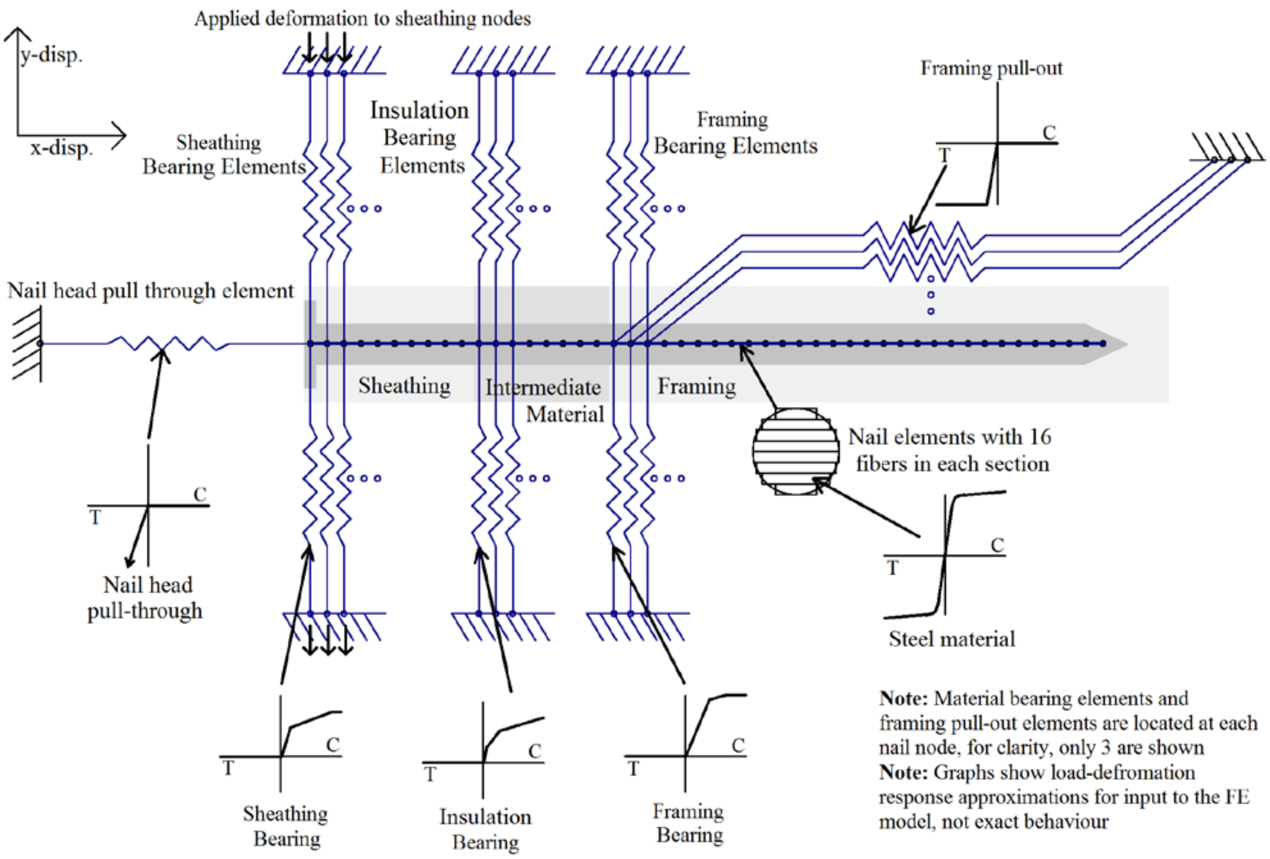

Fig. 6 - Finite element model diagram

The FE model contains the following components:

- A line of beam-column elements with fiber sections which simulate the steel nail behaviour in bending. The material has a modulus of elasticity of 200 GPa, and a yield stress calibrated according to separate center-point bending tests conducted on individual nail specimens of the same size and composition. Center-point nail bending tests were done in agreement with ASTM F1575 (ASTM, 2008).
- A series of spring bearing elements which simulate the embedment resistance of the member materials: sheathing (OSB), framing/stud (SPF), and intermediate material (XPS insulation). These elements were calibrated based on dowel-bearing tests conducted on samples of OSB and SPF, and compression tests on specimens of XPS insulation. Dowel-bearing tests were performed in agreement with ASTM D5764 (ASTM, 2005).
- A series of spring elements distributed along the length of the nail, which simulate the resistance of the nail to being pulled out of the framing/stud. These elements were calibrated based on nail pull-out tests conducted on specimens of SPF. Nail pull-out tests were done in agreement with ASTM D1761 (ASTM, 2012).
- An additional truss element was added to the nail head to simulate the resistance of the nail head to penetrating though sheathing (OSB). This element was calibrated based on the surface area of the nail head bearing on the sheathing, and a commonly accepted elasticity of OSB in compression of 3 GPa (FPL, 2010).

The far end-nodes for all spring elements are fixed. The model was loaded by applying a controlled lateral displacement to the sheathing (in the up-down direction in Fig. 6). A sample load-deformation response is shown in Fig 7, in comparison with the load-slip response of the same connection tested experimentally on specimens with a 10d nail and 12.7 mm of intermediate insulation. The experimental minimum and maximum curves shown in the figure represent the maximum and minimum strength tests from the six identical specimens. Fig. 7 shows that the model captures the average magnitude of the ultimate connection capacity well, as well as the level of deformation at which this maximum capacity occurs; however, the model does not capture the initial stiffness of the connection well.

