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FINITE ELEMENT MODELLING OF HYBRID WOOD/ALUMINIUM ASSEMBLY WITH WOOD-FILLED ALUMINIUM AND STEEL DOWELS

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ABSTRACT: This paper presents a Finite Element modelling procedure for hybrid structures made of confined wood within a thin aluminium envelope using the explicit dynamic analysis through the use of LS-DYNA® software. The primary use of hybrid structures will be for highway bridge safety barriers in order to assess the energy absorption capabilities during an impact due to a car accident. The mechanical behaviour of the wood was modelled using the built-in material model MAT-143 in LS-DYNA. The comparison of the numerically predicted failure behaviour and the global response expressed as force-displacement responses of the studied hybrid structures to those reported in the literature, has shown the ability of the model to simulate the failure behaviour of such hybrid structures.

KEYWORDS: Wood, Aluminium, Finite Element, Hybrid structures, wood-filled aluminium composites.

1 INTRODUCTION

Timber is known as one of the oldest and longest standing building materials in existence, with evidence showing homes built over 10,000 years ago used wood as a primary source for construction materials [1]. In the last two decades, the used of wood in the construction sector has increased due to the development of engineered wood products (EWPs) such as cross-laminated timber (CLT), laminated veneer lumber (LVL) and glued laminated timber (glulam), which offer improved and homogenous mechanical properties for their use as structural materials. Massive timber construction requires suitable connections in order to join the different elements of the building. The most common connection in contemporary timber structures are manufactured using steel plates and laterally loaded metal dowel-type fasteners (Figure 1). The benefits of these types of connections are the ease of manufacturing, design, and assembly, in addition to their high load carrying capacity and ductility. However, the use of metallic connections in timber structures can reduce the fire resistance of the structure as metallic components increase the heat transfer in the connection [2]. In addition, the weight of the steel elements (plate, dowels, bolts) in the connection can be regarded as drawbacks during the operating phase. In fact, the high stiffness of steel in comparison to wood can increase the stress in the wood, thus increasing the probability of brittle failure in the timber members, which is undesirable in timber construction. In this respect, the use of lightweight et competitive connection systems by reducing the amount of metal used within the timber structure would be most advantageous in terms of the improvement of the fire resistance, the corrosion resistance and the reduction of the weight of the connection.

Figure 1: *Metal fasteners in timber construction [3]*

Glued connection is also used in the category of non-metallic connection in timber structures. However, the use of adhesives has some drawbacks as they can produce volatile organic compounds (VOCs) and reduce the recyclability of the wood products. In this context, a

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research program called: “Towards Adhesive-Free Timber Buildings (AFTB)” and funded by the North-West-European Interreg program was born. The aim was to develop ‘‘green” and adhesive free EWPs and connection systems using compressed wood dowels as a joining fastener to substitute the traditional adhesives (or metallic fasteners) [4]. In the same context, El-Houjeyri et al. [4] have designed some novel adhesive free engineered Wood Products by using compressed wood dowels (CWD) as a joint element to connect timber laminates and members. The strength and stiffness properties of the CWD were characterized based on three-point bending tests and compared to the values obtained from uncompressed wood specimens. The CWD were used as connection elements in timber-to-timber connections in double shear push-out tests and the results were compared to those of a timber-to-timber connection with a steel dowel. The authors [4] have found that, in terms of load-carrying capacity, the joints assembled using compressed wood dowels compared well to their counterparts assembled using a steel dowel, but have a strength and stiffness characteristic values lower than to the joints assembled using a steel dowel. In this respect, an optimization of the CWD could be achieved for better structural performance.

