Short-Term Scientific Mission report

Finite element modelling of metal connectors for CLT buildings under seismic conditions

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November 01, 2014 – January 31, 2015

Introduction

Cross-Laminated Timber (CLT) has gained a significant popularity as construction material in recent years. Since such panels are fairly stiff in their plane, with a linear-elastic behaviour and a tendency to brittle failure mechanisms, the behaviour under seismic conditions is highly dependent on the connections used. It is known that a wide range of parameters influences the performances of those systems, such as the strength and stiffness characteristics of the metal connectors, the number of fasteners utilized (e.g. nails, screws) as well as the density and the moisture content of the timber. To ensure adequate ductility and sufficient energy dissipation, experimental programmes have investigated the behaviour of single-joints (e.g. [1-4]) and wall-systems (e.g. [5-7]) under monotonic and cyclic loads. Shear and pull-out tests have been carried out on hold-downs and steel angle connectors used to anchor the wall panels; in addition, full-scale tests on single and coupled CLT walls subjected to lateral force have been carried out with different configurations and connectors (e.g. [1, 3, 5, 8-10]).

This report presents the results of an extensive experimental programme performed at the Institute of Timber Engineering and Wood Technology, Graz University of Technology, on Simpson Strong-Tie CNA [11] (annular ringed shank nails, also referred to as anker nail, Figure 1) used in CLT structures to anchor the metal connectors to the timber panels. Shear tests in parallel and perpendicular direction to the face lamination of the panels, as well as withdrawal tests have investigated the performance of those fasteners under monotonic and cyclic conditions. To obtain a full insight of the connection behaviour, uniaxial tension tests and bending tests have been performed on single anker nails to determine the ultimate tensile strength and the yielding moment. Furthermore measurements of moisture content and density of the timber have been taken in correspondence of the position at which the nails were located during the tests. Mean values have been obtained in accordance to current standards [12-18].

Figure 1: Simpson Strong-Tie annular ringed shank nail [11].

The results of the experimental programme have been used to calibrate a numerical model of a nail, in which the behaviour of the metal fastener is modelled by means of newly developed nonlinear springs. This model can be implemented into Finite Element (FE) software, to create accurate FE models of single-joints and wall-systems. The use of this numerical models would limit the need for experimental testing to a minimum and would allow the prediction of the monotonic and cyclic behaviour of a certain metal connector such as a hold-down or an angle bracket where some elements (e.g. the number of nails or the position of the connector in the wall-systems) have been changed with respect to the original test.

Description of the work carried on during the STSM

An experimental programme has been performed at the Institute of Timber Engineering and Wood Technology, Graz University of Technology, under the supervision of Professor Gerhard Schickhofer and in collaboration with Georg Flatscher, Ph.D. Candidate. The performances of Simpson Strong-Tie CNA [11] of length $L = 60\text{mm}$ and diameter $D = 4.0\text{mm}$ driven into 134mm-thick CLT panels (5 layers) have been investigated. The timber panels have been conditioned at 20°C and 65% relative humidity before the execution of the tests.

Shear tests in parallel ($\|$) and perpendicular ($\perp$) direction to the face lamination of the panels

Monotonic $(8 \| + 5 \perp)$ and cyclic $(15 \| + 15 \perp)$ shear tests have been performed in parallel and perpendicular direction to the face lamination of the panels (Figure 2). As stated in [12], a symmetric system has been adopted with two nails driven at the same location in two opposite sides of the CLT panel. The test protocol of the monotonic tests has been chosen in accordance with [13] considering an estimated load of 9.0kN (4.5kN for each nail). The first two tests in parallel direction to the face lamination of the panels have been performed with an estimated load of 7.0kN and the LVDTs used for the local measurements have been removed before the end of the tests. For this reason, those tests have not been considered for the mean calculations.

Figure 2: Setup adopted for the shear tests in parallel (left) and perpendicular (right) direction to the face lamination.

Figures 3-6 display one significant test of each series, while Tables 1-4 show the mean values and the coefficients of variation (COV) obtained by post processing the test data with respect to the maximum load. The backbone curves have been obtained as stated in [15].