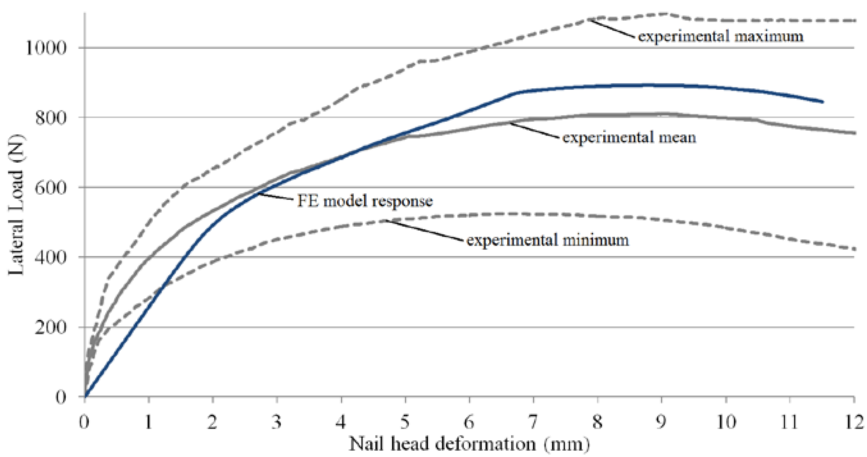

Fig. 7 - Sample finite element model response for 10d nails and 1/4" (12.7mm) of insulation

Fig. 8a and 8b compare the ultimate capacity predicted by the analytical model with the capacity of previously-described experimental tests for connections with 10d and 16d nails, respectively. These figures show that the model captures the decline in connection capacity with respect to insulation thickness for both nail sizes well. Given the variability in the experimental data, this model seems to be reliable, and can likely be used to predict the behaviour of other similar nailed connections with an intermediate material between two wood members.

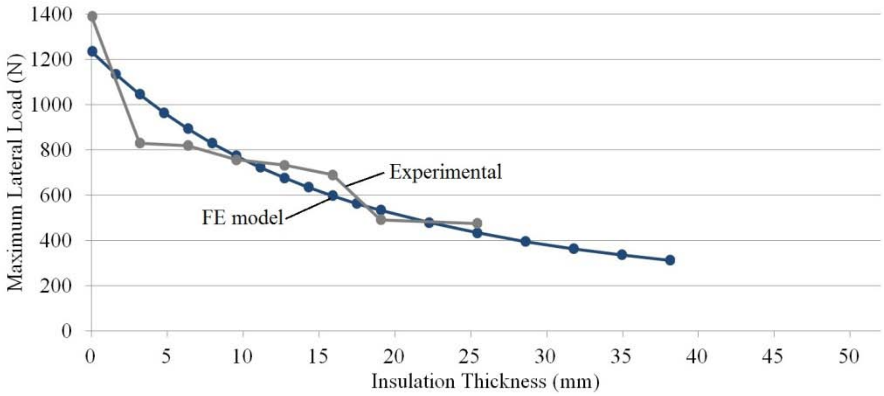

Fig. 8a - Finite element model results for specimens with 10d nails

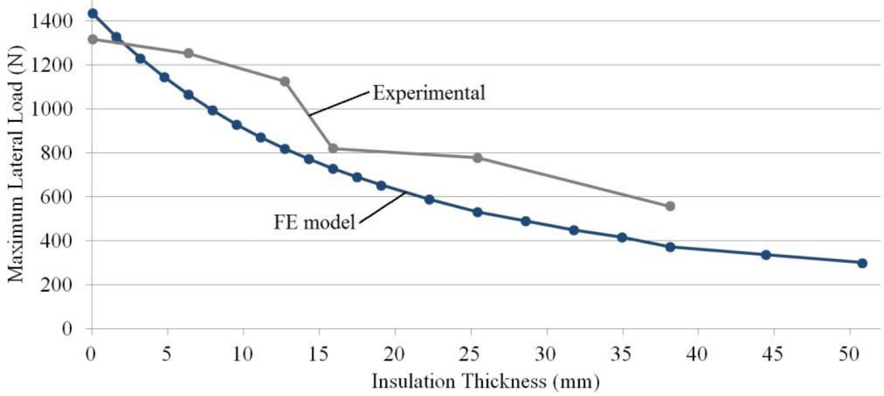

Fig. 8b - Finite element model results for specimens with 16d nails

5. Conclusions

Experimental testing of light frame nailed connections with intermediate insulation of various thicknesses was conducted. In addition to this, a finite element model of the same nailed connection with a zero-strength intermediate layer was developed. The load-deformation behaviour of the experimentally tested nails was compared with the output of the finite element model. The study's findings are:

- There is a significant decline in the capacity of a sheathing-to-framing nailed connection with the addition of an intermediate layer of insulation in between the sheathing and the framing. Increasing the insulation thickness results in an approximately linear loss of 20% of capacity per cm of insulation thickness. In addition to this, an immediate loss in strength is seen when any amount of insulation is included, with this effect being more significant for the connections with smaller nails.
- There is an exponential decay in connection stiffness with increasing insulation. The losses in relative stiffness are fairly consistent with nail size and calculation method at roughly 50% for every cm of intermediate insulation.
- A newly-developed analytical model of nailed connections with intermediate insulation has been shown to be effective in predicting the ultimate capacity, displacement at the ultimate capacity, and decline of capacity with increasing intermediate insulation.

It is recommended that full-scale shear wall testing with different thickness layers of intermediate insulation between the sheathing and the studs be conducted to expand on the results presented here and explore other potential failure modes that could arise due to the inclusion of the insulation layer.

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