As some countries in Europe, some countries in North America like Canada have shown also interest in using those EWPs and lightweight materials in the construction sector. For example, the government of Quebec published in 2013 the Wood Charter [5] and in 2015 the Quebec Aluminium Development Strategy (SQDA) [6], which aim to promote the use of EWPs and aluminium in the construction sector. In fact, these two materials (wood and aluminium) have low environmental impact in comparison to steel et concrete, are recyclable, sustainable and are locally produced in Québec. In this context, Rollo et al. [7] have investigated a solution of a hybrid dowel by confining a CWD in an aluminium tube in order to improve the mechanical characteristics of the CWD developed by El-Houjeyri et al. [4]. Following the work of El-Houjeyri et al. [4] and Rollo et al. [7], Tétreault et al. [8] have proposed a novel hybrid timber-to-aluminium connection by using hybrid wood-filled aluminium dowels and steel dowels. However, due to the novelty of these hybrid structures using wood and aluminium, they are not yet considered in calculation standards like the CSA-O86 (National Standards of Canada: Engineering design in wood). Thus, to obtained reliable and safe application of these products, experimental tests are needed and the tests need to cover as many scenarios as possible. In contrast, the use of numerical simulation means of the finite element (FE) method appears to be a good alternative in order to reduce the number of experimental tests. In this study, it is proposed to investigate and evaluate a numerical procedure for the design and the analysis of hybrid structures with confined wood. We investigate the capability of the wood material formulation (*MAT_143/*MAT_WOOD) available in LS-DYNA for simulating the mechanical behaviour and the failure response of hybrid assembly (Wood/Aluminium) using either wood-filled aluminium hybrid dowels or steel dowels.

2 FINITE ELEMENT MODELLING

Different hybrid wood/aluminium structures including confined wood available in the literature were selected to evaluate the performance of the built-in material model **MAT_143/*MAT_WOOD*. Three-Point Bending test on densified wood dowel and on hybrid wood-filled aluminium dowel (Figure 2) were carried out by Rollo et al. [7]. Double shear tests on hybrid systems (timber-to-aluminium connections) assembled using wood-filled aluminium hollow tube dowel and steel dowel were carried out and analysed experimentally by Tétreault et al. [8]. This section presents the different material models used in the FE model, the FE modelling techniques used to simulate the different loading and geometric conditions.

2.1 MATEIRAL MODELLING

2.1.1 Wood material model: MAT-143

At macroscopic scale, wood material is commonly assumed to be orthotropic as its properties vary in the three directions: longitudinal (L or 1), radial (R or 2) and tangential (T or 3). Wood material model MAT-143 [9] in LS-DYNA considers the wood as a transversely isotropic. Parallel direction represents longitudinal (L) axis and perpendicular direction refers to radial (R) or tangential (T) axis of timber. The strength criteria are defined using Hashin’s formulation with different analytical forms for the parallel $f_{||}$ and perpendicular $f_{\perp}$ criteria according to equations (1) and (2) respectively:

$$f_{||} = \frac{{\sigma_{11}}^2}{X^2} + \frac{({\sigma_{12}}^2 + {\sigma_{13}}^2)}{{S_{||}}^2} - 1 \tag{1}$$

$$f_{\perp} = \frac{(\sigma_{22} + \sigma_{33})^2}{Y^2} + \frac{{\sigma_{23}}^2 - \sigma_{22}\sigma_{33}}{{S_{\perp}}^2} - 1 \tag{2}$$

where σ_{11}, σ_{22}, σ_{33}, σ_{12}, σ_{13}, σ_{23} are the stress components; X and Y are the tensile or compressive strength in parallel and perpendicular to the grain direction respectively. $S_{\parallel}$ and $S_{\perp}$ are the shear strength in parallel and perpendicular to the grain direction respectively. Failure occurs in parallel to the grain direction when $f_{\parallel} > 0$ and in perpendicular to the grain direction when $f_{\perp} > 0$.

The evolution of the damage parameter *d* follows separate rules for parallel and perpendicular to the grain directions. In parallel direction, failure is often considered to be catastrophic and failure in this direction renders the wood useless. When failure occurs in parallel direction, all six stress components are degraded uniformly and wood cannot carry any load after failure. However, if failure occurs in perpendicular to the grain direction, only the perpendicular stress components are degraded. The two expressions of the damage are given by equations (3) and (4) for parallel and perpendicular modes respectively:

