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# INFLUENCE OF ANISOTROPY ON THE ENERGY RELEASE RATE $G_{\mathrm{I}}$ FOR HIGHLY ORTHOTROPIC MATERIALS

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The paper presents results of a numerical analysis concerning the energy release rate, $G_{\mathrm{I}}$, for highly orthotropic materials such as composites, laminates or wood. The values of $G_{\mathrm{I}}$ were calculated using the Adina v. 8.1 Finite Element Method (FEM) program. Different material models were considered to establish the influence of anisotropy on $G_{\mathrm{I}}$. Two-dimensional (2D) and three-dimensional (3D) isotropic and anisotropic models were employed to study the performance of a Double Cantilever Beam (DCB) with various crack length-to-thickness ratios. It was reported that the smaller the ratio, the bigger the difference between the energy release rates $G_{\mathrm{I}}$ calculated for the isotropic and anisotropic (transversal isotropic and orthotropic) material models. Thus, it is important that a fracture or fracture toughness analysis should be based on the transversal isotropic and orthotropic models and it should take into account anisotropy.

*Key words*: fracture toughness, pinewood, highly orthotropic materials, mode I loading, energy release rate $G_{\mathrm{I}}$

## Notations

| | | |
|---|---|---|
| $a$ | – | crack length |
| $B$ | – | specimen width |
| $E_i$ | – | elastic modulus in the $i$-direction $(i = 1, 2, 3)$ |
| $G_{\mathrm{I}}$ | – | mode I energy release rate |
| $G_{\mathrm{I}c}$ | – | critical value of mode I energy release rate |
| $G_{i,j}$ | – | shear modulus in the $ij$-orientation $(i, j = 1, 2, 3;\ i \neq j)$ |
| $H$ | – | specimen half-thickness |
| $h$ | – | cantilever thickness |
| $i, j$ | – | indices |

$P$ – load
$P_c$ – critical load
$U$ – potential energy
$\nu_{i,j}$ – Poisson's ratio in the $ij$-orientation $(i,j = 1,2,3;\ i \neq j)$
$E_L, E_T, E_R$ – elastic modulus of wood in the $L$-, $T$- and $R$-direction, respectively
$G_{LT}, G_{LR}, G_{TR}$ – shear modulus of wood in the $LT$-, $LR$- and $TR$-orientation, respectively
$\nu_{LT}, \nu_{TL}, \nu_{LR}, \nu_{RL}, \nu_{TR}, \nu_{RT}$ – Poisson's ratio of wood in the $LT$-, $TL$-, $LR$-, $RL$-, $TR$- and $RT$-orientation, respectively

## 1. Introduction

A variety of inhomogeneous materials are applied in structural engineering. The most common are composites, laminates and wood. As structural elements made of such materials are prone to cracking, they need to be designed for particular service conditions. Their strength and stiffness decrease with crack extension, which may eventually lead to failure.

One of the most frequent loading modes that occur in orthotropic structural elements is the opening, denoted by mode I. In order to avoid fracture, it is essential to assess the crack driving force and fracture toughness. This requires determination of the energy release rate $G_{\rm I}$, which defines the load causing delamination. The energy release rate can be determined analytically as a function of the load $P$. Its critical value, $G_{{\rm I}c}$, is a parameter that characterizes fracture toughness of a material for mode I loading. It is established on the basis of $G_{\rm I}$ for the critical load $P_c$ determined experimentally at the crack initiation. As analytical solutions are suitable only for simple loading cases, specimens and crack configurations, their application is limited. More general solutions are obtained by means of numerical methods. Various numerical techniques have been used to calculate $G_{\rm I}$. They were described, for example, by Hellen (1975), Parks (1977), Nikishkov and Vaynshtok (1980), Haber and Koh (1985), and Seweryn (1998). It should be noted that, unlike analytical solutions, numerical techniques are reported to be very useful in fracture analyses. They make it possible to determine the energy release rate of a structural element, $G_{\rm I}$, for any geometry, any material (for instance, isotropic and anisotropic), and any crack location.

