Analysis of fracture toughness of structural timber

Part I
Theory and experimental tests

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ABSTRACT

This paper presents fundamentals of fracture mechanics of anisotropic materials. Fracture toughness of anisotropic materials, e.g. structural timber, depends a. o. on state of stress, environment, temperature and changes due to ageing, therefore in such materials cracking process runs in various ways. Timber is characterized by eighteen coefficients which determine its fracture toughness in contrast to metals for which this number is as low as three. In this part of considerations a way of conducting the tests of specimens subjected to cracking as well results of the tests of natural and modified timber, are presented.

Keywords: anisotropic material; anisotropic material cracking; CAD specimens; test stand; complex loading; stress distribution

INTRODUCTION

In the majority of structures operating under load the sudden cracking of elements occur in spite of that stresses in them do not exceed their allowable level. Such cracks can be caused both by material defects resulting from improper technological processes, and by external random overloading.

This work is aimed at the determination of relations between fracture toughness of natural and modified wood and size of defects, in given loading conditions. Results of the tests should reveal an effect of modification of wood on its fracture toughness.

In order to be able to determine structural material fracture toughness it is necessary to determine experimentally material constants, mainly the stress intensity factor and critical crack length. It was consisted in determining quantitative relations between resistance against the cracking in given loading conditions and size of defect. Fundamentals of fracture theory of orthotropic materials are presented. Ways are discussed of determining the critical load and possibilities in determining the structural timber fracture toughness in selected anatomic directions.

The tests were conducted for the two crack propagation modes where stratification develops along fibres in crack containing specimen: tangential-longitudinal (TL), radial-longitudinal (RL). Specimens were subjected to load leading to crack (gap) opening (disruption).

BASIC RELATIONS WHICH DESCRIBE CRACKING PROCESS OF ISOTROPIC MATERIALS

Fracture mechanics is applied to assessing material resistance against loss of its coherence. As results from many literature sources concerning fracture of isotropic materials, crack-containing material can be loaded in three ways which may lead to crack opening (rupture), longitudinal shearing (slipping) or lateral shearing [5, 6]. The specified modes are called pure modes of loading the crack (gap) - containing element, marked I, II and III, respectively, (Fig. 1), [5, 6].
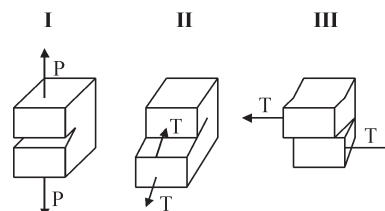
*Fig. 1. Basic modes of cracking depending on a mode of loading applied to a body: **I)** Rupture (crack opening, pulling apart); **II)** Longitudinal shearing (slipping); **III)** Lateral shearing*

Apart from the specified loading modes a few cases of complex loading which are combinations of the above mentioned cracking modes, can be met in reality.

For description of fracture toughness of specimens made of a given material the following parameters are used: critical value of the energy release coefficient $G_{\alpha c}$, stress intensity factor $K_{\alpha c}$, and integral J_c. The parameter $G_{\alpha c}$ is determined as the derivative of the potential energy released during cracking process, U, taken with respect to the crack length a [2]:

$$G_\alpha = -\frac{\partial U}{\partial a} \ , \ \alpha = I, II, III \qquad (1)$$

The energy release coefficient corresponding to the loading modes I, II, III are marked G_I, G_{II}, G_{III}, respectively. As assumed, if material fracture toughness is only slightly dependent on crack length rate then in order the gap to be capable of developing in an uncontrollable way, the following condition is to be satisfied:

$$G_\alpha \geq G_{\alpha c} \qquad (2)$$

The condition (2) is assumed to be the crack propagation criterion, and the parameter G_α which characterizes material fracture toughness, is determined experimentally[6]. The critical values of the energy release coefficients G_{Ic}, G_{IIc}, G_{IIIc} characterize material fracture toughness. The stress intensity factor K_α is used as a measure of stress and displacement field in the vicinity of gap vertex. Its value depends on value of the external loading σ_{zw}, crack length a as well as factor Y (a constant dependent on a crack opening mode and specimen geometry, [1, 3, 5]).

$$K_\alpha = K_\alpha(\sigma_{zw}, a, Y) \ \alpha = I, II, III \qquad (3)$$

In the subject-matter literature the stress intensity factor corresponding to the pure loading modes is marked K_I, K_{II}, K_{III}, respectively [2, 3]. To initiate cracking process, its value, like that of the stress intensity factor, should exceed the critical value $K_{\alpha c}$ for a given material, in compliance with the following inequality [3, 5]:

$$K_\alpha \geq K_{\alpha c} \qquad (4)$$

The relation (4), in contrast to the relation (2), concerns only the area around gap vertex.

