



**HAL**  
open science

# Analytical characterisation in Mode I fracture of adhesively bonded Double Cantilever Beam mixed glue joints

Cédric Horphe Ndong Bidzo, Claude Feldman Pambou Nziengui, Serge Ekomy Ango, Samuel Ikogou, Beat Kaiser, Moutou Pitti

## ► To cite this version:

Cédric Horphe Ndong Bidzo, Claude Feldman Pambou Nziengui, Serge Ekomy Ango, Samuel Ikogou, Beat Kaiser, et al.. Analytical characterisation in Mode I fracture of adhesively bonded Double Cantilever Beam mixed glue joints. International Conference on Structural Integrity, Aug 2023, Madeira, Portugal. hal-04887259

**HAL Id: hal-04887259**

**<https://hal.science/hal-04887259v1>**

Submitted on 14 Jan 2025

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution - NonCommercial - NoDerivatives 4.0 International License

International Conference on Structural Integrity 2023 (ICSI 2023)

# Analytical characterisation in Mode I fracture of adhesively bonded Double Cantilever Beam mixed glue joints

Cédric H. NDONG BIDZO<sup>a</sup>, Claude F. PAMBOU NZIENGUI<sup>b</sup>, Serge Ekomy ANGO<sup>c</sup>, Samuel IKOGOU<sup>b</sup>, Beat KAISER<sup>a</sup>, Rostand MOUTOU PITTI<sup>c,d\*</sup>

<sup>a</sup>*Ecowood SA, Z.I des Acaés, BP 4016 Lbreville, Gabon*

<sup>b</sup>*Université des Sciences et Technique de Masuku, EPM, URMM, B.P. 941, Franceville, Gabon*

<sup>c</sup>*IRT, Libreville Gabon*

<sup>d</sup>*Université Clermont Auvergne, Clermont Auvergne INP, CNRS, Institut Pascal, Clermont-Ferrand, France*

---

## Abstract

This paper studies experimental and analytical investigations on mode I crack opening of GLT made by multi tropical species to assess the influence of strength of glue joints on such assemblies. Indeed, it should be noted, however, that for any glued composite element, the integrity and the strength of the glue joints are a basic prerequisite for the structure. Specimens are tested in Double Cantilever Bending (DCB), a crack is initiated on the glue joint to facilitate the delamination under a quasi-static loading. An analytical model is proposed for characterizing the fracture behaviour of an adhesively bonded double cantilever beam joint under Mode I loading. The full field measurement technique (grid method) was used to follow the crack propagation. A quantitative formulation for the energy release rate has been derived through the integration of beam theory and the compliance method. The analytical values of the energy release rate are compared with the experimental values obtained in a previous study. Results show that specimens composed of homogeneous glue joints and that cracking parameters are better when the initial crack is placed in the glue joint. The theoretical values of homogeneous specimens are closets to experimental values in comparison with those of mixed specimens.

*Keywords:* Tropical species, Glued Laminated Timber, Grid method, Cracking parameters, Double Cantilever Bending

---

## 1. Context of the study

Stabilising the damaging effects on our environment today means preserving tropical forests such as the one in Gabon in the Congo Basin, which is one of the planet's real lungs. One solution is to maximise the mechanical strength of the species currently cut by incorporating lower-quality species into glued laminated timber (GLT) structures to support service structures. This technique minimises losses due to sawing and maximises the mechanical strength of the structural elements obtained. However, it should be noted that for any glued composite element, the integrity and strength of the glue joints are a basic prerequisite for the structure according to Aicher *et al.* (2018). Indeed, the glue joint plays an increasingly important role in construction with composite materials and, therefore, specifically also in civil engineering structures made of wood materials by Vallé *et al.* (2016).

---

\* Corresponding author. Tel.: +241 77422048.