This paper is concerned with the influence of anisotropy on the energy release rate, $G_{\rm I}$. It is possible to determine how anisotropy affects fracture toughness of highly orthotropic materials such as composites, laminates or wood. It enables us to use proper material models in fracture toughness examinations and calculations of $G_{\mathrm{I}}$ for any structural element containing a crack.

In the analysis, wood was selected to act as a model of an inhomogeneous material. The analysis results are found to be universal and, thus, applicable to other anisotropic materials with less complex structure, for instance, composites and laminates.

The principles of fracture mechanics have been determined for isotropic materials mainly. Being a complex and highly anisotropic material, wood is defined on the basis of an orthotropic model. As can be seen in Fig. 1, there are three main directions in wood: longitudinal $(L)$, tangential $(T)$ and radial $(R)$.

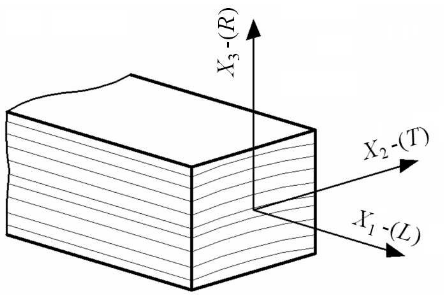


Fig. 1. Orthotropic material model of wood

Consequently, there are six main systems of crack propagation in wood denoted by $TL$, $TR$, $RL$, $RT$, $LR$ and $LT$ (Fig. 2). The first letter stands for the direction normal to the crack plane, while the other denotes the direction of crack propagation. In order to characterize the fracture mechanics of wood for mode I loading, it is necessary to determine six critical values of the energy release rate, $G_{\mathrm{I}c}$.

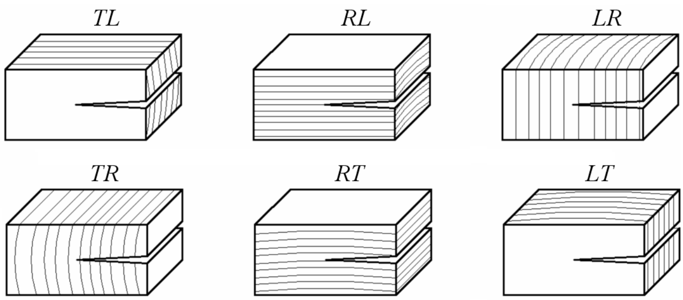


Fig. 2. Systems of crack propagation in wood

A fracture toughness analysis of an inhomogeneous material requires taking into account anisotropy. A majority of authors involved in the research into the mode I loading treat wood as an isotropic material, for example, Atack *et al.* (1961), Porter (1964), DeBaise *et al.* (1966), Johnson (1973), Schniewind and Lyon (1973), Schniewind and Centeno (1973), Schniewind (1977), Petterson and Bodig (1983), Yeh and Schniewind (1992), Ando *et al.* (1992), and Ando and Ohta (1995). In order to determine fracture toughness of wood they often applied the same solutions as those for metal testing. Some authors, for instance, Wu (1967), Stanzl-Tschegg *et al.* (1995, 1996), Reiterer *et al.* (2000), and Kossakowski (2004), studied wood anisotropy basing on the orthotropic model.

To estimate fracture toughness of wood, it is necessary to specify under what conditions the isotropic model is used. This problem has been analyzed by several authors, yet the focus was on another fracture parameter of anisotropic materials, the so-called stress intensity factor. According to Patton-Mallory and Cramer (1987), the isotropic stress intensity can be used to determine the orthotropic stress intensity under certain circumstances. For infinite bodies, where the crack surface is not subjected to any local loads, the isotropic and orthotropic stress intensity factors were the same (Cook and Rau, 1974; Tomin, 1972; Williams and Birch, 1976). For a finite element with real boundary conditions, a change in the material or geometry causes that the isotropic and orthotropic stress intensity factors are different (Tomin, 1971). For a finite orthotropic plate with a center crack, subjected to tensile isotropic stress, the intensity factors lied within 10 percent of the orthotropic values (Bowie and Freese, 1972; Ghandi, 1972). However, for specimens subjected to uniform tension and pure bending, the isotropic and orthotropic stress intensity factors differed less than 7 percent (Walsh, 1972). Mandel *et al.* (1974) found the difference between isotropic and orthotropic stress intensity to be as much as 25 percent for an edge crack in a cantilever beam specimen. It seems that the isotropic stress intensity factors can be employed to estimate orthotropic stress intensity, yet they depend on the calculation accuracy and problem type.