Between the energy release coefficient G_α and stress intensity factor K_α the following relation occurs [3, 5]:

$$G_\alpha = c_\alpha K_\alpha^2 \qquad (5)$$

where:

c_α - coefficient depending on state of stress, loading mode and mechanical properties of a given material.

The third parameter which determines resistance of materials to loss of coherence, is the so-called integral J_c. The integral J_c, like the preceding parameters, is a measure of energy necessary to trigger crack developing. In contrast to the parameters $G_{\alpha c}$ and $K_{\alpha c}$, the parameter in question accounts for a significant plastic deformation occurring in structural materials [1, 3, 5].

BASIC RELATIONS WHICH DESCRIBE CRACKING PROCESS OF ANISOTROPIC MATERIALS

Structural timber, an orthotropic material, is characterized by that it is subjected to cracking in variuos ways, depending on stress state, environment, temperature and ageing changes. The material is stratified and undergoes delamination under load. The delamination of such composite material results from many factors such as: assembling errors, mechanical failures, stress concentration in vicinity of defects nad cracks as well as changes in material structure during drying.

Timber is a non-homogenous, anisotropic (multi-directional) material, that makes decribing its strength properties difficult.
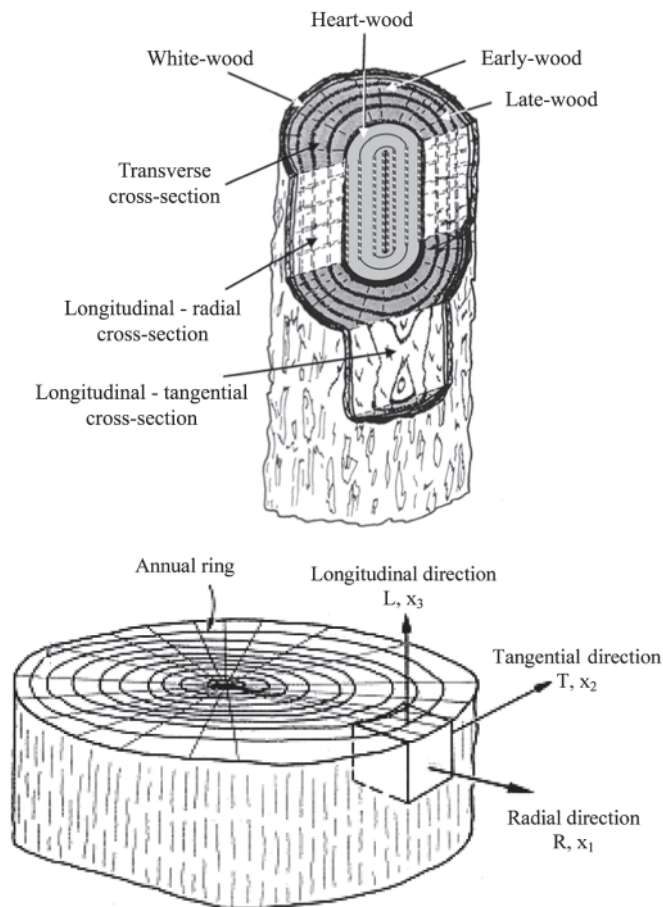

Fig. 2. *A stump of wood with marked anatomic directions*

As arrangement of rings in a given volume is differentiated, three principal directions (three planes of symmetry) are specified in wood: radial – R (x_1), tangential – T (x_2) and longitudinal one - L (x_3), Fig. 2. If a wood specimen is cut sufficiently far from the centre of wood stump, so as to be able to consider curvature of rings negligible, then its properties can be deemed orthotropic. Wood considered as an orthotropic material have three characteristic directions strictly associated with its anatomic structure [4].

For orthotropic materials six basic modes of crack propagation are distinguished (Fig. 3). The first letter of the symbols stands for the direction normal to plane of crack, the second - direction of its propagation. Hence the tangential - longitudinal mode of propagation TL, tangential-longitudinal TR, radial-tangential RT, radial-longitudinal RL, longitudinal-tangential LT and longitudinal-radial LR, are distinguished [4].