*E-mail address:* Rostand.moutou\_pitti@uca.fr

Delamination is one of the most observed failure modes in laminated composites, the existence of which significantly reduces the stiffness and strength of the structure by V.Q. Bui *et al.* (2000). Progress has been made in developing test methods for measuring the interlaminar fracture toughness of laminated composites by assessing the rate of critical energy release. Commonly used specimens for unidirectional composites are the double cantilever beam (DCB) for mode I (Hashemi *et al.* (1989), Nageswara Rao *et al.* (1995)).

The objective of this study is to define an analytical expression for the energy release rate and to compare the analytical values with those determined experimentally using the grid method. The grid method is employed here to measure the in-plane displacement field on the front face of the specimen in order to detect and track the crack tip during the tests of Odounga *et al.* (2017). This technique involves processing images of a grid transferred onto the specimen prior to testing to determine displacement and strain maps Grédiac *et al.* (2016). The compliance-based beam method was used to determine an analytical expression of the ERR, it takes into account elastic strain energy and that due to shear.

## 2. MATERIAL AND METHOD

### 2.1. Wood species and specimens

Three different wood species were selected namely *Staustia kamernesis*, the *Pterocarpus osun* and the *Dacryodes buettneri* commonly called Niove, Paduk and Ozigo respectively, in Gabon. Table 1 gives the main characteristics of these species: density, Module of Rupture (MOR) and Module of Elasticity module (MOE) as given by CIRAD (2011).

Table 1: Main physical and mechanical characteristics of wood species used.

Specimens	Average density* g/cm <sup>3</sup>	MOR ** MPa	MOE ** MPa
Ozigo (Oz)	0.59 ± 0.06	91 ± 11	13820 ± 2273
Padouk (Pdk)	0.66 ± 0.01	116 ± 24	15870 ± 1885
Niove (Ni)	0.80 ± 0.01	151 ± 23	18510 ± 3100

\* C. H. Ndong Bidzo *et al.* (2021) \*\*CIRAD (2011)

DCB specimens (Fig.1b), developed by Chow and Woo (1979) for the conduct of crack tests in Mode I, allow the determination of the critical energy release rate. DCB test is frequently used in fracture characterization of wood and bonded joints by De Moura *et al.* (2008). An initial notch is machined with a cutter along the glue joint between the two layers to make easy the crack propagation in the glue joint (Fig.1 b).

A Phenol Resorcinol Formalehyde adhesive combined with a HRP 155 hardener with a ratio of 100/20 was used for specimens bonding. An Ozigo layer was glued with a Padouk (Oz-Pdk) or a Niove layer (Oz-Ni), to obtain mixed glue joints. These specimens have been compared to the Ozigo-Ozigo specimens. We obtained Nine DCB specimens consisting of three Oz-Oz types, three Oz-Pdk types and three Oz-Ni types. Mechanical testing was conducted on all nine specimens.

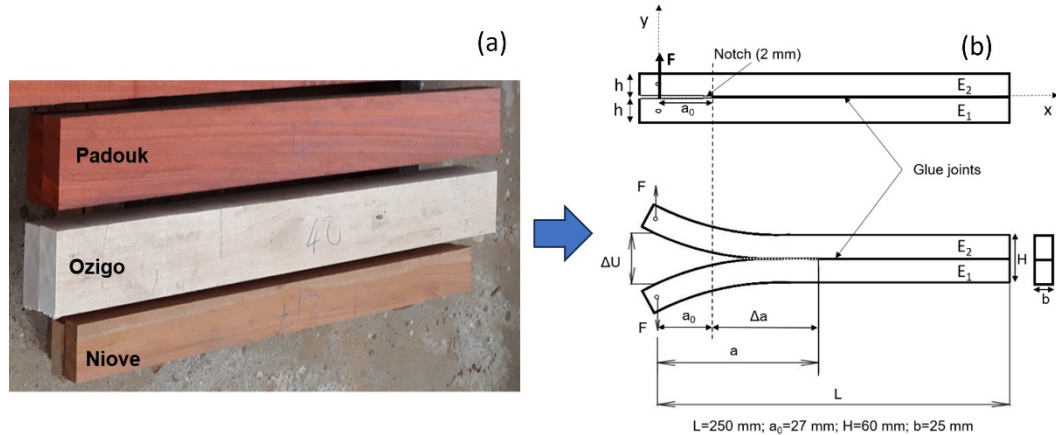


Fig. 1: (a)Wood species used aspect; (b) DCB specimens.