## 2. Numerical procedures

The Adina version 8.1 Finite Element Method (FEM) program was used for the numerical analysis. The calculations were made for Double Cantilever Beam (DCB) specimens subjected to mode I loading (Fig. 3).

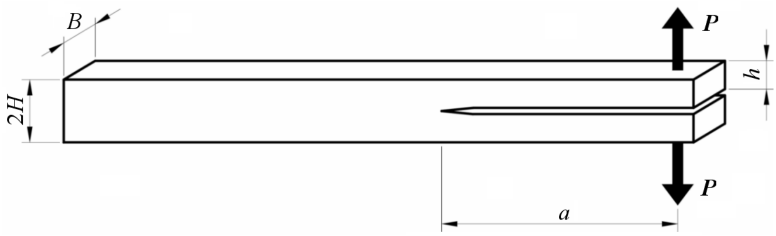


Fig. 3. DCB specimen

Two- (2D) and three-dimensional (3D) elements were considered. The geometry and boundary conditions were the same for the 2D and 3D numerical models. As the DCB specimen is symmetrical, only half was modeled for numerical calculations.

In order to establish the effect of the element geometry on the energy release rate for different material models, it was assumed that the cantilever thickness, $h$, and the element thickness, $2H$, were different. Four types of 2D and 3D DCB elements were examined. The dimensions of the numerical models with the cantilever thickness ranging from 4.5 mm up to 9.0 mm are presented in Table 1.

**Table 1.** Dimensions and loadings of DCB models

| Element No. | $B$ [mm] | $H$ [mm] | $h$ [mm] | $a$ [mm] | $a/h$ | $a/H$ | $P$ [N] |
|---|---|---|---|---|---|---|---|
| 2D-1 | 18 | 4.5 | 3.6 | 80.0 | 22.22 | 17.78 | 16.46 |
| 2D-2 | 18 | 6.0 | 5.1 | 80.0 | 15.69 | 13.33 | 26.75 |
| 2D-3 | 18 | 7.5 | 6.6 | 80.0 | 12.12 | 10.67 | 38.00 |
| 2D-4 | 18 | 9.0 | 8.1 | 80.0 | 9.88 | 8.89 | 50.00 |
| 3D-1 | 18 | 4.5 | 3.6 | 80.0 | 22.22 | 17.78 | 16.46 |
| 3D-2 | 18 | 6.0 | 5.1 | 80.0 | 15.69 | 13.33 | 26.75 |
| 3D-3 | 18 | 7.5 | 6.6 | 80.0 | 12.12 | 10.67 | 38.00 |
| 3D-4 | 18 | 9.0 | 8.1 | 80.0 | 9.88 | 8.89 | 50.00 |

The fracture analysis module was used to perform a linear-elastic fracture mechanics analysis. A stationary crack with a singularity in the crack tip was modeled for all the elements. Middle nodes in the vicinity of the crack tip were moved to the so-called Quarter-Point Location. All the two-dimensional (2D) specimens were modeled using eight-node elements in a plane stress system. Accordingly, twenty-node elements were used to build three-dimensional (3D) models. The numerical models of the DCB specimens for 2D and 3D analyses are shown in Figs. 4 and 5.