For three modes of loading eighteen possible modes of crack propagation are assumed. Two modes are distinguished where delamination develops along fibres: tangential – longitudinal – TL and radial-longitudinal – RL, as well as four ones in lateral direction. In practice, structures are subjected to complex loads, e.g. I/II or II/III.

For assessment of fracture toughness of orthotropic materials linear fracture mechanics is used as any standard method is still lacking. In fracture toughness testing, critical values of the coefficients G_{Ic}, G_{IIc}, G_{IIIc} and factors K_{Ic}, K_{IIc}, K_{IIIc} have to be determined for every propagation mode. Wood is characterized by eighteen coefficients which determine its
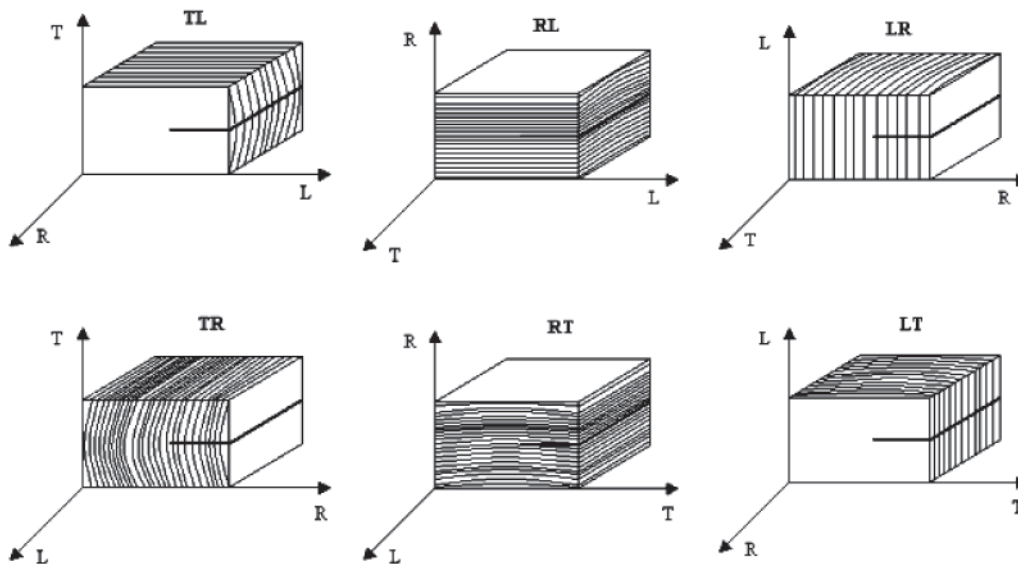
Fig. 3. Crack propagation modes in orthotropic material

fracture toughness in contrast to metals for which the number is reduced to three.

An important problem of fracture toughness of materials is determination of the critical load P_c. The critical load is defined as such value of force under which loss of specimen material coherence occurs. Its determination is complex. For determining P_c value a few methods are used out of which the following can be distinguished [6, 7, 8]:

- the method NL in which it is assumed that initiation of cracking process is commenced in the instant when a non-linearity of the P-δ (force- gap opening) diagram appears (Fig. 4);

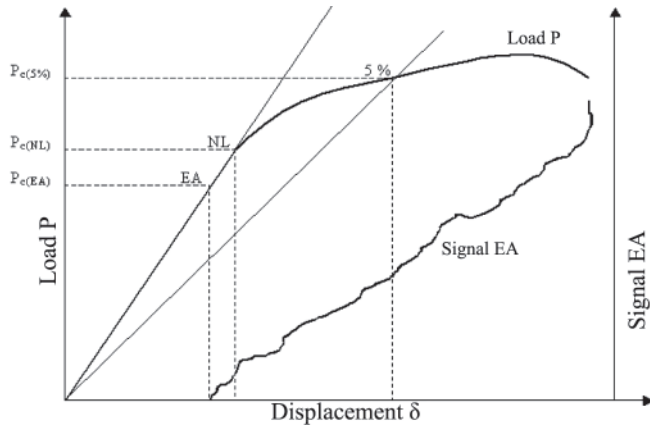*Fig. 4. Methods for determining the critical load P_c*

- the method P(δ) in which the point of intersection of the diagram P(δ) and the straight line whose slope angle tangent is smaller by 5 % than that of the straight line which contains the linear part of the diagram P(δ), is assumed the beginning of cracking process (Fig. 4);
- the method based on non-linear and linear approximation of the diagram P(δ), (Fig. 5)
- the method based on acoustic emission (EA) [6].

