

Thesis of the PhD. Dissertation

**Investigation into the Usability of the Strength Criteria
Applied to Wood and Wood Based Materials**

GARAB, József

University of West-Hungary

Sopron

2012

Thesis of the PhD. Dissertation
University of West-Hungary, Faculty of Wood Science
József Cziráki Doctoral School of Wood Sciences and Technologies
Leader: Dr. Dr. h.c. András Winkler professor

PhD program: Timber structures
Program leader: Dr. Ferenc Dívós CSc.

Discipline:
Material sciences and technologies

Supervisor: Dr. József Szalai CSc.

Symbols

$a_i, a_{ij}, a_{ijk}, a_{ijkl}, \dots a_{ijkl\dots q}$ – strength tensors on the rank of 1-, 2-, 3-, 4-, ... z and its' components in the coordinate system of the geometrical axes of the sample ($i, j, k, l, \dots q=1, 2, 3$),

$a_i, a_{ij}, a_{ijk}, a_{ijkl}, \dots a_{ijkl\dots q'}$ – previous tensors and its' components in the transformed coordinate system ($i', j', k', l', \dots q'=1, 2, 3$),

c – optional scalar,

CoV [%] – coefficient of variation,

I_1, I_2 – the first and the second stress invariant,

L, R, T – anatomical main directions of wood: longitudinal, radial, and tangential direction,

n – failure prediction number,

P – side pressure during the triaxial tests,

u – moisture content of wood,

x^i – geometrical axes of the sample ($i=1, 2, 3$),

$\beta_i^i, \beta_i^{i'}$ – transformation matrices,

ϑ – coordinate-transformation angle,

ρ – density of wood,

Σ Biax – all biaxial stress states,

Σ Triax – all triaxial stress states,

σ^{ij} – stress tensor and its components in the original coordinate system ($i, j=1, 2, 3$),

$\sigma^{i'j'}$ – stress tensor and its component in the transformed coordinate-system

($i', j'=1', 2', 3'$),

φ – coordinate-transformation angle which is equal to the grain angle,

ψ – coordinate-transformation angle which is equal to the growth ring angle.

1. Introduction

Basically, all the materials are anisotropic in the nature. The physical-mechanical properties of several materials used in the engineering practice can be modeled as isotropic material. However, various materials (e.g. composites, wood) have significant grain dependent properties. Thus applying anisotropic models is necessary. The load bearing capacity or strength is a basic property for all structural materials. The strength of a structural element is predicted by using anisotropic failure criteria. Numerous strength criteria were created during the development of mechanics, including several focused on anisotropic materials. However, three fundamental strength criteria can be applied in most general conditions. These are: the von Mises, the Tsai-Wu, and the Ashkenazi strength criteria. In our research, the usability of these failure theories was investigated.

2. Purpose of the research

Biaxial tests were carried out on spruce wood (*Picea abies*) at the TU Vienna, Institute for Mechanics of Materials and Structures by Prof. Dr. Josef Eberhardsteiner. One of the goals of this research was to determine the biaxial stress state on the samples at the failure. During our work, we processed the data regarding the failure theories. We got the experimental data from Prof. Dr. Eberhardsteiner through cooperation between the two institutes. After our evaluation, we evaluated the strength criteria in the biaxial stress state.

Moreover, doing experiments was also an aim of our research. Analogies of the biaxial experiments, triaxial tests were performed on spruce wood to investigate the failure theories in the triaxial stress state. Based on our evaluation, we were able to decide which strength criterion most accurately describes the failure behaviour of wood.

3. Theoretical Background

The strength criteria work only when the stress states are in the main anatomical directions of the wood.

Formulas of the anisotropic strength criteria are most often polynomial equations. The left side contains polynomials of the component of the stress tensor. The right side contains scalar. The general anisotropic strength criterion has the following form (Szalai 1994):

$$a_{ij}\sigma^{ij} + a_{ijkl}\sigma^{ij}\sigma^{kl} + a_{ijklmn}\sigma^{ij}\sigma^{kl}\sigma^{mn} + a_{ijklmnop}\sigma^{ij}\sigma^{kl}\sigma^{mn}\sigma^{op} + \dots \leq c, \quad (1)$$

$$i, j, k, l, m, n, o, p, \dots = 1, 2, 3$$

ahol,

σ^{ij} – components of the stress tensor,

$a_{ij}, a_{ijkl}, a_{ijklmnop}, \dots$ – strength tensors of 2,4,6,8... rank,

c – optional scalar.

