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Analysis of fracture toughness of modified timber

Part II
Mathematical description

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ABSTRACT

This paper presents results of fracture toughness tests on DCB specimens made of natural and modified pine wood. The energy release coefficients G_α were calculated for both the materials under TL and RL crack propagation modes and the 1st mode of loading. Relations between the energy release coeffcients $G_{\alpha I}$ and the stress intensity factors $K_{\alpha I}$ have been determined. The obtained test results are presented in the form of tables and diagrams.

Keywords: anisotropic material; energy release coefficient; stresss intensity factor; anisotropic material cracking

INTRODUCTION

In the earlier phase of tests the critical stress intensity factor K_{Ic} [5, 6] was used for description of wood fracture toughness. Finally, the critical energy release coeffcient G_{Ic} was applied to describe wood cracking [4, 7, 8].

In the 1960s were made the first attempts to determining wood fracture toughness which consisted in testing the pine wood specimens under 1st mode of loading at TL and RL crack propagation modes, [4]. To the tests the DCB cantilever specimens were used to determine critical values of the energy release coeffcient G_{Ic}. By making use of the earlier obtained results of the tests on specimens of geometrical dimensions only a little different from the laboratory specimens, intended for describing wood fracture toughness, it was stated that the minor differences in dimensions did not affected values of the determined critical coeffcient G_{Ic}. Moreover it was observed that at both the considered modes only minor differences appeared in values of the critical coeffcient G_{Ic}. Many conducted tests have demonstrated that for the modes RL and TL the fracture toughness is multifold greater than for other modes, and it was the reason that in this work the fracture toughness tests of modified wood and, for comparison, also natural wood have been undertaken for both the mentioned modes.

This work has been aimed at determining fracture toughness of modified wood in contrast to natural wood. Results of the tests have been expected to show impact of modification of wood on its fracture toghness. The earlier performed tests on modified wood demonstrated significant increase of its strength properties both statical and dynamical in contrast to natural wood [1], therefore the determining of fracture toughness of the material has been deemed purposeful.

RESULTS OF THE TESTS

The tests of modified and natural wood were performed on 10 specimens at RL and LT crack propagation modes. On the basis of the tests (whose description was in detail presented in Part I) the below presented results were achieved.

In Tab. 1 are presented the example results of crack propagation run in the tested specimen C1 of natural wood in the direction of RL mode, and in Fig. 1 - the collective diagram which presents crack development in function of loading at the RL mode.

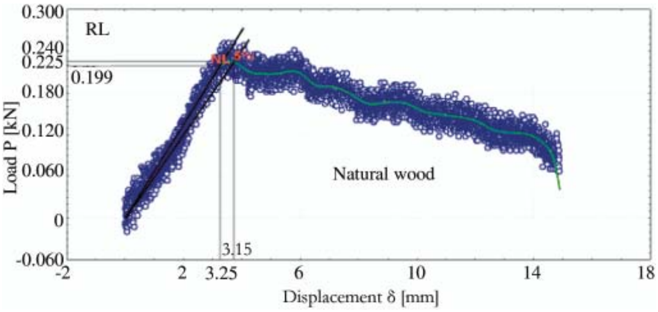

Fig. 1. *Collective diagram of the displacement δ in function of the load P for the specimens at RL crack propagation mode, with depicted value of critical load determined by using the P(δ) method (natural wood)*

Tab. 1. Results of crack propagation tests of the C1RL specimen of natural wood

Time [s]	Length of developed crack [mm]	Axial force [N]
0.540	0.01	6.0
5.745	0.11	8.0
10.050	0.20	10.0
15.054	0.29	12.0
20.059	0.40	18.0
25.064	0.49	20.4
30.069	0.60	25.0
35.074	0.70	30.0
40.079	0.80	34.0
45.084	0.90	44.0
50.089	0.99	54.0
55.094	1.10	58.0
60.098	1.20	60.0
…	…	…
325.057	6.50	200.0
330.062	6.60	195.0
335.067	6.70	190.0
340.072	6.80	187.0
345.076	6.90	186.0
350.081	7.00	185.0
355.086	7.10	178.0
360.091	7.21	163.0

In Fig. 2 is below presented the collective diagram of crack development run for structural natural wood in the TL crack propagation direction.