TESTS ON STRUCTURAL TIMBER CRACKING

Geometry of specimens

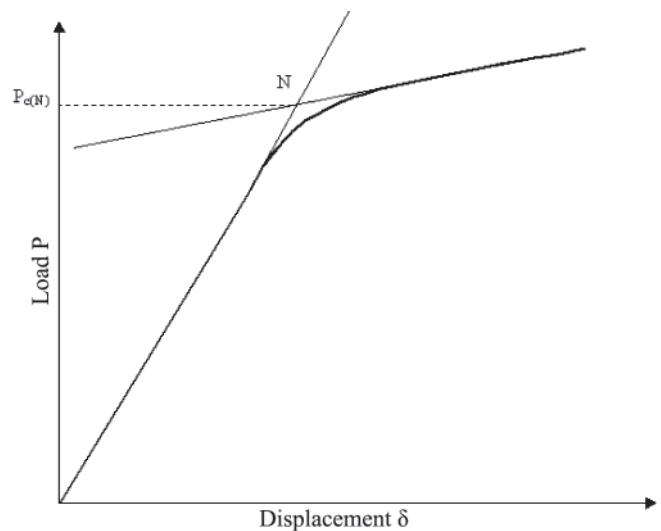Tests of fracture toughness of composite materials can be performed with the use of specimens of different geometrical

Fig. 5. Method for determining the critical load P_c, based on approximation of the diagram P(δ)

forms (Fig. 6) [6]. In structural timber testing the double cantilever beam specimens (DCB) were used.

The critical energy release coefficient G_{1c} [2] for a given specimen is described by the relation:

$$G_{1c} = \frac{1}{2} \cdot \frac{P_c^2}{B} \cdot \frac{\partial C}{\partial a} \qquad (6)$$

where:
P_c – critical load
C – specimen flexibility
B – thickness (breadth)
a – crack (gap) length.

The critical energy release coefficient G_{1c} for an assumed type of specimen is determined from the following formula [2]:

$$G_{1c} = \frac{3}{2} \cdot \frac{P_c \cdot \delta}{B \cdot a} \qquad (7)$$

where:
δ – crack (gap) opening.

The corrected crack length equal to $a + |\Delta|$ was determined on the basis of the beam theory in which experiment conditions and influence of real geometry have been accounted for. The
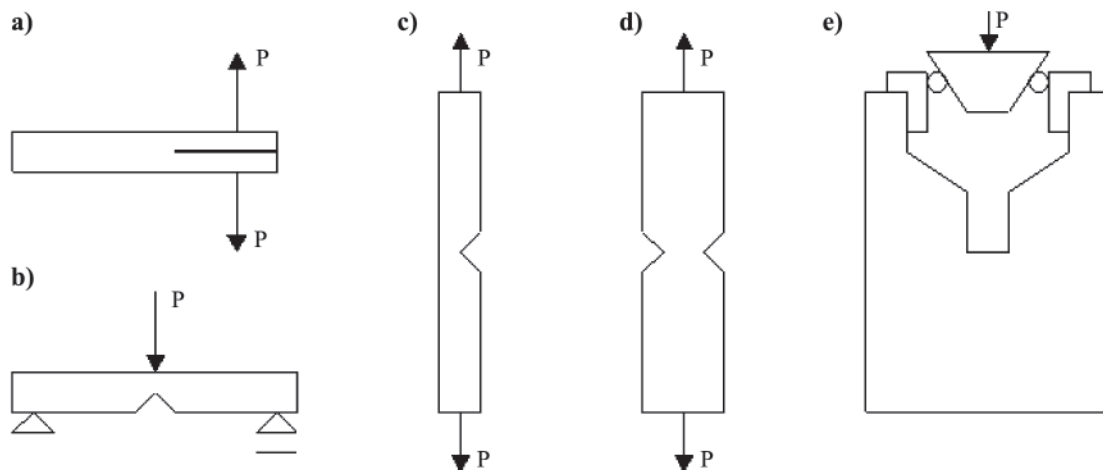
Fig. 6. *Specimens for determining fracture toughness of wood elements loaded in compliance with the mode I: **a)** double cantilever beam specimen, **b)** one-sided -notched specimen under three- point bending, **c)** one-sided-notched specimen under tension, **d)** double-sided- notched specimen under tension, **e)** specimen for splitting test*