## 2.2. Grid method

Grid method is a full field method that allows to measure vertical and horizontal displacement fields on the surface of materials. In the present study, this method is used to track the crack length and crack opening on each specimen during the tests. This technique already used in previous studies Piro and Grédiac (2004), Odounga *et al.* (2019), consists in analyzing the images of a two-way grid printed on a thin polymer sheet and glued on the specimen surface with a white adhesive (Epotecny E504). The pitch of the grid is equal to 0.04 mm. The specimens were placed for two days in a climatic room with an ambient temperature of 38° C to facilitate the polymerization of the adhesive. Thus, the polymer sheet that protected the grid is easily peeled off (Fig. 2b), only the ink remains glued to the thin layer of adhesive. For the rest, it can be assumed that the grid faithfully reflects the deformations on the area specimens. The grid images are taken with a high-resolution camera during testing. Figure 2a shows the typical close of the grid.

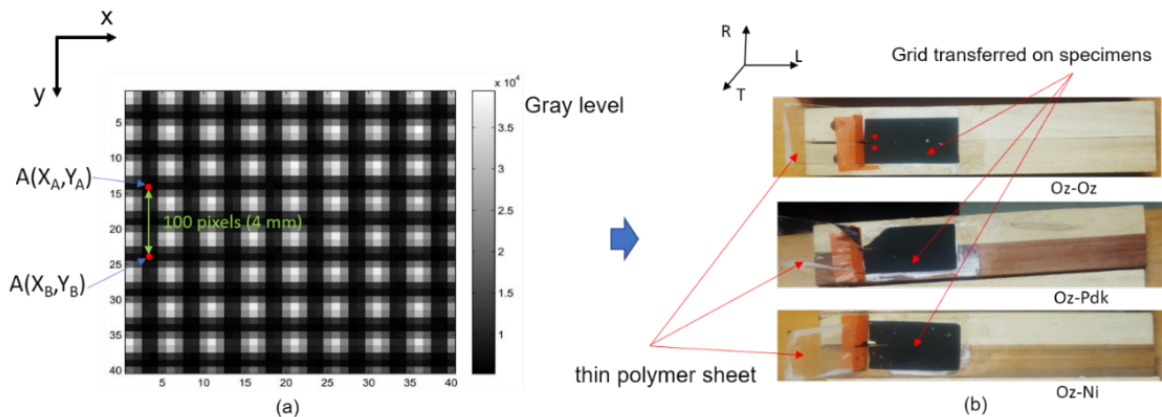


Fig. 2:(a) Bidimensional grid with 0.04 mm pitch, (b)Specimens with grid.

The comparison of two images (one before the test and one during the test) allows determining displacements and strains fields Odounga *et al.* (2018). Figure 2b shows typical specimens tested in the study. The crack opening  $U_i$  was determined from the displacement fields. Two points  $A (X_A, Y_A)$  and  $B (X_B, Y_B)$  (Fig. 2a) are placed on either side of the crack, the initial distance between these two points is equal to 100 pixels, corresponding to 4 mm. The crack opening is obtained with the relationship  $|Y_A - Y_B|$ .

To determine the increment of the crack length, the location of the crack tip must be defined beforehand. It is noted

that the precise location of the crack tip cannot be defined by a simple observation of the displacement fields, as the measured displacement is equal to the actual displacement. An algorithm developed by Odounga *et al.* (2018) and Ndong Bidzo (2021), is used to determine the increment of crack length. A rectangular area containing the crack tip is defined; then, an estimation of the vertical displacement gradient is calculated by numerical differentiation.