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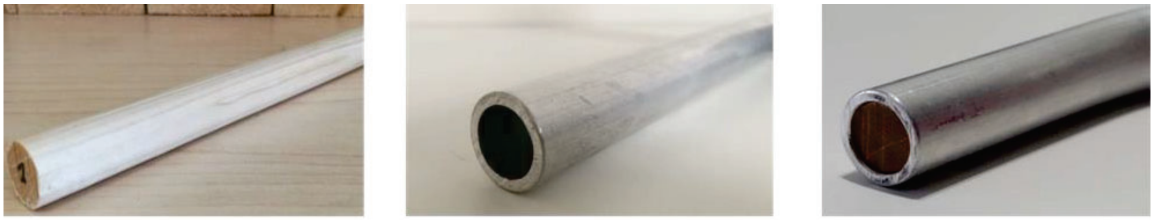
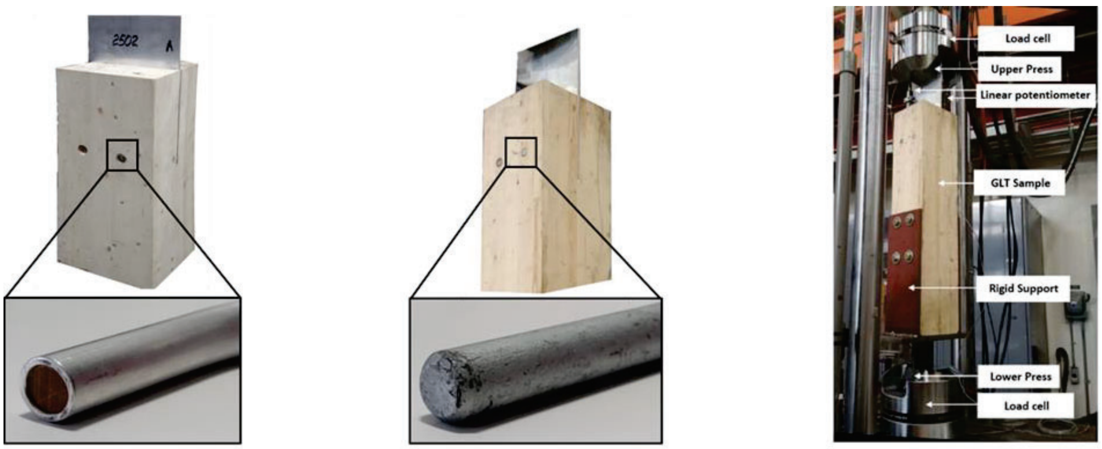


(a) (b) (c)

Figure 2: *Different parts of the hybrid wood-filled aluminium dowel: (a) compressed wood dowel; (b) aluminium tube; (c) hybrid wood-filled aluminium dowel [7]*



(a) (b) (c)

Figure 3: *Hybrid wood/aluminium system: (a) assembled with hybrid wood-filled aluminium dowel; (b) assembled with galvanized steel dowel; (c) experimental setup [8]*

$$d(\tau_{\parallel}) = \frac{d_{max_{\parallel}}}{B}\left[\frac{1+B}{1+Be^{-A(\tau_{\parallel}-\tau_{0\parallel})}}-1\right] \quad (3)$$

$$d(\tau_{\perp}) = \frac{d_{max_{\perp}}}{D}\left[\frac{1+D}{1+De^{-C(\tau_{\perp}-\tau_{0\perp})}}-1\right] \quad (4)$$

where B and D are the softening parameters obtained from experimental data. A and C are internally calculated based on the value of fracture energy G_f according to equations (5) and (6):

$$A = \tau_{0\parallel} L\left(\frac{1+B}{BG_{f\parallel}}\right) log(1+B) \quad (5)$$

$$C = \tau_{0\perp} L\left(\frac{1+D}{BG_{f\perp}}\right) log(1+D) \quad (6)$$

The laminated stock used during the experimental test for the Glued Laminated Timber (GLT) were made of Spruce-Pine-Fir. The wood dowel used for the manufacturing of the hybrid wood-filled aluminium dowel were made of French spruce. The material properties as applied for MAT-143 in this study are summarized in Table 1. The mechanical parameters are either identified based on the mean experimental values or by means of the well-known inverse approach.