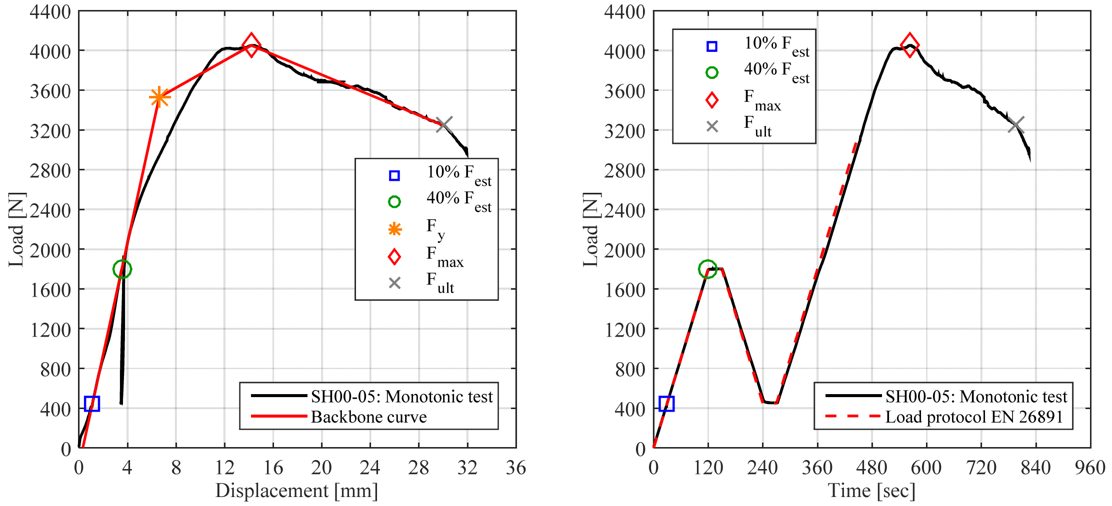

Figure 3: SH00-05: Monotonic test - parallel direction to the face lamination of the panel (F_{max}).

$K_{ser,0}$ [N/mm]	$K_{ser,2}$ [N/mm]	u_y [mm]	F_y [N]	u_{max} [mm]	F_{max} [N]	u_{ult} [mm]	F_{ult} [N]	Duct [-]
492.65	4201.29	7.41	3490.33	13.06	3904.84	22.66	3275.26	3.16
16.05%	24.88%	23.80%	4.82%	12.72%	4.26%	27.23%	4.32%	33.56%

Table 1: Monotonic shear series SH00 – Mean values (first line) and COV (second line).

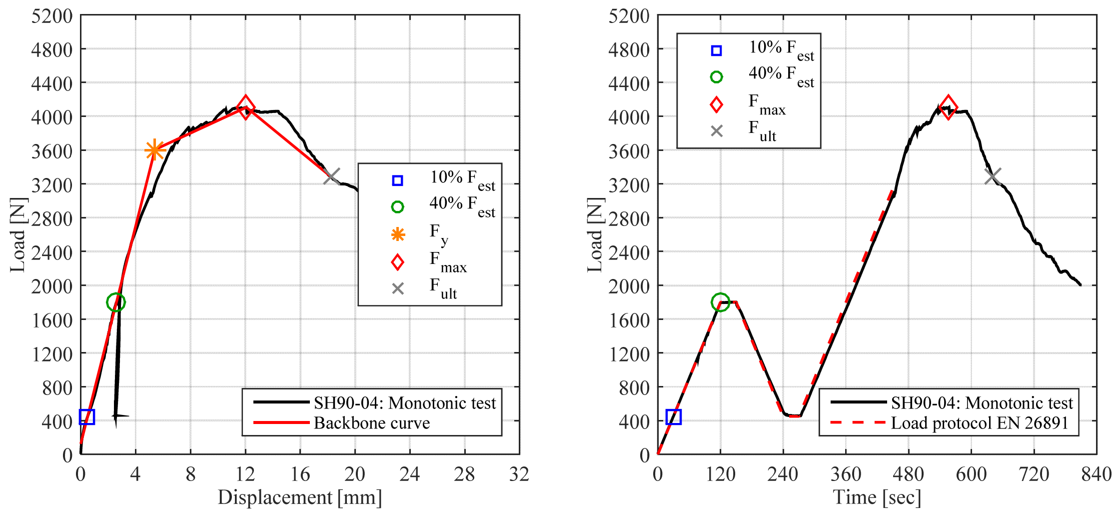

Figure 4: SH90-03: Monotonic test - perpendicular direction to the face lamination of the panel (F_{max}).