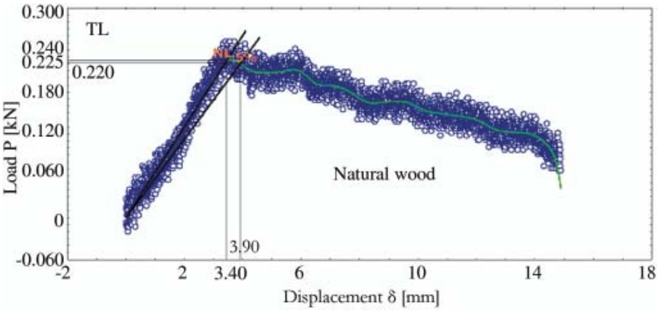

***Fig. 2.** Collective diagram of the displacement δ in function of the load P for the specimens at TL crack propagation mode, with depicted value of critical load determined by using the P(δ) method (natural wood)*

Analysis of the crack propagation in natural wood specimens (Fig. 1 and 2) demonstrated that for the TL mode the values of critical load and relevant displacement according to the P(δ) method were only a little greater. It results from the structure of wood being an orthotropic material.

As results from the available subject-matter literature no fracture toughness tests of modified wood have been performed so far.

The modification of wood consisted in introducing a synthetic polymer to wood structure, and then its thermal polymerization. As a result of the process the material of properties different from its components was obtained [1].

In Fig. 3 and 4 are presented the collective diagrams of crack propagation run for the tested specimens of modified pine wood at the TL and RL direction modes.

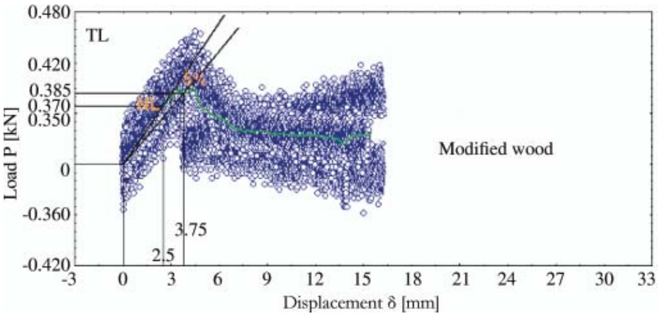

***Fig. 3.** Collective diagram of the displacement δ in function of the load P for the specimens at RL crack propagation mode, with depicted value of critical load determined by using the P(δ) method (modified wood)*

Initial fracture toughness tests of modified wood have made it possible to determine loss of integrity of the composite depending on crack propagation mode. Like in the case of natural wood the tests were performed for the radial-longitudinal mode RL and tangential – longitudinal mode TL. The tested cases were characterized by single cracks which were developing up to exceedance of allowable stresses. In the tangential-longitudinal mode TL the crack propagated in the direction almost parallel to the material fibres, and in the radial-longitudinal one RL - along the material fibres.

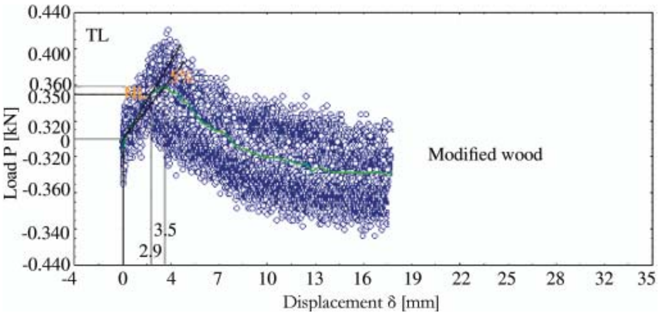

***Fig. 4.** Collective diagram of the displacement δ in function of the load P for the specimens at TL crack propagation mode, with depicted value of critical load determined by using the P(δ) method (modified wood)*

The selected results of the tests on structural wood specimens loaded in accordance with the 1st mode at the TL and RL crack propagation modes, are presented in Tab. 2 (natural wood) and Tab. 3 (modified wood).

The analysis of the cracking of modified wood specimens, performed on the basis of the results given in Fig, 3 and 4, has demostrated that the critical loads and the displacements corresponding to them, according to the applied method P(δ), showed greater values than for natural wood. As results, the modified wood is more tough against cracking. The increase of strength properties and fracture toughness of the modified wood is due to the strengthening of the porous structure of wood by filling it with the polymer. As a result of polymerization of the monomer introduced to wood structure a new material of improved properties as compared with natural wood, was achieved. The results of the fracture toughness tests of the modified wood confirmed the positive influence of the polymer on improving mechanical properties of wood [1].