A threshold value for the apparent value of the  $\text{Eps}_{YY}$  vertical strain is chosen, allowing the localization of the crack tip. In our case, the threshold value has been set to 0.14.

The determination of the crack opening and the increment of crack length was performed using an in-house *Matlab* program using the procedures described in previous paragraphs.

### 2.3. Experimental device

A Zwick/Roel compression-traction press of a maximum load cell of 200 kN was used for the testing (Fig. 3). The mobile jaw of the press is controlled in imposed displacements with a speed of 0.01 mm/s. A 'PCO' camera synchronized with the press via the 'Catman AP' software was placed on a tripod to record the images during the test, the camera recorded about 2 frames/seconds. The tests are carried in a room with a temperature of 20°C and a relative humidity of 45%.

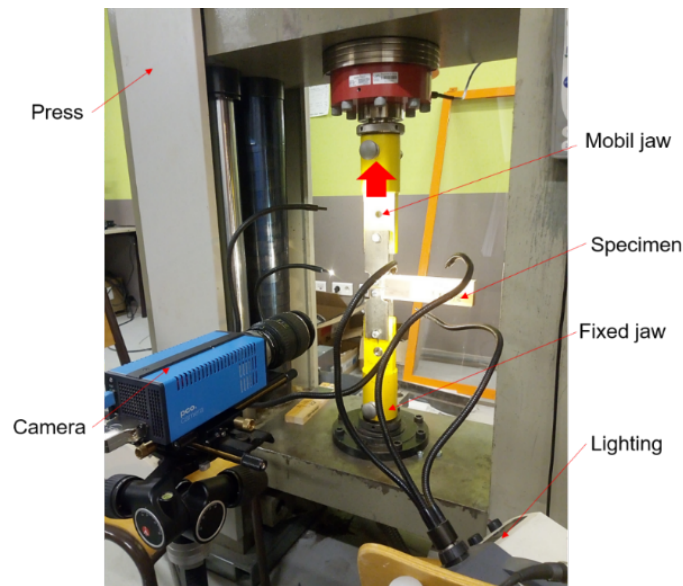


Fig. 3: Experimental device

This device combined to the grid method allow obtaining the load evolution according to the crack opening

### 2.4. Compliance-Based Beam Method (CBBM)

The Compliance calibration method and the corrected beam theory are frequently used to measure the fracture energies by De Moura *et al.* (2006). An analytical model based on the energy method was used for the calculation of the experimental energy release rate. Using the beam theory and strain energy of specimen due to bending and including shear effect, the total strain energy  $W_t$  is therefore given by the expression of De Moura *et al.* (2008):

$$W_t = \iint_0^L \frac{M^2 y^2}{2E_k I^2} dAdx + \int \frac{\tau^2}{2G} dV \quad (1)$$

where  $M$  is the bending moment,  $\tau$  is shear strength,  $I$  the inertia moment of the cross-section area,  $E_k$  the materials

MOE ( $k=1,2$ ) and  $G$  the shear modulus in the  $LT$  plane,  $b$  and  $h$  are specimen dimensions. The shear strength expression is determined in the equation (2)

$$\tau = \frac{3V}{2bh} \left(1 - \frac{y^2}{c^2}\right) \quad (2)$$

The parameters  $c$  and  $V$  represent, respectively, the half-thickness and the transverse load acting on each arm. Applying the Castigliano theorem, the displacement  $U$  following charge  $F$  axis becomes:

$$\Delta U = \frac{\partial W}{\partial F} = \frac{16FL^3}{(E_1+E_2)bh^3} + \frac{12FL}{5bhG} \quad (3)$$