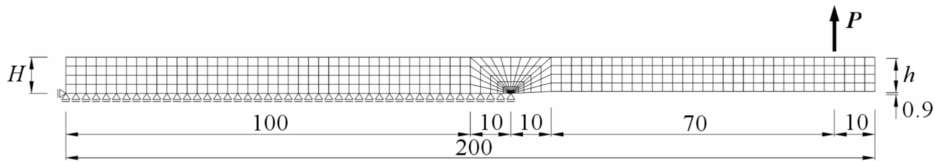


Fig. 4. Two-dimensional (2D) DCB element (dimensions in mm)

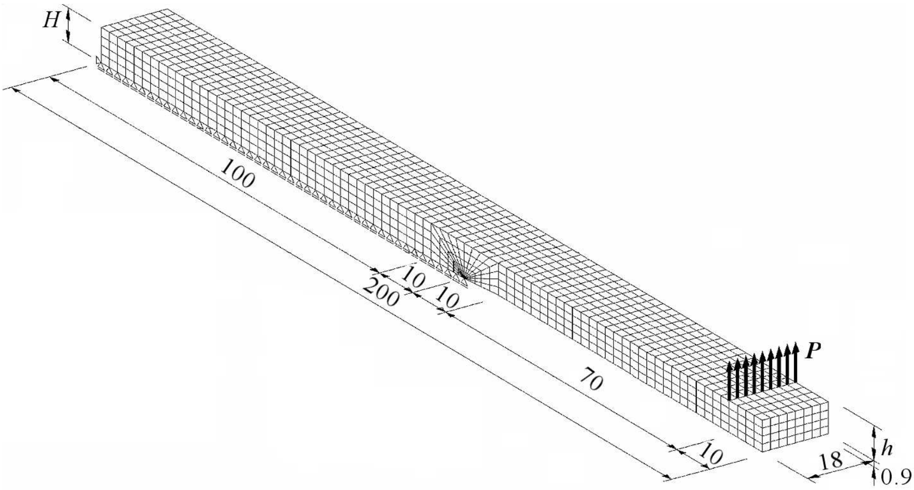


Fig. 5. Three-dimensional (3D) DCB element (dimensions in mm)

The virtual crack extension method was used to calculate the energy release rates directly on the basis of changes in the potential energy of the element. In the Adina Manual (Adina 1999), one reads that the virtual crack extension method evaluates the J-integral for a given body using the difference in the total potential energy between two configurations with slightly different cracks. The energy release rates, $G_{\mathrm{I}}$, were calculated on the basis of the value of the J-parameter adopted directly from the Adina program.

Studying the results of his previous research (Kossakowski, 2004), the author assumed that the critical value of the energy release rate for pinewood, $G_{\mathrm{I}c}$, was 228 J/m$^2$. In the analysis, the loads $P$ were considered to be the same for all the examined elements. The load values had to be calibrated so that the energy release rates, $G_{\mathrm{I}}$, were in the elastic range. They had to be smaller than the critical energy release rates, i.e. $G_{\mathrm{I}} < G_{\mathrm{I}c} = 228\,\mathrm{J/m^2}$. The loads $P$ were calibrated to obtain a constant value of $G_{\mathrm{I}} \approx 209\,\mathrm{J/m^2}$ for the transversal-isotropic material model, which is used in the Polish standards (PN-EN 338) as the basic material model of wood. Table 1 shows values of the loads $P$ for particular models.

## 3. Material models

In order to analyze the influence of different material models on the values of $G_{\mathrm{I}}$ for pinewood, the isotropic and anisotropic, i.e. transversal isotropic and orthotropic models, were considered.

First, the elastic constants were calculated for pinewood using the orthotropic material model. Three main directions were taken into account: longitudinal ($L$), tangential ($T$), and radial ($R$). The values of the elastic moduli, $E_L$, $E_T$, $E_R$, and shear moduli, $G_{LT}$, $G_{LR}$, $G_{TR}$, were determined in accordance with the Polish standards (PN-EN 380, PN-EN 384 and PN-EN 408), while Poisson's ratios, $\nu_{LT}$, $\nu_{LR}$, $\nu_{RT}$, were established on the basis of the statistical methods proposed by Bodig and Goodman (1973). The values of $\nu_{TL}$, $\nu_{RL}$, $\nu_{TR}$ were calculated from the following constants $E_L$, $E_T$, $E_R$, $G_{LT}$, $G_{LR}$, $G_{TR}$, $\nu_{LT}$, $\nu_{LR}$, $\nu_{RT}$, assuming the symmetry of the compliance matrix of wood. Table 2 presents the values of all the 12 elastic constants obtained for pinewood (Kossakowski, 2004).