Table 1: *Material properties for the compressed spruce and for the Glued Laminated Timber used in the FE model for MAT-143 (LS-DYNA parameters in parentheses)*

Mechanical property	Compressed spruce	GLT
$\boldsymbol{\rho = \rho_{wood}}$ [kg/m^3]	1174	560
$\boldsymbol{E_L}$ ($\boldsymbol{EL}$) [MPa]	30000	1200
$\boldsymbol{E_T}$ ($\boldsymbol{ET}$) [MPa]	2000	480
$\boldsymbol{G_{LT}}$ ($\boldsymbol{GLT}$) [MPa]	1750	720
$\boldsymbol{G_{TR}}$ ($\boldsymbol{GTR}$) [MPa]	1000	130
$\boldsymbol{v_{LT}}$ ($\boldsymbol{PR}$) [-]	0,41	0,26
$\boldsymbol{f_{t,L}}$($\boldsymbol{XT}$) [MPa]	125	60
$\boldsymbol{f_{c,L}}$($\boldsymbol{XC}$) [MPa]	120	50
$\boldsymbol{f_{t,T}}$($\boldsymbol{YT}$) [MPa]	12,5	3,5
$\boldsymbol{f_{c,T}}$($\boldsymbol{YC}$) [MPa]	104	13,5
$\boldsymbol{f_{v,L}}$($\boldsymbol{SXY}$) [MPa]	85	6,5
$\boldsymbol{f_{v,T}}$($\boldsymbol{SYZ}$) [MPa]	120	6,5
$\boldsymbol{G_{f,L,I}}$($\boldsymbol{GF1\parallel}$) [MPa.mm]	40,5	25
$\boldsymbol{G_{f,L,II}}$($\boldsymbol{GF2\parallel}$) [MPa.mm]	291,5	90
$\boldsymbol{G_{f,T,I}}$($\boldsymbol{GF1P}$) [MPa.mm]	1,35	0,24
$\boldsymbol{G_{f,T,II}}$($\boldsymbol{GF2P}$) [MPa.mm]	2,75	0,7
$\boldsymbol{B}$($\boldsymbol{BFIT}$)	300	30
$\boldsymbol{D}$($\boldsymbol{DFIT}$)	300	30
$\boldsymbol{d_L}$($\boldsymbol{DMAX\parallel}$)	0,9999	0,9999
$\boldsymbol{d_T}$($\boldsymbol{DMAXP}$)	0,9900	0,9900

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2.1.2 Material model for the aluminium: MAT-024

The mechanical behaviour of aluminium was modelled with MAT-024 material model in LS-DYNA. MAT-024 describes an elastic-plastic material with an arbitrary stress versus strain response and arbitrary strain rate dependency can be defined. Strain rate may be accounted for using the Cowper and Symonds model. The stress-strain curve of the aluminium is given using the Ramberg-Osgood law using equation (7):

$$\varepsilon = \frac{\sigma}{E} + K\left(\frac{\sigma}{E}\right)^{n} \tag{7}$$

where $\boldsymbol{E}$ is the Young's modulus and K and n the hardening parameters. Equation (7) represents the evolution of the engineered strain as a function of the engineered stress. Material model MAT-024 requires the true stress as a function of the true strain. The curve of the engineered stress as a function of the engineered strain is transformed into a curve representing the true stress as a function of the true strain and is given through the material model MAT-024. The material properties used in the FE were defined as:

- Density: 2700 kg/m^3
- Young's modulus: 70 000 MPa
- Poisson's ratio: 0,33
- Yield stress: 210 MPa
- Hardening parameters for aluminium A6061-T6: n = 45 for an ultimate strain of 8% as prescribed by Eurocode 9.

2.1.3 Material model for the steel dowel: MAT-003-Plastic Kinematic

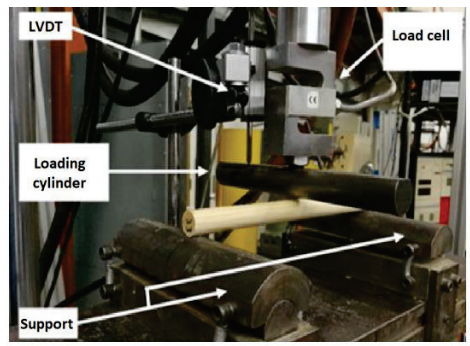
The material behaviour of the steel dowel was modelled with the material model MAT-003 representing an elastic-plastic isotropic material behaviour with the option of including rate effects by using the Cowper and Symonds model. The material properties used in the FE were defined as:

- Density: 7877 kg/m^3
- Young's modulus: 210 000 MPa
- Poisson's ratio: 0,33
- Yield stress: 450 MPa