The linear elastic fracture mechanics principles are used to compute the critical strain energy release rate of the wood material under mode I loading by Grédiac et al. (2016). The critical energy release rate of the specimens was calculated, with the compliance method using the general Irwin-Kies expression:

$$G_{ic} = \frac{F_{ci}^2}{2b} * \frac{\Delta C}{\Delta a} \quad (4)$$

Where  $F_{ci}$  ( $i = 1,2, 3,..$ ) is the critical strength which induces an increase  $\Delta a$  of the crack length  $a$ ,  $b$  is the thickness of the specimen and  $\Delta C$  is the increase in compliance corresponding to the increase in crack length  $\Delta a$  defined by  $\Delta C = \Delta U_i / F_{ci}$ . In the last expression,  $\Delta U_i$  denotes the crack opening induced by each critical load  $F_{ci}$ .  $\Delta C$  and  $\Delta a$  increments are calculated between two stable configurations of the crack. Using equation (4), the energy release rate becomes

$$G_I = \frac{F^2}{b^2h} \left[ \frac{8L^2}{h^2(E_1+E_2)} + \frac{6}{5G} \right] \quad (5)$$

### 3. Results and discussions

#### 3.1. Displacement maps

The displacement maps of the specimens were determined using the method described in the preceding paragraph (§ see 2.2.). The figures 4a, 4b et 4c show respectively the vertical displacement maps ( $Uy$ ) at the failure of the Oz-Oz, Oz-Pdk and Oz-Ni specimens, where crack propagation can be seen.

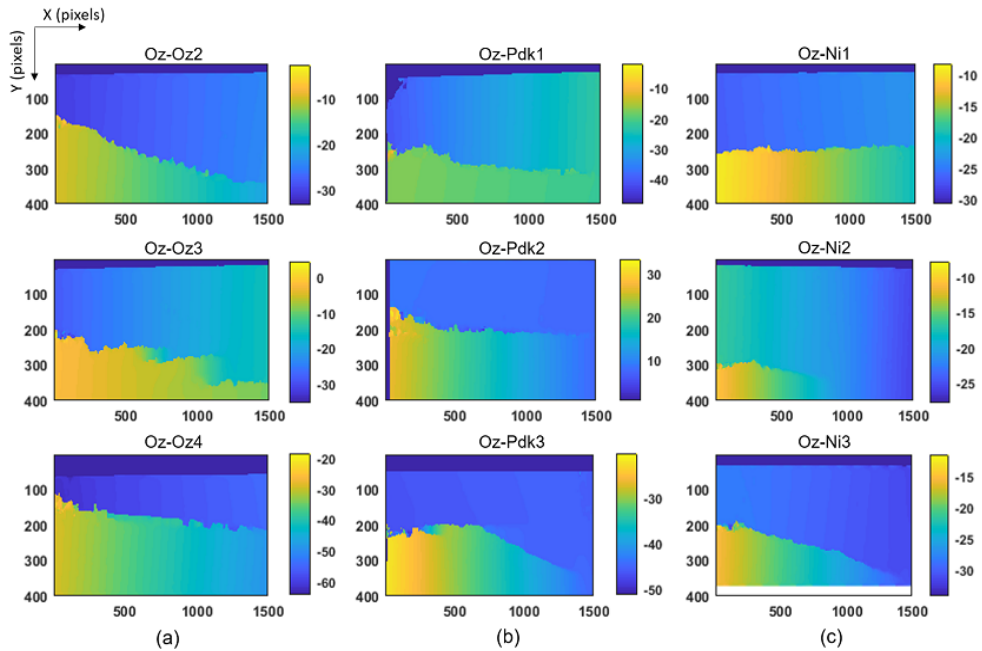


Fig. 4: Displacement maps, (a) Oz-Oz specimens, (b) Oz-Pdk specimens (c) Oz-Ni specimens.

In Figure 4 crack propagations correspond to the discontinuities observed on the displacement maps. These maps will therefore allow us to define exactly the area of crack propagation (solid wood or glue joint).

It is observed that for the majority, that the crack propagation takes place in the solid wood, especially in the lower lamella, this shows the good performance of the adhesive. On the other hand, for the Oz-Ni2 specimens, the crack propagated in the glue joint, this can be seen by a linear and horizontal discontinuity.