On plastic materials with equal tensile and compressive strength, von Mises (1928) applied a second order polynomial equation:

$$a_{ijkl}\sigma^{ij}\sigma^{kl} \leq 1 \quad i, j, k, l = L, R, T \quad (2)$$

Tsai and Wu (1971) applied the first two parts of the general strength criterion (1). They assumed that their theory works not only for plastic but also for brittle materials. The Tsai-Wu strength criterion has the following form:

$$a_{ij}\sigma^{ij} + a_{ijkl}\sigma^{ij}\sigma^{kl} \leq 1 \quad i, j, k, l = L, R, T \quad (3)$$

Ashkenazi (1966) defined a strength tensor of the fourth rank. The structure of the tensor is similar to the compliance tensor. Ashkenazi applied the second and the fourth part of the general strength criterion (1).

* Einstein's convention was used herein and hereinafter. E.g.: $a_{\dot{x}}^{\dot{x}} = a_1 x^1 + a_2 x^2 + a_3 x^3$.

After transformation (Szalai 1994), the following terms are applicable:

$$\frac{a_{ijkl}\sigma^{ij}\sigma^{kl}}{\sqrt{|I_1^2 - I_2|}} \leq 1 \quad i, j, k, l = L, R, T \quad (4)$$

I_1, I_2 – the first and the second stress invariant.

All of the three theories work in a similar method. If the inequality is valid, the material will not fracture. If there is equality, the material is at the border condition of failure.

After theoretical investigations, only the Ashkenazi strength criterion works for anisotropic materials (e.g. Szalai 1994, 2008). The von Mises and the Tsai-Wu strength criterion state the same thing: the orientation of the stress tensor plays no role, because the fracture of wood occurs achieving the same conjugated work. However, it is an obvious statement: if a longitudinal and a tangential oriented wood bar (but with similar geometry) is in tension, the conjugated energy accumulated until the fracture is significantly different. Among the three strength criteria, only the Ashkenazi states this.

If (2), (3), and (4) are in equality and the right side of the equation is changed for n (which we determined as the failure prediction number) the strength criteria can be evaluated by experiments. If n equals 1, the strength criterion will describe the failure. It is an ideal case. If n is less than 1, the strength criterion will not predict any failure but the material will be damaged. If n is more than 1, the theory will predict failure but the material remains intact. The closer the failure prediction number is to 1 the more accurately the theory describes the failure.

4. The subject of the research – Materials and methods

The von Mises, the Tsai-Wu, and the Ashkenazi strength criteria were validated by the experimental results of the biaxial and the triaxial tests. The strength criteria can be used only in the main anatomical directions of wood. Therefore the experimental stress states were transformed. The failure prediction numbers for all stress states were determined by the three theories. The strength criteria could be evaluated with

the failure prediction numbers because the failure prediction number correlates to the failure.

4.1. Biaxial experiments

Eberhardsteiner (2002) measured 423 pieces of cross-shaped spruce specimens under biaxial loads. Specimens were cut along the *LR* (longitudinal-radial) main anatomical plane from the board (Figure 2). The estimated cross section was 140 x 140 mm. Linear u and v displacements were applied along the x and y axes, according to the axes of the biaxial testing machine. The reaction was a planar stress state with σ^{xx} , σ^{yy} stress components. The grain angle (φ) was different. $\varphi = 0^\circ$ (*L*), $7,5^\circ$, 15° , 30° , and 45° . The tests were performed at 20°C and at 65% RH (relative humidity). The average moisture content of the samples was 12%. After biaxial load test, 423 pieces of biaxial stress states were available at the moment of the failure.

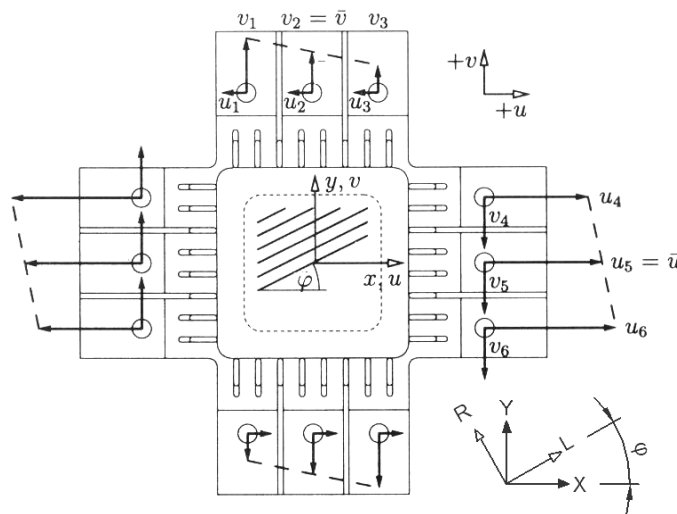


Figure 1: Specimen for biaxial test. Sample shape, load directions, and the coordinate system are shown.