unknown quantity Δ was experimentally determined from the diagram $C^{1/3}(a)$. The relation was built graphically by measuring the flexibility C for a few different values of the crack length a. The straight line approximating the diagram $C^{1/3}(a)$ determines the quantity Δ on the horizontal axis level (Fig. 7). The way of determining the quantity Δ is descibed in detail in the work [7].
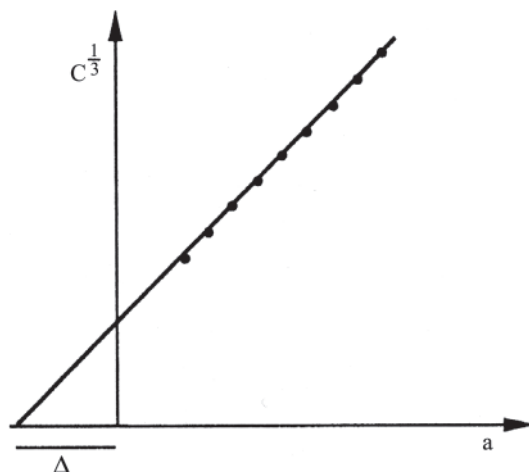

Fig. 7. *Method for determining the linear correction Δ to the beam theory[3]*

For the double cantilever beam specimens the critical energy release coefficient G_{lc} is determined from the formula as follows [7]:

$$G_{lc} = \frac{3}{2} \cdot \frac{P_c \cdot \delta}{B \cdot (a + |\Delta|)} \qquad (8)$$

The specimen flexibility C is determined by using Berry method, i.e. by means of the relation:

$$C = K \cdot a^n \qquad (9)$$

where:
n – a coefficient experimentally determined on the basis of the diagram ln(C) versus ln(a)
K – numerical value determined from the point of intersection of the diagram with the ordinate axis.

The diagram ln(C) versus ln(a) can be built by measuring the flexibility C for different values of the crack length a (Fig. 8).

The coefficient n is equivalent to its slope angle tangent. The critical energy release coefficient G_{lc} is determined by using the following relation [8]:

$$G_{lc} = \frac{1}{2} \cdot \frac{n \cdot P_c \cdot \delta}{B \cdot a} \qquad (10)$$
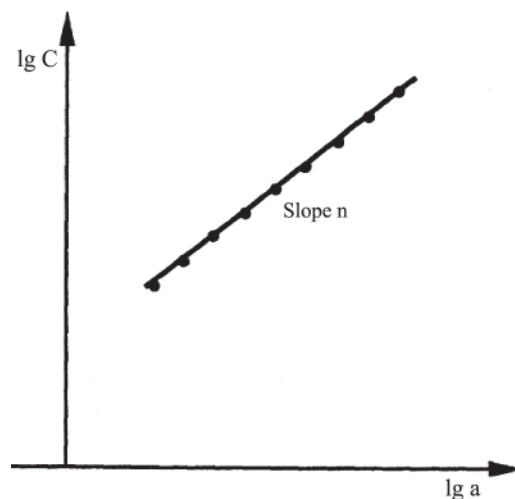

Fig. 8. *Method for determining the coefficient n*

Characteristics of the tested material and description of the test running

A natural and modified pine wood was used in the tests. Modification of wood by means of methyl polymethacrilate improves its properties. The detailed decription of run of the modification process by using methyl polymethacrilate as well as properties of the modified wood are given in the work [4]. In Tab. 1 and 2 are exemplified values of material constants as well as strength properties of the natural and modified wood [4].

The fracture toughness tests of natural and modified wood were conducted with the use of the universal electrohydraulic testing machine MTS-81012. The tested specimens were made of the natural wood of abt. 12% humidity and modified one of abt. 8% humidity. The tests were performed in the room temperature of abt. 20° C. The DCB specimens were used in the tests (Fig. 9). They were made of the same batch of wood on the basis of which their strength properties were earlier determined [4]. For the specimens the square cross-section of 20 mm x 20 mm sides, was assumed. The gap was cut by using

a saw of 1.8 mm in thickness and 70 mm in length, and then it was deepened up to 80 mm by using a thin blade.