$K_{ser,0}$ [N/mm]	$K_{ser,2}$ [N/mm]	u_y [mm]	F_y [N]	u_{max} [mm]	F_{max} [N]	u_{ult} [mm]	F_{ult} [N]	Duct [-]
567.54	3472.62	6.78	3870.70	12.90	4405.73	15.59	3877.99	2.50
22.18%	15.69%	27.10%	10.52%	9.83%	8.84%	14.75%	12.06%	39.39%

Table 2: Monotonic shear series SH90 – Mean values (first line) and COV (second line).

As suggested in [13] two values of K_{ser} are given for the monotonic tests, respectively $K_{ser,0}$ on branch 0 (first loading path) and $K_{ser,2}$ on branch 2 (second loading path). The monotonic tests have been carried out with a load-based protocol with 0.9kN/min for each nail until $\text{Time} = 450\,\text{sec}$, and subsequently with a displacement-based protocol with 4.0mm/min until the end of the test. Figures 3-right and 4-right compare the applied load (solid black line) with load-based protocol defined in the standard (red dashed line).

The displacement protocols of the cyclic tests have been defined in accordance with [14] considering the mean ultimate displacement obtained from the monotonic tests. Furthermore, a modified protocol with an increased number of cycles before failure has been used in the last four tests of each series, to obtain a more accurate description of the impairment of strength and of the equivalent damping in the inelastic field. The ultimate point of each envelope curve of the cyclic tests have been defined in accordance with [14] considering either the failure or the point at which the 80% of the maximum force is reached. Future studies will investigate in detail the shape of the envelope curves and the performances of the metal fasteners under cyclic loads, and will consider a limitation of the 20% on the impairment of strength as defined into [19].

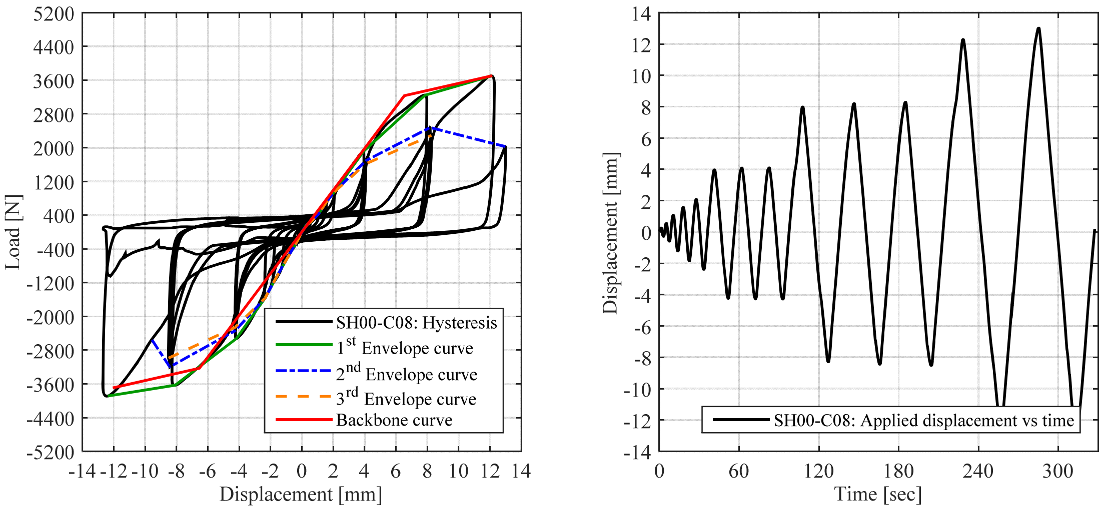

Figure 5: SH00-C08: Cyclic test - parallel direction to the face lamination of the panel (F_{max}).

K_{ser} [N/mm]	u_y [mm]	F_y [N]	u_{max} [mm]	F_{max} [N]	u_{ult} [mm]	F_{ult} [N]	Duct [-]
545.55	6.66	3393.21	10.73	3756.32	10.94	3667.64	1.75
32.04%	26.50%	14.80%	11.63%	17.12%	7.98%	19.88%	25.87%

$Imp_{1\text{-}3}$ [%]	$Imp_{1\text{-}2}$ [%]	$\nu_{eq,1st\ env}$ [%]	$\nu_{eq,3rd\ env}$ [%]	$\nu_{eq,2nd\ env}$ [%]
14.35	11.08	15.70	8.64	9.74
5.05%	8.43%	9.32%	6.23%	5.43%

Table 3: Cyclic shear series SH00-C – Mean values (first line) and COV (second line).