4.2. Triaxial experiments

We performed triaxial compression experiments on spruce wood at our institute (Garab et al. 2012). The testing machine operated with hydraulic side pressure to prepare cylindrical samples from spruce wood. The dimensions of the specimen were the following: the diameter was 50 mm and the length was 100 mm (Figure 2).

The mean of the density was 0.39 g/cm^3 ; the mean of the moisture content was 13.9%. Three different orientations were cut from the lumber $\varphi = 0^\circ (L)$, 22° , and 45° . The grain angle and the growth ring angle were measured on the samples before turning. The side pressures were 5, 10 and 15 bar. Each side pressure-orientation combination was tested 6 times and 54 samples were tested. During the experiments, 4 pieces of samples were broken due to only the side pressure. Hence, 50 triaxial stress states resulted in failure.

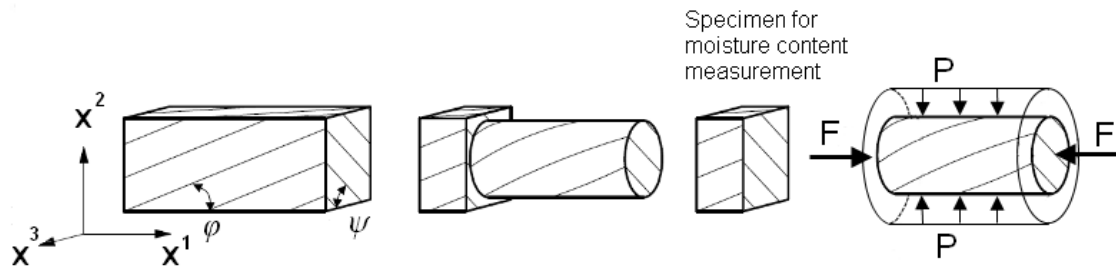


Figure 2: Sample preparation, orientation and the applied loads. The grain angle (φ) was $0^\circ(L)$, 22° , and 45° . The growth ring angle (ψ) varied from $0^\circ(T)$ - $90^\circ(R)$. The direction of the axial load (F) was along the x^1 axis. The side pressure (P) arisen at the x^2 - x^3 plane.

4.3. Transformation of the Multi-axial Stress States into the Anatomical Coordinate System of Wood

The strength criteria work only when the stress states are in the main anatomical directions of the wood. However, the stress states were given in the coordinate system of the axes of the board or the axes of the testing machine. Thus, the stress states from the experiments had to be transformed.

Szalai (1994) presented a coordinate transformation method for transforming the stress states in the axes of the board into the anatomical coordinate system of wood. The transformation operates by three rotation angles (ϑ , φ , ψ). Fortunately, the raw material (spruce boards) did not allow us to cut general oriented samples. Therefore, it was not necessary to apply the general transformation method. The long direction of the board was equal to the grain direction (L). In this case, the φ rotation angle was equal to the grain angle; the ψ rotation angle was equal to the growth ring angle (Figure 3).

The transformation matrix for transforming the stress states is the following from Szalai (1994):

$$\beta_i^{i'} = \begin{bmatrix} \cos \varphi & \sin \varphi \sin \psi & \sin \varphi \cos \psi \\ \sin \varphi \cos \vartheta & -\cos \varphi \sin \psi & -\cos \varphi \cos \psi \\ 0 & \cos \psi & -\sin \psi \end{bmatrix}. \quad (5)$$

The stress states in the axes of the board were transformed into the anatomical coordinate system of wood by applying the tensor theory and the components of the transformation matrix (5):

$$\sigma^{i'j'} = \sigma^{ij} \beta_i^{i'} \beta_j^{j'}. \quad i, j, k= 1,2,3 \text{ and } i', j', k' = L, R, T \quad (6)$$

$\beta_i^{i'}$ és $\beta_j^{j'}$ – components of the transformation matrix (5),

$\sigma^{i'j'}$ – stress tensor and its components in the coordinate system of wood (L, R, T),

σ^{ij} – stress tensor and its components in the axes of the board (x^1, x^2, x^3).