Tab. 1. Values of the material constants of the natural and modified wood

Material constant	K0.0	K0.56
$E_R = E_1$ [GPa]	2.15	5.09
$E_T = E_2$ [GPa]	2.35	5.12
$E_L = E_3$ [GPa]	11.85	16.45
$G_{TL} = G_{23}$ [GPa]	0.72	2.57
$G_{LR} = G_{31}$ [GPa]	1.04	2.34
$G_{RT} = G_{12}$ [GPa]	0.91	1.94
$\nu_{RL} = \nu_{13}$	0.06	0.08
$\nu_{TL} = \nu_{23}$	0.07	0.05
$\nu_{LT} = \nu_{32}$	0.35	0.18
$\nu_{RT} = \nu_{12}$	0.58	0.34
$\nu_{TR} = \nu_{21}$	0.66	0.35
$\nu_{LR} = \nu_{31}$	0.32	0.28

Notation: the symbol K0.0÷K0.56 stands for amount of methyl methacrilate [kg] per 1 kg of dry wood

Tab. 2. Strength limits for natural and modified wood under tension, compression and shear load, respectively

Kind of material	$R_{m_{II}}$ [MPa]	$R_{c_{II}}$ [MPa]	$R_{m\perp}$ [MPa]	$R_{c\perp}$ [MPa]	R_t [MPa]
K0.0	95	55	4.5	8.5	22.10
K0.56	118	98	9	32	30.20

Notation: $R_{m_{II}}$ - tensile strength along fibres; $R_{c_{II}}$ - compression strength along fibres; $R_{m\perp}$ - tensile strength across fibres; $R_{c\perp}$ - compression strength across fibres; R_t - shear strength
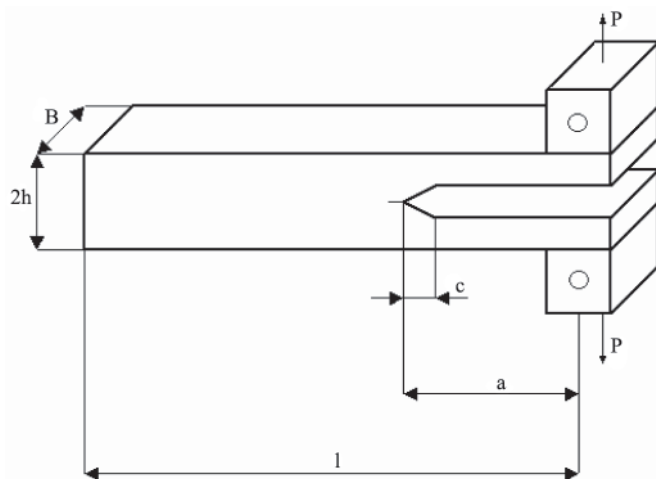

Fig. 9. DCB specimen used in the tests, of the dimensions: l = 200 mm, a = 80 mm, c = 10 mm, B = 2h = 20 mm

For description of wood fracture toughness the energy release coefficients G_{ac} were used in view of anisotrophy of the tested material. The tests were conducted for two modes of crack propagation in wood, i.e. for the tangential – longitudinal direction TL and the radial – longitudinal direction RL. They were performed for the gap length a = 80 mm. The specimens complied with the provisions of the PN-EN 408 standard. The pine wood was suitably dried and prepared to testing. For the specimens 200 mm length was selected, i.e. ten times greater than the greater dimension of their cross-section which was on average equal to 20 mm in the case of the modes RL and TL. Load was applied to the specimens at the constant rate of 0.03 mm/s. Special holding devices (chucks) had to be manufactured to make performing the tests with the use of the MTS machine possible. The tested material was glued to the chucks by means of the „PATTEX", a universal glue for wood.

Each of the specimens was measured with the accuracy of 0,01 mm and marked in line with its direction of orientation. On each specimen measuring length was made with the accuracy up to 0,01 mm, in order to analyze fracture toughness coefficient. During the tests values of the load P and displacement δ were recorded. Value of the critical load was determined by means of the method P(δ) (Fig. 4). The load P and displacement δ was recorded by using the measuring system consisted of a computer and A/D card.