### 3.2. Load-crack opening and crack length curves

figure 5 shows us the crack force-opening and crack force-length curves, the crack openings and lengths were directly recovered from the displacement maps. The crack opening did not come from the moving bits of the press because it was higher than that determined from the vertical displacement maps, due to the takeover that occurs during the test by Odounga *et al.* (2017).

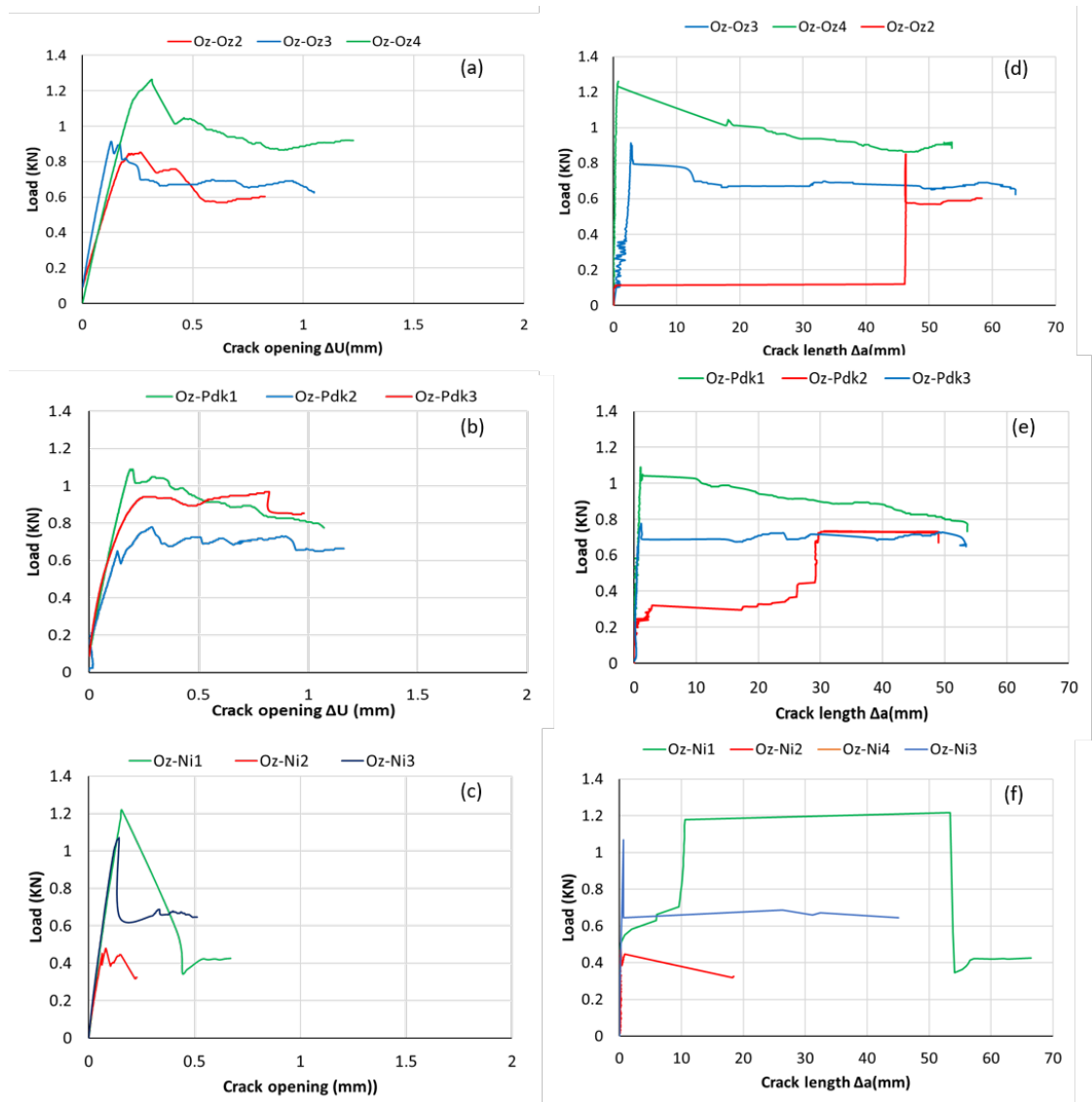


Fig. 5: Load crack opening and load crack length, (a) and (d) Oz-Oz specimens, (b) and (e) Oz-Pdk specimens, (c) and (f) Oz-Ni specimens.