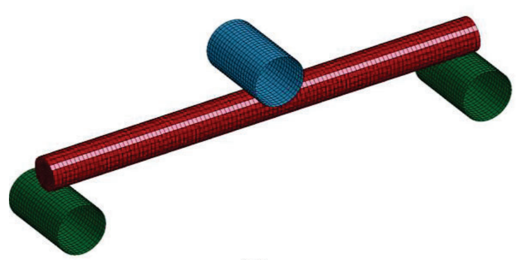
2.2 FE MODELLING OF THE THREE-POINT BENDING TEST ON HYBRID WOOD-FILLED ALUMINIUM DOWEL

The FE model of the Three-point bending test was done first for the compressed wood dowel and then for the hybrid wood-filled aluminium dowel. Figure 4.b shows the FE model of the three-point bending test and Figure 4.a shows the experimental set up used by Rollo et al. [7]. Constant stress eight-node solid elements (LS-DYNA ELFORM 1) and fully integrated shell elements (LS-DYNA ELFORM 16) are applied to represent the geometrical setup of the test. The wood dowel is meshed using solid elements and the loading cylinder and support are meshed using shell elements. The material behaviour of the loading cylinder and the supports is modelled with the rigid material model MAT-020 with a Young's modulus $E = 207\,000\ MPa$ and a Poisson's ratio of $\nu = 0{,}3$. All nodes of the supports are fully clamped and a velocity control was applied to the rigid loading cylinder using an explicit time integration. A rate of $5mm/min$ was used during the experimental tests, which is like a quasi-static test.

The FE model of the hybrid wood-filled aluminium dowel was done by inserting under compression the wood dowel inside the aluminium tube. Constant stress eight-node solid elements are used to mesh the aluminium tube. The boundary conditions used for the hybrid wood-filled aluminium dowel are the same as those used for the compressed wood dowel. The contact between the wood dowel and the aluminium tube was defined using the AUTOMATIC_SURFACE_TO_SURFACE contact with a friction coefficient of 0,3. Figure 5 shows the FE model of the Three-Point Bending test on the hybrid wood-filled aluminium dowel.



(a)



(b)

Figure 4: *Three-Point Bending test on compressed wood dowel: (a) experimental setup [7]; (b) FE model*

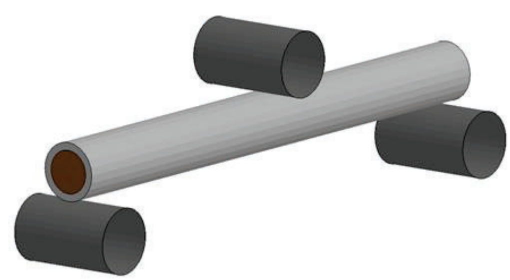


Figure 5: *FE model geometry for the Three-Point Bending test on hybrid wood-filled aluminium dowel*

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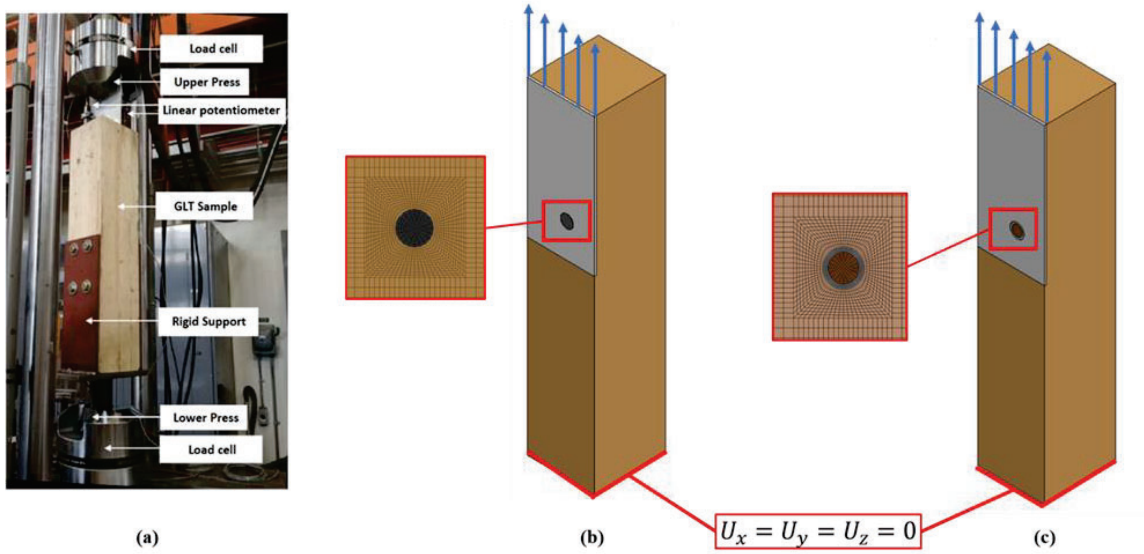