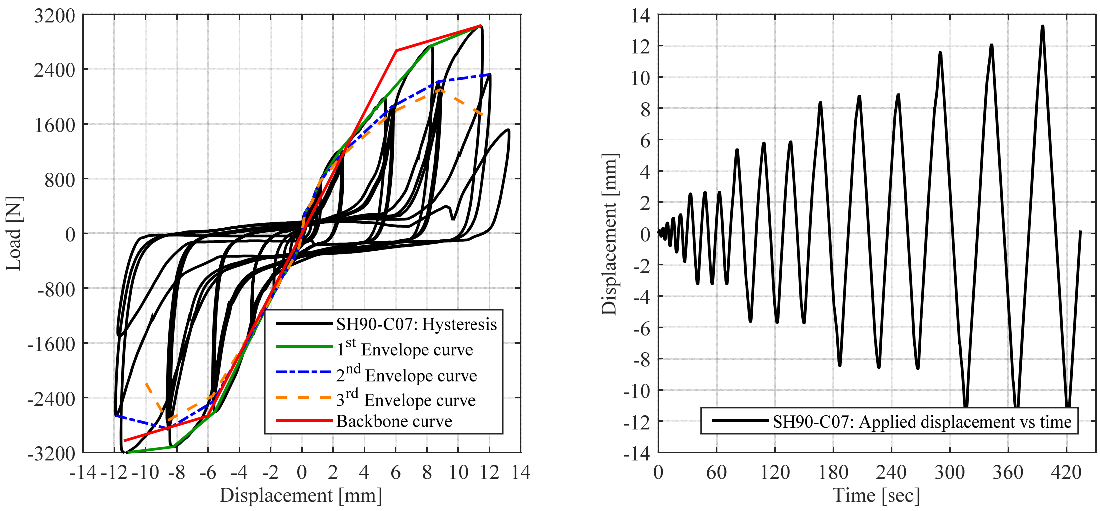

Figure 6: SH90- C07: Cyclic test - perpendicular direction to the face lamination of the panel (F_{max}).

K_{ser} [N/mm]	u_y [mm]	F_y [N]	u_{max} [mm]	F_{max} [N]	u_{ult} [mm]	F_{ult} [N]	Duct [-]
513.69	5.46	2738.04	8.62	3007.93	9.94	2562.63	2.00
27.32%	31.49%	11.16%	23.97%	13.21%	24.98%	17.00%	43.47%

Imp_{1-3} [%]	Imp_{1-2} [%]	$\nu_{eq,1st\ env}$ [%]	$\nu_{eq,3rd\ env}$ [%]	$\nu_{eq,2nd\ env}$ [%]
12.02	8.83	13.91	8.77	9.63
11.99%	20.05%	8.50%	9.23%	9.47%

Table 4: Cyclic shear series SH90-C – Mean values (first line) and COV (second line).

Withdrawal tests

The withdrawal tests have been performed on 22 nails, driven into seven different CLT specimens; Figures 7 and 8 show the setup adopted and the results of a significant test, while Table 5 shows the mean values and the coefficient of variation obtained from the post processing.

Figure 7: Setup adopted for the withdrawal tests (left) and detail of the fixation (right).