### 3.3. Comparison between the analytical and experimental values of ERR

Table 2 shows the different mean values of the ERR obtained experimentally and that of the proposed analytical model. The observations in Table 2, shows that the Oz-Oz and Oz-Pdk glue joints have better ERR compared to the Oz-Ni glue joint, it can be explained by the fact that these specimens are composed of lamellas with the same density (Oz-Oz) or close (Oz-Pdk) as shown in Table 1.

**Tableau 2:** Average value ERR from experimental and analytical values

Specimens	Crack tip area	Maximal load	Crack opening	Crack length	Experimental value	Theoretical value	Error
		N	mm	mm	J/mm <sup>2</sup>	J/mm <sup>2</sup>	%



Oz-Oz2	Solid wood	853	0.265	36.65	155	136	-
Oz-Oz3	Solid wood	900	0.171	28.85	140	149	-
Oz-Oz4	Solid wood	1262	0.315	37.41	266	300	-
<b>Average value</b>		<b>1005 ± 223</b>	<b>0.250 ± 0.073</b>	<b>34.30 ± 4.73</b>	<b>187 ± 69</b>	<b>195 ± 91</b>	<b>+4.2</b>
Oz-Pdk1	Solid wood	1089	0.195	42.1	107	162	-
Oz-Pdk2	Solid wood	732	0.744	82	141	128	-
Oz-Pdk3	Solid wood	968	0.816	64.16	232	136	-
<b>Average value</b>		<b>929 ± 181</b>	<b>0.585 ± 0.339</b>	<b>67.75 ± 19.98</b>	<b>160 ± 64</b>	<b>142 ± 17</b>	<b>-11.2</b>
Oz-Ni2	<b>Glue joint</b>	478	0.081	30.76	32	<b>38</b>	<b>+15.78</b>
Oz-Ni1	Solid wood	1217	0.157	32.29	149	252	-
Oz-Ni3	Solid wood	1069	0.143	32.02	101	135	-
<b>Average value</b>		<b>921 ± 391</b>	<b>0.127 ± 0.040</b>	<b>31.69 ± 0.81</b>	<b>125 ± 33.94</b>	<b>193.5</b>	<b>+35.4</b>

On the other hand, there is a significant difference in the experimental and analytical values of Oz-Ni glue joints with an error of  $\varepsilon = +35.4\%$  and compared to Oz-Oz ( $\varepsilon = +4.2\%$ ) and Oz-Pdk ( $\varepsilon = -11.2\%$ ) specimens.

#### 4. CONCLUSION

The adhesively bonded Double Cantilever Beam test was analyzed in context the glue joint fracture characterization under mode I loading. Analytical model which considers the elastic a shear strain energy was proposed. The model is capable of predicting critical ERR of DCB joint system. The results show a better correlation of the theoretical and experimental values of the specimens with homogeneous glue joint 'Oz-Oz' compared to the values of the other specimens. The results also showed that the error is less important when crack propagates in the glue joint than when the propagation occurs in the wood.

#### ACKNOWLEDGEMENTS

The authors thank EcoWood SA society for the supply of wood and making of specimens, the PEPS CNRS project "RUMO", the Auvergne Rhône Alpes region (SCUSI Project).