**Table 2.** Elastic constants of pinewood

| Elastic constant | Value |
|---|---|
| $E_L$ | 6 919 MPa |
| $E_T$ | 271 MPa |
| $E_R$ | 450 MPa |
| $G_{LT}$ | 262 MPa |
| $G_{LR}$ | 354 MPa |
| $G_{TR}$ | 33.8 MPa |
| $\nu_{LT}$ | 0.387897 |
| $\nu_{LR}$ | 0.374817 |
| $\nu_{RT}$ | 0.462337 |
| $\nu_{TL}$ | 0.015187 |
| $\nu_{RL}$ | 0.024377 |
| $\nu_{TR}$ | 0.278327 |

Four material models were analyzed for all the numerical 2D and 3D elements:

- isotropic (ISO), described by 2 elastic constants: $E_1$ and $\nu_{12}$
- transversal-isotropic (TRANS), described by 5 elastic constants: $E_1$, $E_2$, $G_{12}$, $\nu_{12}$ and $\nu_{23}$

- orthotropic for the $TL$ orientation (TL), described by 9 elastic constants: $E_1$, $E_2$, $E_3$, $G_{12}$, $G_{13}$, $G_{23}$, $\nu_{12}$, $\nu_{13}$ and $\nu_{23}$
- orthotropic for the $RL$ orientation (RL), described by 9 elastic constants: $E_1$, $E_2$, $E_3$, $G_{12}$, $G_{13}$, $G_{23}$, $\nu_{12}$, $\nu_{13}$ and $\nu_{23}$.

For the isotropic and transversal-isotropic models, the elastic modulus $E_1$ was assumed to be equal to $E_L$. The other constants, i.e. elastic and shear moduli and Poisson's ratios were the mean values for the isotropic plane $TR$ on the basis of elastic constants presented in Table 1 prepared for the orthotropic model. For example, the elastic modulus $E_2$ for the transversal-isotropic model was equal to the mean value of moduli $E_T$ and $E_R$, i.e. $E_2 = (E_T + E_R)/2$.

In wooden structural elements, cracks usually propagate in the longitudinal direction ($L$), so two crack propagation systems, $TL$ and $RL$, were considered for the orthotropic material models. In this case, elastic constants were determined basing on the values presented in Table 1.

## 4. Results

The analysis shows that the energy release rates, $G_{\text{I}}$, are dependent on the material model, whether two- and three-dimensional DCB ones. The values of $G_{\text{I}}$ for all the considered material models are presented in Fig. 6.

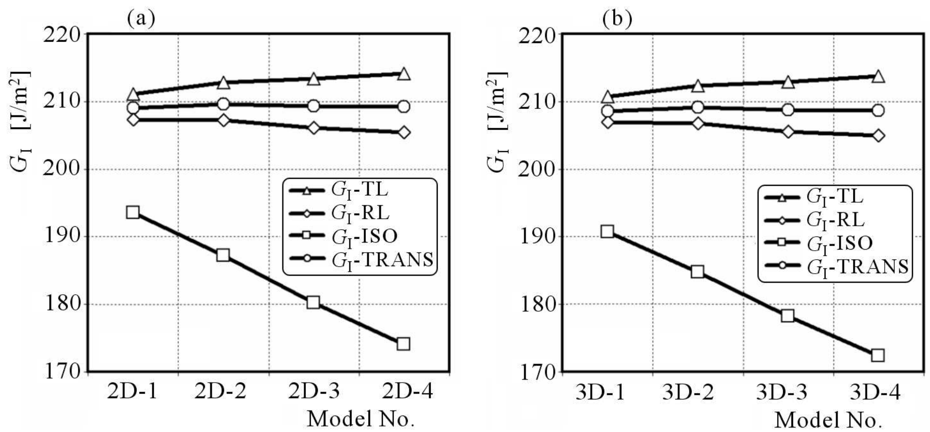


Fig. 6. Changes in $G_{\text{I}}$ for different material models; (a) 2D models; b) 3D models

As can be seen, there are several relationships between the energy release rates $G_{\text{I}}$, material models and geometry of elements.