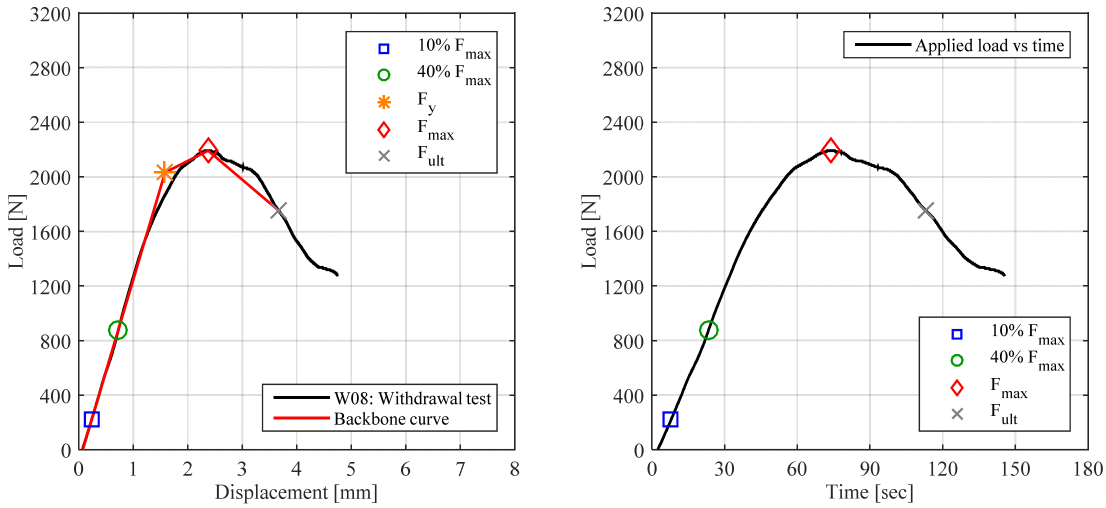

Figure 8: W08: Withdrawal test - Post processing with respect to F_{max} .

K_{ser} [N/mm]	u_y [mm]	F_y [N]	u_{max} [mm]	F_{max} [N]	u_{ult} [mm]	F_{ult} [N]	Duct [-]
1283.01	1.73	2018.13	2.41	2148.66	3.74	1718.45	2.27
23.52%	24.18%	15.05%	12.82%	14.76%	10.41%	14.75%	23.82%

Table 5: W - Withdrawal tests – Mean values (first line) and COV (second line).

Each test was carried out with a displacement based protocol until a loss of 40% of the maximum load was reached.

Measurement of moisture content and density

Measurements of moisture content and density of the timber have been taken in correspondence of the position at which the nails were located during the tests (Figure 9). Those results have not been used at this stage of the research and will be considered in the future, to discuss and compare the previous test results.

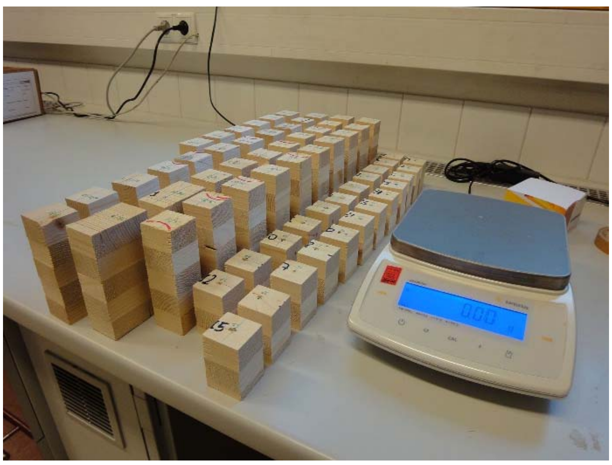

Figure 9: Samples used to measure moisture content and density of the timber.

Moisture [%]	Density [N/mm]
11.49	409.23
2.24%	5.49%

Table 6: Moisture content and density – Mean values (first line) and COV (second line).

Uniaxial tension tests and bending tests

Uniaxial tension tests (5) and bending tests (10) have been performed on single anker nails to determine the ultimate strength (Figure 10-left) and the yielding moment (Figure 10-right) of the metal fastener. Table 7 shows the results obtained by post processing the data.

Figure 10: Setup adopted for the uniaxial tension tests (left) and for the bending tests (right).

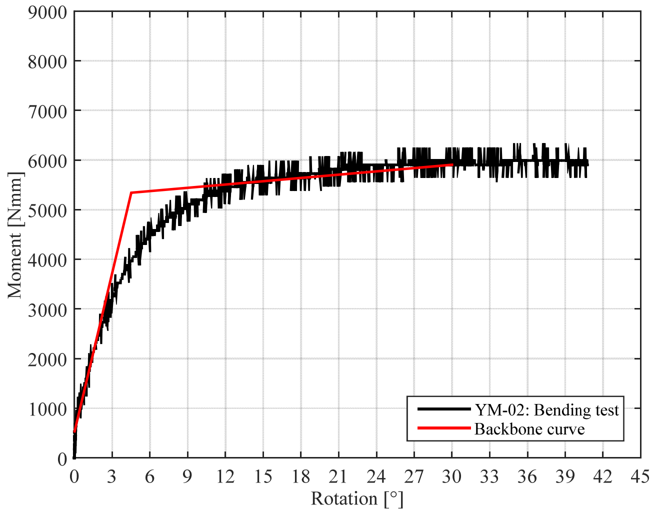

Figure 11: YM-02: Bending test of a annular ringed shank nail.