For determining the critical fracture toughness coefficient G_{Ic}, it is necessary to know the coefficient n whose value for a given kind of wood is determined experimentally on the basis of the approximation of function of flexibility versus gap length. As in the available literature sources the n-coefficient value for Douglas fir equal to n = 2.80 is found and pine wood properties are close to those of Douglas fir, hence for further calculations n = 2.80 was assumed for the pine wood [9]. On the basis of the relation (11) were determined critical values of the energy release coefficient G_{Ic} of the natural and modified wood specimens for the directions RL and TL.

Based on the assumed value of the coefficient n = 2.80, the critical coefficient G_{Ic} of the tested and modified wood for the modes TL and RL can be determined from the relation:

$$G_{Ic} = \frac{1}{2} \cdot \frac{2{,}80 \cdot P_c \cdot \delta}{B \cdot a}$$

The tests of natural and modified wood fracture toughness for the mode TL demonstrated that the crack initiation was triggered off before the load applied to the specimens obtained its maximum value. The determined critical load was equal on average to 80% of the maximum load. The initial cracking run was mild, then passing to violent. As observed, in the natural wood specimens occurred a single crack which was next developing until the maximum stresses were exceeded (Fig. 10). In the case of the mode TL the crack propagated almost parallel to direction of the fibres.

In the case of the mode RL the crack was initiated, like in the preceding case, already before the element reached its maximum load. The determined average load was equal to 85% of the maximum one. In the mode RL the crack was developing in a stable way both in the specimens of natural and modified wood, as shown in Fig. 10. The specimens under tension in the mode RL, cracked along the fibres. The crack propagation direction was in line with the anatomic direction of the fibres. The crack propagated along the hardwood-softwood boundary. In the mode TL, like in the mode RL, the crack propagated up to the moment of splitting the specimens, however in the specimens of modified wood it was propagating slowly.

Results of the tests of the specimens made of natural and modified wood, loaded in the way I of the modes TL and RL, will be presented in the next part of the paper.

RESULTS OF FRACTURE TOUGHNESS TESTS OF STRUCTURAL TIMBER

The cracks in wood specimens have developed in different ways depending on a propagating mode. For the mode TL, value of the applied axial force was increasing up to the critical load P_c. In this mode, single cracks appeared in the specimens; they were developing until the maximum stress values were reached. As shown in Fig. 10, the cracks propagated parallel to direction of fibres. It was observed that cracks were developing in the same way in the tested specimens for the same loads and constant time intervals. The 20 mm long fracture was formed. The identical crack development process in the tested specimens results from the fact that they were cut from neighbouring areas of the tested material.

Fig. 10. *Images of crack propagation surfaces in the specimens in the mode TL: a) natural wood, b) modified wood*

In the case of the mode RL (Fig. 11) the crack was propagating steadily along wood fibres. The cracking process of the specimens developed faster as it met a smaller resistance than in the mode TL. It results from the internal structure of the wood, an orthotropic material. In the mode RL the alternate softwood and hardwood layers makes that in their planes cracks develop under smaller loads than in the case of the mode TL.

Rys. 11. *Images of crack propagation surfaces in the specimens in the mode RL: a) natural wood, b) modified wood*

SUMMARY

- This work aimed at fracture thoughness determination of natural and modified pine wood, made it possible to determine, by means of the method $P(\delta)$, the load which initiates cracking process. The method is capable of determining, in a simple and sufficiently accurate way, the instant of initiating the cracking process. As results from the performed tests, the ratio of the load in question and the maximum load was equal to about 0,80 for the mode TL and about 0.85 for the mode RL.
- The fracture toughness of natural and modified pine wood was determined experimentally by means of critical values of the energy release coefficients G_{Ic} complying with the relation (11), to be presented in the next part of the work.
- In the tests were used the beam specimens which make it possible to model real phenomena of cracking the wood elements containing defects. The critical coefficients G_{Ic} were determined with the use of the beam theory accounting for material anisotrophy. The critical values of the coefficients G_{Ic}, determined for the splitting of natural and modified pine wood, were practically identical for both analyzed crack propagation modes: RL and TL.

NOMENCLATURE

a - crack length
B - specimen thickness
G_α - energy release coefficient
K_α - stress intensity factor
L - longitudinal direction
R - radial direction
T - tangent direction
l - specimen length
P - load
U - potential energy released during cracking
δ - crack opening.

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