Firstly, the values of $G_{\rm I}$ are the same for the orthotropic (TL and RL) as well as transversal-isotropic (TRANS) 2D and 3D elements. In the isotropic (ISO) 2D models, the values of $G_{\rm I}$ are slightly higher than for 3D elements, but the differences are small, i.e. 1-1.5%.

Another relationship is the influence of the element geometry, i.e. the ratio of the crack length $a$ (cantilever length) to the cantilever thickness $h$ on the values of $G_{\rm I}$. For the isotropic model, $G_{\rm I}$ decreases linearly along with the element thickness. In this case, the difference between the values of $G_{\rm I}$ is 9.6% for models 2D-1 and 2D-4, and 10.1% for models 3D-1 and 3D-4. The ratio $a/h$ is 22.22 and 9.88, respectively. A similar interdependence is observed in the case of an orthotropic element in the orientation $RL$, but the difference is smaller, 1% only. For an orthotropic element in the orientation $TL$, a reverse relationship was reported; the values of $G_{\rm I}$ increase with the element thickness, and the difference is small – 1.4%. Because the load $P$ was calibrated to the constant values of $G_{\rm I}$ for the transversal-isotropic material model, $G_{\rm I}$ is independent of the element geometry. For the isotropic material model, the energy release rates, $G_{\rm I}$, are affected by the specimen geometry, thus for the anisotropic material models there is slight influence of geometry on the energy release rates $G_{\rm I}$. It can be assumed that the energy release rates $G_{\rm I}$ are independent of geometry whenever anisotropy is taken into consideration.

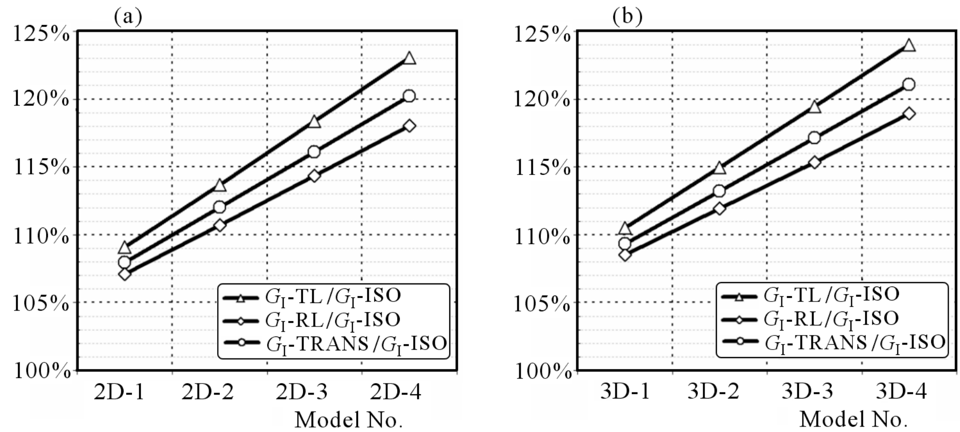


Fig. 7. Changes in the ratio of $G_{\rm I}$ determined for the anisotropic material models (TRANS, TL and RL) to $G_{\rm I}$ determined for the isotropic material model (ISO): (a) 2D models; (b) 3D models

It seems important to study the values of the energy release rates, $G_{\rm I}$, determined for the anisotropic models, as they are higher than those reported for the isotropic models (Figs. 6 and 7). The differences between the ratios of $G_{\rm I}$ determined for the anisotropic material models to $G_{\rm I}$ determined for the isotropic material models change linearly from 7.1-23.1% for 2D elements and 8.5-24.0% for 3D numerical elements (Fig. 7). Thus, the differences between the energy release rates, $G_{\rm I}$, determined for the anisotropic and isotropic material models increase if the $a/h$ ratio decreases. The information is very important as it can be used in practice. In the case of elements containing a relatively short crack in comparison to its thickness, it is essential to take anisotropy into account so as to properly determine fracture toughness. Assuming that the difference between $G_{\rm I}$ determined for the isotropic and anisotropic models is 5%, it is possible to estimate the corresponding $a/h$ ratio, thus $a/h = 25$. When $a/h > 25$, the difference between $G_{\rm I}$ determined for the isotropic and anisotropic models should be less than 5%. In such a case, it is possible to use the isotropic material model instead. For $a/h < 25$, the differences between $G_{\rm I}$ determined for the isotropic and anisotropic models are significant and higher than 5%. In order to calculate fracture toughness properly and accurately, material anisotropy should be taken into consideration. These relationships can be used for wood and other highly anisotropic materials, especially when high accuracy of results is required. This is important in the case of laminates, and some composites, when the scatter of elastic constants is small. As fracture toughness is dependent on the material model, it is necessary that, in calculations, the material anisotropy should be taken into consideration.