Figure 6: *Double shear tensile test on hybrid wood/aluminium assembly: (a) Experimental setup [8]; (b) FE model of the assembly with galvanised steel dowel; (c) FE of the assembly with hybrid wood-filled aluminium dowel*

2.3 FE MODELLING OF THE DOUBLE SHEAR TESTS ON HYBRID SYSTEMS (TIMBER-TO-ALUMINIUM CONNECTIONS)

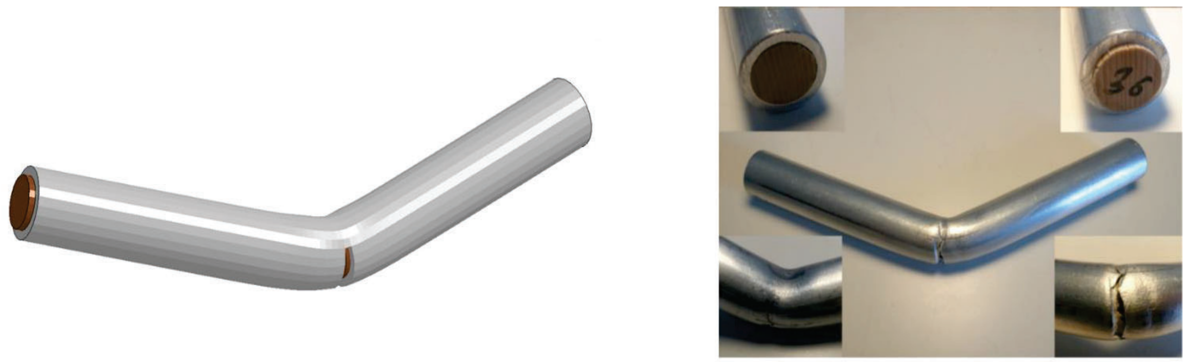
Two series of experimental tests were conducted on structural timber-to-aluminium assemblies. The first series of tests were carried out on hybrid timber-to-aluminium assemblies connected with galvanised steel dowels (Figure 3.b). The second series of tests were done on hybrid timber-to-aluminium assemblies connected with wood-filled aluminium dowel (Figure 3.a). For the two series of tests, the hybrid assembly is made of Glued Laminated Timber with a groove in which an aluminium plate is inserted and hold with the dowels. The assembly is hold on the bottom with screws on a rigid support and the aluminium plate is given a displacement at a rate of $2mm/min$.

The FE model of the two types of assemblies was done using eight-node constant stress solid elements (LS-DYNA ELFORM 1) with hourglass control type 6 (which use the Belytschko-Bindemann approach) for the Glued Laminated Timber, the aluminium plate, the galvanised steel dowel, as well as for the wood-filled aluminium dowel. The presence of two symmetry planes allows to modelled only one-quarter of the model by applying symmetry boundary conditions in the two symmetry planes. The mesh was refined in the vicinity of the dowel's holes in the Glued Laminated Timber (Figure 6.b and 6.c). In the FE model, only the part of the assembly above the rigid support is modelled by assuming that the dowels used to assembly to the rigid support stay undeformed during the test and so no failure happens in the part of the Glued Laminated Timber in contact with the rigid support.
The nodes on the bottom surface of the Glued Laminated Timber are all constrained ($U_x = U_y = U_z = 0$) and a velocity control is applied on the top nodes of the aluminium plate (Figure 6.b and 6.c) using an explicit time integration.
All contacts in the FE model, either existing at the beginning or developing during the simulation are set to be automatically detected by the software by using the AUTOMATIC_SURFACE_TO_SURFACE contact algorithm.