$\sigma_{u,axial}$ [N/mm^2]	K_{el} [Nmm/deg]	φ_y [deg]	M_y [Nmm]	K_{pl} [Nmm/deg]
892.22	1476.83	3.54	5391.08	22.02
0.80%	34.86%	28.56%	9.61%	37.25%

Table 7: Uniaxial tension tests and bending tests – Mean values (first line) and COV (second line).

The numerical model of a nail

The numerical model of a nail in the following presented was developed in the frame of my Ph.D. research project in collaboration with Giovanni Rinaldin, Ph.D. In the model, the shear behaviour in direction parallel and perpendicular to the face lamination of the panels and the resistance to withdrawal forces are modelled by means of newly developed non-linear springs [20] (Figure 12).

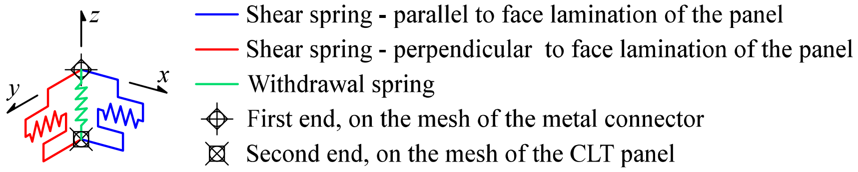

Figure 12: Schematization of the numerical model of a nail.

Each non-linear spring connects one node on the mesh of the metal connector, placed in the exact position at which the nail was located in the experimental setup, to the corresponding node on the mesh of the CLT element. Two different hysteresis laws have been adopted in the model, to characterize the shear and the withdrawal behaviour of the nail (Figures 13 and 14).

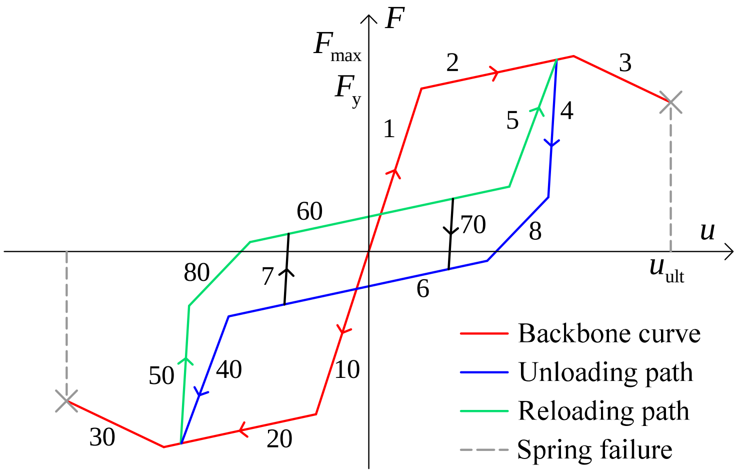

Figure 13: Piecewise-linear laws for the shear springs (image reproduced from [20]).

The piecewise linear-law used for the shear springs (Figure 13) is symmetric and is made of 16 branches; the backbone curve considers an elastic branch until yielding and two inelastic branches until failure, the first with hardening and the second with softening. If the nail is unloaded, branch #4 is followed until a given percentage (chosen by means of a dedicated input parameter) of the maximum force on the backbone curve is reached.

The piecewise linear-law used for the withdrawal springs (Figure 14) is made of 11 branches and considers hysteresis loops in tension and contact behaviour in compression, to simulate the interaction between the foundation point of the nail and the timber. The backbone curve is not symmetric, with three branches in tension whereas branches #10 and #20 are overlapped in compression.

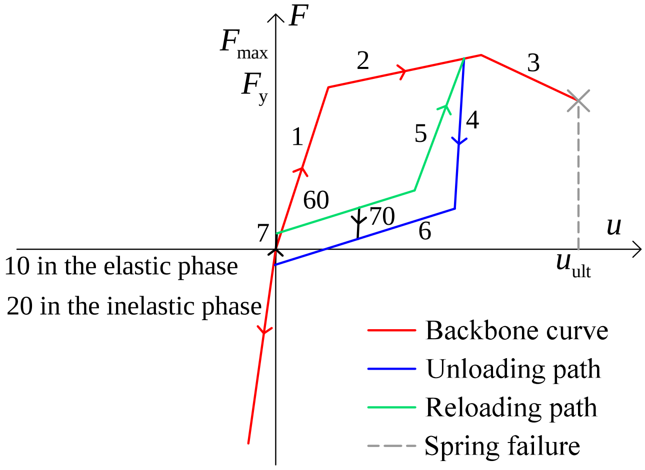

Figure 14: Piecewise-linear laws for the withdrawal springs (image reproduced from [20]).