As can be seen, the values of $G_{\rm I}$ for the transversal-isotropic and orthotropic models are similar (Fig. 6). It can be assumed that in technical calculations it is possible to use the transversal-isotropic model described by 5 elastic constants: $E_1$, $E_2$, $G_{12}$, $\nu_{12}$ and $\nu_{23}$.

As mentioned above, it is possible to determine the critical values of the energy release rate, $G_{\rm Ic}$, by employing a numerical method and basing on the critical load, $P_c$. Then, the material fracture toughness can be established also numerically. The relationships described above can be applied in a fracture toughness analysis of pinewood, other species of wood and other highly orthotropic materials such as composites and laminates.

## 5. Conclusions

The following conclusions have been drawn basing on the results of the numerical analysis of the influence of anisotropy on the energy release rate, $G_{\rm I}$, for pinewood.

- The numerical analysis showed that the energy release rate $G_{\rm I}$ depends on the material model.
- Similar values of the energy release rates $G_{\rm I}$ are obtained for both anisotropic models, i.e. the orthotropic TL and RL and transversal-isotropic TRANS ones. They are higher than those reported for the isotropic models.
- It can be assumed that the values of the energy release rate, $G_{\rm I}$, are independent of the geometry of the anisotropic material models. However, for the isotropic model, $G_{\rm I}$ is dependent on the specimen geometry, i.e. the ratio of the crack length, $a$, to the cantilever thickness, $h$. The energy release rate, $G_{\rm I}$, for the isotropic model decreases when there is a fall in the $a/h$ ratio.
- Differences between the energy release rates $G_{\rm I}$ observed for the anisotropic and isotropic material models increase when the $a/h$ ratio decreases. If $a/h < 25$, the material anisotropy should be taken into consideration, otherwise fracture toughness cannot be calculated precisely.
- The values of $G_{\rm I}$ for the transversal-isotropic and orthotropic models are similar, thus for practical reasons, the calculations can be made using the transversal-isotropic model. Accordingly, the number of elastic constants required for describing the material is reduced to 5 only: $E_1$, $E_2$, $G_{12}$, $\nu_{12}$ and $\nu_{23}$.

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**Wpływ anizotropii na współczynnik uwalniania energii $G_\mathrm{I}$ dla materiałów wysokoortotropowych**

Streszczenie

W artykule przedstawiono wyniki analizy numerycznej dotyczącej współczynnika uwalniania energii $G_\mathrm{I}$ dla materiałów wysokoortotropowych takich jak kompozyty, laminaty czy drewno. Współczynnik $G_\mathrm{I}$ obliczano przy użyciu programu Adina v. 8.1 opartego na metodzie elementów skończonych (MES). Określając wpływ anizotropii na $G_\mathrm{I}$, przyjmowano różne modele materiałowe. Podczas analizy użyto dwuwymiarowych (2D) i trójwymiarowych (3D) modeli numerycznych próbek podwójnie wspornikowych (ang. *Double Cantilever Beam* – DCB) o różnych proporcjach długości pęknięcia do grubości elementu. Zauważono, że im te proporcje są mniejsze, tym większe są różnice pomiędzy współczynnikami $G_\mathrm{I}$ obliczanymi przy założeniu izotropowego i anizotropowych modeli materiałowych (transwersalnie izotropowych i ortotropowych). Dlatego też analiza pękania czy odporności na pękanie powinna być oparta na modelach transwersalnie izotropowych lub ortotropowych oraz powinna być uwzględniana anizotropia materiału.

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