As follows from the test results presented in tab. 2 and 3, the similar values of the critical coefficients G_{Ic} were obtained for both the analyzed crack propagation modes (TL and RL). And, the values of the coefficients for the modified wood are more than twice greater than for the natural wood. This confirms

Tab. 2. *Results of the tests on natural wood specimens loaded in accordance with the 1st mode at the RL and TL crack propagation modes*

No. of specimen	$2h_i$ [mm]	Humidity [%]	δ_i [mm]	P_i [N]	B_i [mm]	n	G_i [J/m^2]
C1RL	19.9	12.8	3.15	215	20.1	2.80	589
C2RL	20.1		2.35	208	19.9		429
C3RL	19.9		1.95	195	19.8		336
C4RL	20.1		2.05	185	20.1		330
C5RL	20.2		2.15	198	19.9		374
C6RL	19.7		1.97	187	20.2		319
C7RL	19.9		2.56	201	20.3		443
C8RL	20.1		1.97	197	20.3		334
C9RL	19.6		2.08	200	19.8		367
C10RL	19.8		1.98	189	20.1		325
Mean value			**2.22**	**197**			**384**
C1TL	20.0		3.55	215	20.2		661
C2TL	20.2		3.08	200	20.1		536
C3TL	19.9		1.97	189	20.3		320
C4TL	20.2		1.75	198	20.6		294
C5TL	19.9		2.06	187	20.1		335
C6TL	20.1		1.97	179	20.2		305
C7TL	19.8		2.05	207	19.6		378
C8TL	20.2		2.38	178	19.5		380
C9TL	19.9		1.95	194	20.1		330
C10TL	20.2		2.56	197	19.8		445
Mean value			**2.33**	**194**			**398**

Tab. 3. *Results of the tests on modified wood specimens loaded in accordance with the 1st mode at the RL and TL crack propagation modes*

No. of speci-men	$2h_i$ [mm]	Humidity [%]	δ_i [mm]	P_i [N]	B_i [mm]	n	G_i [J/m^2]
CM1RL	20.1	8.80	3.50	360	20.1		1097
CM2RL	20.2		3.45	350	19.9	2.80	1061
CM3RL	19.9		2.98	347	20.2		895
CM4RL	19.8		3.45	298	20.1		895
CM5RL	20.0		2.98	267	20.3		686
CM6RL	20.1		2.45	245	20.2		520
CM7RL	19.9		2.16	305	20.1		573
CM8RL	20.1		3.05	276	20.2		729
CM9RL	20.0		3.14	301	19.8		819
CM10RL	19.9		2.94	298	20.2		759
Mean value			**3.01**	**304**			**803**
CM1TL	19.9		3.75	385	20.4		1238
CM2TL	20.1		3.15	320	20.2		873
CM3TL	19.8		2.56	300	20.3		662
CM4TL	19.9		2.78	298	20.4		710
CM5TL	20.1		3.05	276	20.2		729
CM6TL	19.9		3.14	305	20.3		825
CM7TL	20.0		2.87	309	19.9		779
CM8TL	20.1		3.05	298	20.4		779
CM9TL	19.8		3.07	287	20.1		767
CM10TL	20.0		2.78	298	19.9		728
Mean value			**3.02**	**307**			**809**

the earlier obtained results showing that the modification of wood by using methyl polymethacrylate greatly improves its fracture toughness.

ANALYSIS OF RESULTS OF THE TESTS

The general relation between the energy release coefficients G_α, and the stress intensity factors K_α is expressed as follows:

$$G_\alpha = c_\alpha \cdot K_\alpha^2 \quad \alpha = \mathrm{I, II, III} \qquad (1)$$

By making use of the relations between G_α and K_α acc. [10] for wood being an orthotropic material under the 1st mode of loading, the following is obtained for the TL crack propagation mode:

$$G_I = K_I^2 \cdot \sqrt{\frac{1}{2E_L E_T}} \left[\sqrt{\frac{E_L}{E_T}} + \frac{E_L}{2G_{LT}} - \nu_{LT}\right]^{\frac{1}{2}} \qquad (2)$$

and for the RL crack propagation mode:

$$G_I = K_I^2 \cdot \sqrt{\frac{1}{2E_L E_R}} \left[\sqrt{\frac{E_L}{E_R}} + \frac{E_L}{2G_{LR}} - \nu_{LR}\right]^{\frac{1}{2}} \qquad (3)$$

On substitution of material constants appropriate for the natural pine wood and the modified pine wood, the following relations between the energy release coefficients $G_{\alpha I}$ and the stress intensity factors $K_{\alpha I}$ are obtained:

- at the TL crack propagation mode:
  - for the natural wood:

$$G_I = 4.26367 \cdot 10^{-9} \cdot K_I^2 \cdot Pa^{-1} \qquad (4)$$

  - for the modified wood:

$$G_I = 1.6881 \cdot 10^{-9} \cdot K_I^2 \cdot Pa^{-1} \qquad (5)$$

- at the RL crack propagation mode:
  - for the natural mode:

$$G_I = 3.88915 \cdot 10^{-9} \cdot K_I^2 \cdot Pa^{-1} \qquad (6)$$

  - for the modified wood:

$$G_I = 1.63856 \cdot 10^{-9} \cdot K_I^2 \cdot Pa^{-1} \qquad (7)$$

At the TL mode: G_{Ic} = 398 J/m^2 for the natural wood, and G_{Ic} = 809 J/m^2 for the modified wood, whereas at the RL mode: G_{Ic} = 384 J/m^2 for the natural wood, and G_{Ic} = 803 J/m^2 for the modified wood.

If the relations (4) ÷ (7) are taken into account the critical values of the coefficients K_{Ic} at the TL mode are equal to K_{Ic} = 305.5 Pa·m$^{1/2}$ for the natural wood, and K_{Ic} = 692.3 Pa·m$^{1/2}$ for the modified wood, whereas at the RL mode K_{Ic} = 314.2 Pa·m$^{1/2}$ for the natural wood and K_{Ic} = 700.0 Pa·m$^{1/2}$ for the modified wood. On the basis of the literature sources [2, 3] for pine wood at the TL mode the value of the coefficient K_{Ic} = 430 ÷ 450 Pa·m$^{1/2}$, whereas at the RL mode: K_{Ic} = 500 Pa·m$^{1/2}$. The results obtained for the natural wood demonstrate lower values as compared with those found in the literature sources. This may result from many reasons, one of them may be an origin of such wood which grows on various continents and in various climatic zones. Wood reveals different density and consequently different properties. Moreover used determination methods of critical loads may be different. In present for the determining of values of the critical loads the acoustic emission method is used.

The performed tests on cracking the natural and modified wood showed significant differences in values of the displacement **δ** for the same values of the crack length **a**. The tested modified wood showed smaller values of the displacement than the natural wood. The fracture of the modified wood specimens occurred under loads of geater values than for the natural wood at both the tangential-longitudinal crack propagation mode TL and the radial-longitudinal one, RL. Therefore it results that the wood-polymer composite shows greater fracture toughness than the natural wood.

The displacement values in function of the energy release coefficient for both the crack propagation modes were close to each other. Values of the energy release coefficient were increasing up to the instant of reaching the critical load value and then dropping (Fig. 5 ÷ 8). As results, after reaching the critical value of the energy release coeffcient the integrity losing process has been triggered off in the tested specimens.

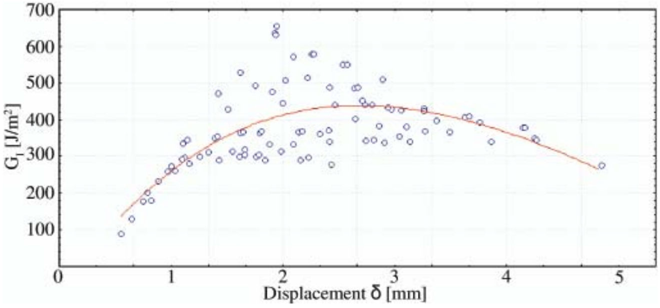

***Fig. 5.** The energy release coefficent in function of the displacement at the TL crack propagation mode (natural wood)*

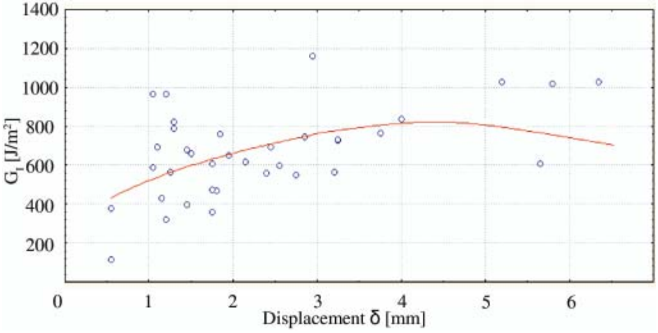

***Fig. 6.** The energy release coefficent in function of the displacement at the TL crack propagation mode (modified wood)*