3 RESULTS

3.1 THREE-POINT BENDING TEST ON WOOD FILLED ALUMINIUM DOWEL

The results of the Three-Point Bending test on the wood-filled aluminium dowel were analysed in terms of the global response expressed as force-displacement curves and the failure predictions. Figure 8 compares the numerically obtained Force-Displacement curve (red dashed curve line) to those reported experimentally (black curves) in literature by Rollo et al [7]. All experimental responses showed a first drop of load, which corresponds to the failure of the confined wood into the aluminium tube. The load is then carried by the aluminium tube until the occurrence of the final failure in the aluminium tube. These results show the ability of the aluminium tube in reducing the brittle failure of the wood material by improving the ductility of the entire hybrid wood-filled aluminium structure. The experimental curves showed also some variations in the peak force as well as in the failure of the confined wood which results from the natural bio-composite characteristic of the wood material. However, with the calibrated material parameters, it can be seen through Figure 8 that the FE model was able to predict the mean value of the experimental responses. Figure 7.a shows the fracture pattern of the FE model which is in good agreement with the experimental observations. The failure occurred in tension on the bottom side of the hybrid dowel and propagated through it.



(a) (b)

Figure 7: *Failure modes during the Three-Point Bending test on hybrid wood-filled aluminium dowel: (a) Numerical; (b) Experimental*

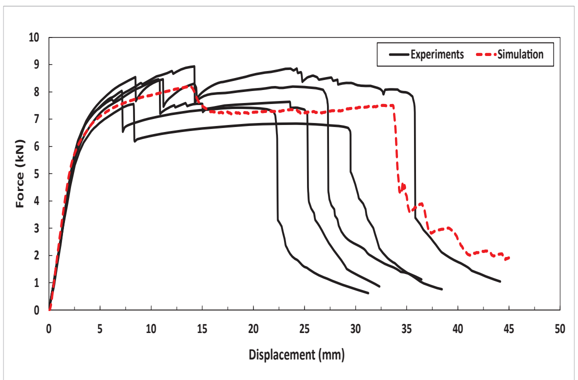
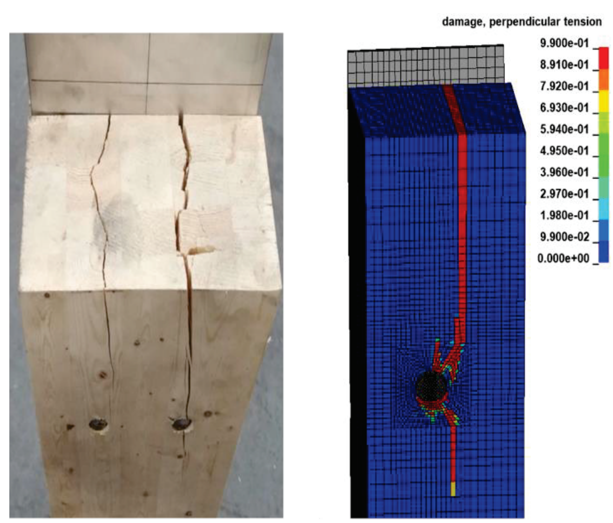


Figure 8: *Force-Displacement curves on the Three-Point Bending test on hybrid wood-filled aluminium dowel*

3.2 DOUBLE SHEAR TEST ON HYBRID WOOD/ALUMINIUM ASSEMBLY

The failure modes observed during the first series of experimental tests on the hybrid assembly connected with galvanised steel dowel was observed in the Glued Laminated Timber. Figure 9.a depicts the experimentally observed failure. The cracks observed along the grain direction in the Glued Laminated Timber members are probably caused by tension load perpendicular to the grain direction resulting from the displacement of the dowels. The predicted failure modes and cracks propagation with the FE analysis are presented in Figure 9.b. A good correlation can be seen between the predicted failure modes and the crack growth and the experimental inspection. The failure starts in the vicinity of the dowels and propagates in the Glued Laminated Timber in transverse tension. A comparison of the load-deflection curves between the numerical prediction and experiments is displayed in Figure 10, in which a good agreement can be seen for the global linear and non-linear behaviour and for the peak load at failure.