Stiffness and strength degradation have been implemented in the model, but are not considered at this stage of the research, and will possibly be introduced in the future.

Finite element modelling of a Simpson Strong-Tie AE116: a first application

The system under analysis investigates the performance of a Simpson Strong-Tie AE116 anchored to two CLT panels by means of 21 nails, 14 located in the long-leg and 7 in the short leg. The numerical model and the results of the experimental programme presented in the previous sections have been used to simulate the nonlinear behaviour of the nails. In the model, the timber parts have an elastic behaviour and layered section with the same layup used in the experimental setup, whereas the metal connector has a nonlinear force-displacement relationship with a yielding tension of 330MPa and an ultimate tensile strength of 250MPa. Figure 15-left compares the experimental force-displacement relationship with the performance of the numerical model while Figure 15-right shows a deformed view in contour of Mises tensions of the FE model.

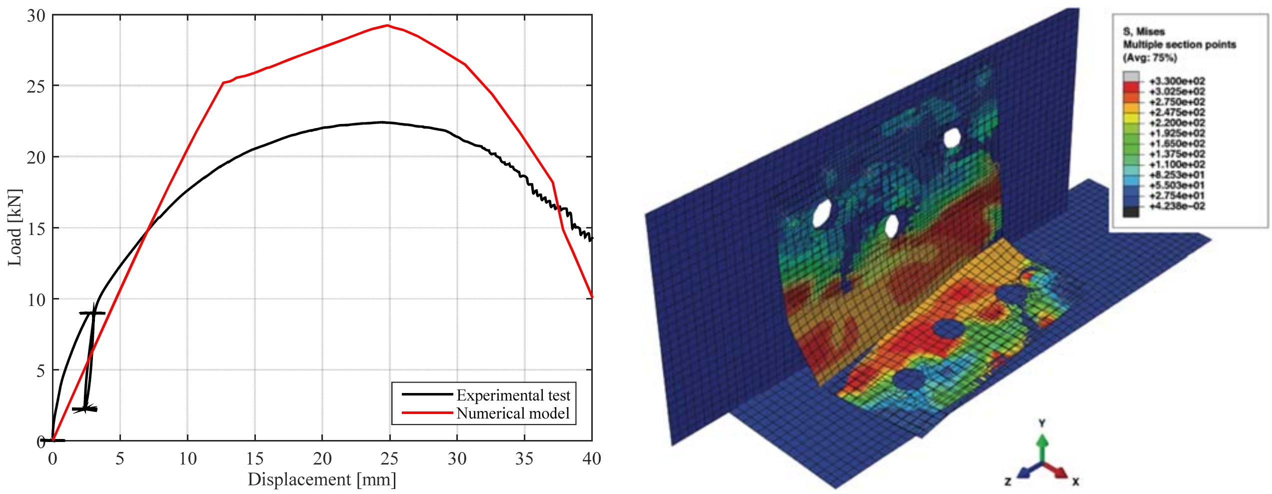

Figure 15: Comparison between experimental and numerical results (left) and deformed view of the FE model (right).

Future collaboration and foreseen publications

This STSM is the beginning of an on-going collaboration between the participants, which will be carried on in the following months. The experimental results obtained during this Short-Term Scientific Mission will be presented in detail in a future journal paper. In addition, over-strength factors for annular ringed shank nails will be obtained by comparing the characteristic values obtained from the previous tests with the formulations provided by the reference literature (Eurocode 5 and publications made by Professors Uibel and Blass).

Acknowledgments

The author would like to acknowledge the representatives of COST Action FP1004 “Enhance the mechanical properties of timber, engineered wood products and timber structures” for the Short Term Scientific Mission grant, which contributed to a successful progress of this research. The local host Professor Gerhard Schickhofer, the Ph.D. Candidate Georg Flatscher, and the Competence Centre holz.bau forschungs gmbh are gratefully acknowledged for giving access to the laboratory and all the facilities provided by the Institute of Timber Engineering and Wood Technology, for sharing the test data obtained in the last COMET K-Project and for the advices, help and collaboration throughout the whole STSM.

Appendix

Confirmation by the host institute of the successful execution of the mission.

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