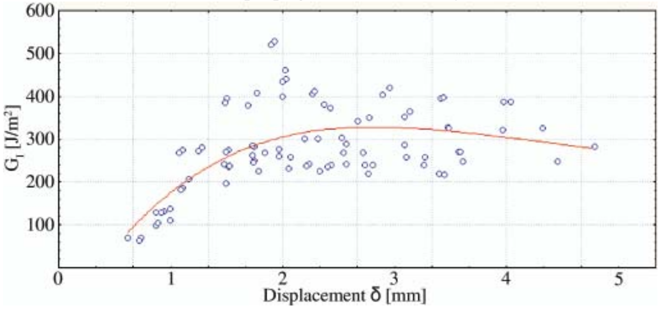

***Fig. 7.** The energy release coefficent in function of the displacement at the RL crack propagation mode (natural wood)*

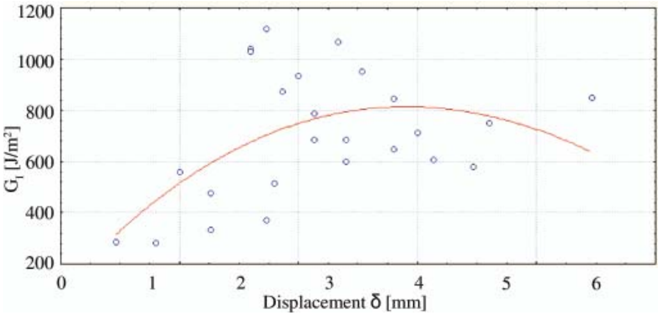

***Fig. 8.** The energy release coefficent in function of the displacement at the RL crack propagation mode (modified wood)*

FINAL CONCLUSIONS

Structural timber being an orthotropic material of different properties in different planes is difficult in testing.

In the performed tests of structural wood the impact of polymer on fracture toughness of the wood-polymer composite was determined as well as the ways of determining the critical load were highlighted. The material integrity loss under the 1st mode load acting perpendicularly to gap plane was discussed in detail.

The performed fracture toughness tests on natural and modified pine wood revealed essential differences in behaviour of the materials under testing. Critical values of the coefficients G_{Ic} and stress intensity factors $K_{\alpha I}$ are deemed the parameters which show how large is fracture toughness of a material. On the basis of the performed tests similar values of the critical coeffcients G_{Ic} were obtained for the both analyzed crack propagation modes (TL and RL). And, the values of the coefficients for the modified wood are more than twice greater than for the natural wood. This confirms the earlier obtained results showing that the modification of wood by means of methyl polymethacrylate greatly improves its strength properties. The values of the displacement $\boldsymbol{\delta}$ showed quantitatively that the tested modified wood exhibited smaller displacement values than the natural wood. Fractures of the modified wood occurred under greater load values than in the case of the natural wood both at the tangential - longitudinal crack propagation mode TL and radial-longitudinal one, RL. Therefore it can be concluded that the wood-polymer composite is characterized by a greater fracture toughness than the natural wood.

BIBLIOGRAPHY

1. Kyzioł L.: *Analysis of properties of structural wood of MM polymer- saturated surface* (in Polish). Akademia Marynarki Wojennej (Polish Naval Academy), Gdynia, 2004.
2. Patton-Mallory M., Cramer S.M.: *Fracture Mechanics: A Tool for Predicting Wood Component Strength*. Forest Products Journal, Vol. 37, 1987.
3. Green D. W., Winandy J. E., Kretschman D. E.: *Wood Handbook – Wood as an Engineering Material. Chapter 4. Mechanical Properties of Wood*, U. S. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, 1999.
4. Debaise G. R., Porter A. W., Pentoney R. E.: *Morphology and Mechanics of Wood Fracture.* Materials Research & Standards, Vol. 6, 1966.
5. Wu E. M.: *Application of Fracture Mechanics to Anisotropic Plates*. Journal of Applied Mechanics, Vol. 34, 1967.
6. Ando H., Ohta M.: *Relationships between the Morphology of Micro-Fractures of Wood and the Acoustic Emission Characteristics*. Mokuzai Gakkaishi, Vol. 41, 1995.
7. Kossakowski P.: *Fracture Toughness of Wood*. 2nd International Conference, Fracture Mechanics of Materials and Structural Integrity, Lviv, 1999.
8. Kossakowski P.: *Fracture toughness of wood* (in Polish). VII Krajowa Konferencja Mechaniki Pękania (7th National Conference on Fracture Mechanics), Kielce/Cedzyna, 1999.

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