The failure behaviour during the second series of the experimental tests with the hybrid wood/aluminium assembly connected with the hybrid wood-filled aluminium dowel is displayed in Figure 11.a. The failure happens in the Glued Laminated Timber in the location of the aluminium plate, resulting from the deformation of the hybrid wood-filled aluminium dowel which fits into the groove of the Glued Laminated Timber due to the displacement of the aluminium plate. It can be seen on Figure 11.b that the predicted failure mode is in good agreement with the experimental observations. The comparison of the numerically obtained Force-Displacement curves to the experiments as presented in Figure 12 shows a good agreement in the non-linear behaviour as well as the load-carrying capacity and the failure. It is worth noting that the failure in perpendicular tension along the grain direction in the Glued-Laminated Timber as observed during the first series of test with the galvanised steel dowels initiates also in the Glued Laminated Timber during the second series of the test with the hybrid wood-filled aluminium dowels, but this failure modes do not propagate because of the premature failure of the hybrid dowel. Thus, an optimization of the hybrid wood-filled aluminium dowel is necessary in order to reach the performance of the galvanised steel dowel.



(a) (b)

Figure 9: *Perpendicular tension failure for the hybrid assembly with galvanized steel dowel*

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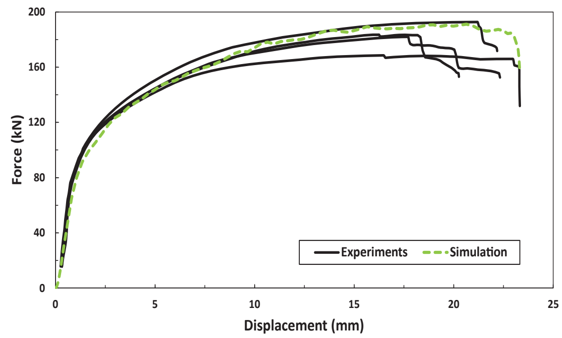

Figure 10: *Force-Displacement curves for the hybrid assembly with galvanised steel dowel*

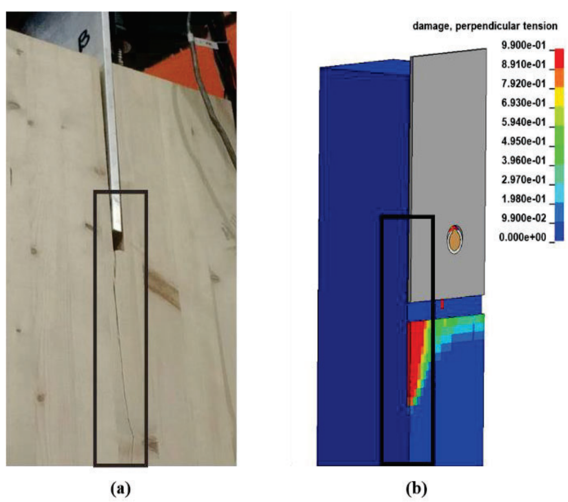

Figure 11: *Perpendicular tension failure for the hybrid assembly with hybrid wood-filled aluminium dowel*

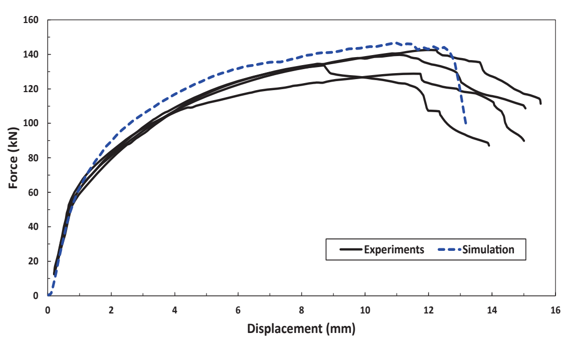

Figure 12: *Force-Displacement curves for the hybrid assembly with hybrid wood-filled aluminium dowel*

4 CONCLUSION

In this study, the ability to predict the mechanical behaviour of wood and confined wood by using the FE method and the built-in LS-DYNA material model MAT-143 was investigated. This material model performs well in simulating the global mechanical behaviour of the confined wood under quasi-static loading condition and the initiation and propagation of the fracture in timber. Though the numerical results are in good agreement with the experimental ones, works are needed in order to asses results of the numerical model, to become a real alternative for predicting the failure of safety barriers for highway bridges.

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