#### References

- S. Aicher, Z. Ahmad, and M. Hirsch, "Bondline shear strength and wood failure of European and tropical hardwood glulams," *Eur. J. Wood Wood Prod.*, vol. 76, no. 4, pp. 1205–1222, 2018, doi: 10.1007/s00107-018-1305-0.
- T. Vallée, T. Tannert, and S. Fecht, "Adhesively Bonded Connections in the Context of Timber Engineering - A Review," vol. 8464, no. April, 2016, doi: 10.1080/00218464.2015.1071255.
- V. Q. Bui, E. Marechal, and H. Nguyen-Dang, "Imperfect interlaminar interfaces in laminated composites: delamination with the R-curve effect," *Compos. Sci. Technol.*, vol. 60, no. 14, pp. 2619–2630, 2000, doi: 10.1016/S0266-3538(00)00088-9.
- K. G. Muthurajan, K. Sankaranarayanan, S. B. Tiwari, and B. Nageswara Rao, "Evaluation of Carbon-Epoxy Delamination Fracture Toughness," *Trends Appl. Sci. Res.*, vol. 1, pp. 144–154, 2006.
- S. Hashemi, A. J. Kinloch, and J. G. Williams, "Corrections needed in double-cantilever beam tests for assessing the interlaminar failure of fibre-composites," *J. Mater. Sci. Lett.*, vol. 8, no. 2, pp. 125–129, 1989, doi: 10.1007/BF00730701.
- B. Nageswara Rao and A. R. Acharya, "Evaluation of fracture energy GIC using a double cantilever beam fibre composite specimen," *Eng. Fract. Mech.*, vol. 51, no. 2, pp. 317–322, 1995, doi: 10.1016/0013-7944(94)00251-C.

- B. Odounga, R. Moutou Pitti, E. Toussaint, and M. Grédiac, “Mode I fracture of tropical woods using grid method,” *Theor. Appl. Fract. Mech.*, vol. 95, no. May 2017, pp. 1–17, 2018, doi: 10.1016/j.tafmec.2018.02.006.
- M. Grédiac, F. Sur, and B. Blaysat, “The Grid Method for In-plane Displacement and Strain Measurement: A Review and Analysis,” *Strain*, vol. 52, no. 3, pp. 205–243, 2016, doi: 10.1111/str.12182.
- C. H. Ndong Bidzo, C. F. Pambou Nziengui, S. Ikogou, B. Kaiser, and R. Moutou Pitti, “Mechanical properties of Glued-laminated timber made up of mixed tropical wood species,” *Wood Mater. Sci. Eng.*, vol. 0, no. 0, pp. 1–14, 2021, doi: 10.1080/17480272.2021.1960422.
- CIRAD, *The main technological characteristics of 245 tropical and temperate species. Bases of databases of forest species*. 2011.
- C. L. Chow and C. W. Woo, “Orthotropic and mixed mode fracture in wood,” in *Proceedings of the 1st international conference of wood fracture. Vancouver*, 1979, pp. 39–52.
- M. F. S. F. De Moura, J. J. L. Morais, and N. Dourado, “A new data reduction scheme for mode I wood fracture characterization using the double cantilever beam test,” vol. 75, pp. 3852–3865, 2008, doi: 10.1016/j.engfracmech.2008.02.006.
- J. L. Piro and M. Grédiac, “Producing and transferring low-spatial-frequency grids for measuring displacement fields with moiré and grid methods,” *Exp. Tech.*, vol. 28, no. 4, pp. 23–26, 2004, doi: 10.1111/j.1747-1567.2004.tb00173.x.
- B. Odounga, R. Moutou Pitti, E. Toussaint, and M. Grédiac, “Mixed mode fracture of some tropical species with the grid method,” *Eng. Fract. Mech.*, vol. 214, no. April, pp. 578–589, 2019, doi: 10.1016/j.engfracmech.2019.04.018.
- M. F. S. F. De Moura, “Numerical simulation of the ENF test for the mode-II fracture characterization of bonded joints,” *J. Adhes. Sci. Technol.*, vol. 20, no. 1, pp. 37–52, 2006, doi: 10.1163/156856106775212422.