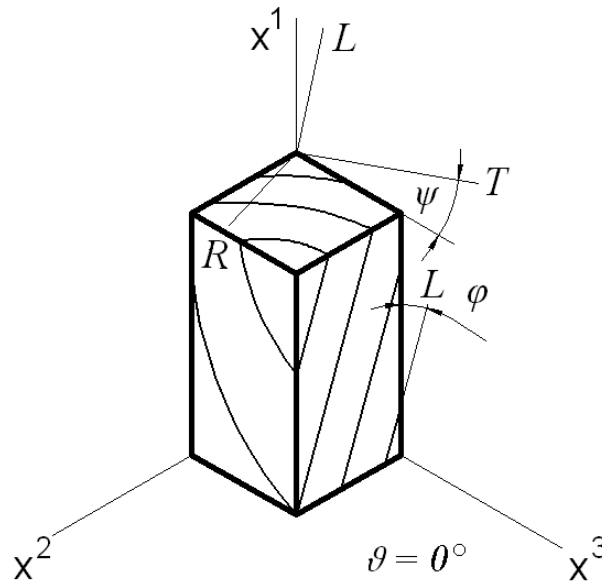


Figure 3: Rotation angles (φ , ϑ and ψ) on the specimen (board) before turning.

4.4. Evaluation the Strength Criteria

If (2), (3), and (4) are in equality and the right side of the equation is substituted for n (which we determined previously as the **failure prediction number**), the size of n correlates to the state of the material (intact or broken). If n equals 1, the strength criterion will describe the failure. It is an ideal case. If n is less than 1, the strength criterion will not predict any failure but the material will be damaged. If n is more than 1,

the theory will predict failure but the material remains intact. The closer the failure prediction number is to 1, the more accurately the theory describes the failure. Therefore the failure prediction number (n) correlates to the conformity of the failure theory.

Performing a large number of tests is obligatory due to the deviation of the wood properties and the circumstances of the experiments. Consequently, the large deviation influences the mean of the failure prediction numbers when only a few tests were carried out. This uncertainty can be decreased by doing a large number of tests. Hence, the determined failure prediction numbers can be evaluated by statistical methods. Thus, the conformity of the strength criteria can be evaluated by the mean, the variance and other statistical parameters.

The failure prediction numbers can be determined after the strength criteria as follows:

von Mises strength criterion:

$$n_{\text{von Mises}} = a_{ijkl} \sigma^{ij} \sigma^{kl}, \quad i, j, k, l = L, R, T \quad (7)$$

Tsai-Wu strength criterion:

$$n_{\text{Tsai-Wu}} = a_{ij} \sigma^{ij} + a_{ijkl} \sigma^{ij} \sigma^{kl}, \quad i, j, k, l = L, R, T \quad (8)$$

Ashkenazi strength criterion:

$$n_{\text{Ashkenazi}} = \frac{a_{ijkl} \sigma^{ij} \sigma^{kl}}{\sqrt{I_1^2 - I_2}}, \quad i, j, k, l = L, R, T \quad (9)$$

where,

$n_{\text{von Mises}}$, $n_{\text{Tsai-Wu}}$, $n_{\text{Ashkenazi}}$ – failure prediction numbers according to the strength criteria,

a_{ij} , a_{ijkl} – components of the strength tensors according to the strength criteria,

σ^{ij} – components of the stress tensor,

I_1 and I_2 – the first and the second stress invariants.

5. Results and Discussion

Failure theories were applied to the transformed stress states which were separated according to the signs of the normal stresses. Failure prediction numbers were deter-

mined for all experimental stress states according to (7-9), in subchapter 4.4. The statistical parameters are shown in Table 1-3.

Table 1: Statistical evaluation of the failure prediction numbers (n) determined by the von Mises strength criterion. Results are presented for the four groups of the biaxial stress states, for all of the biaxial stress states, and for the triaxial stress states.

	$\sigma^{LL+} \sigma^{RR+}$	$\sigma^{LL+} \sigma^{RR-}$	$\sigma^{LL-} \sigma^{RR-}$	$\sigma^{LL-} \sigma^{RR+}$	Σ Biax	Σ Triax
Sample size [pcs]:	145	103	113	62	423	50
Minimum [-]:	0.16	0.00	0.00	0.40	0.00	0.00
Maximum [-]:	4.09	1.96	5.78	3.13	5.78	3.30
Median [-]:	0.74	0.00	0.00	1.22	0.56	0.00
Modus [-]:	0.75	0.00	0.00	1.25	0.00	0.00
Mean [-]:	0.99	0.27	0.48	1.29	0.73	0.42
SD ² [-]:	0.51	0.18	1.08	0.34	0.69	0.50
SD [-]:	0.72	0.43	1.04	0.58	0.83	0.71
CoV [%]:	72.1	155.1	215.5	44.8	114.5	170.2
Slope [-]:	2.06	1.68	3.60	0.92	2.31	2.13
Kurtiosis [-]:	4.67	2.36	14.18	1.04	8.54	5.02

Table 2: Statistical evaluation of the failure prediction numbers (n) determined by the Tsai-Wu strength criterion. Results are presented for the four groups of the biaxial stress states, for all of the biaxial stress states, and for the triaxial stress states.

	$\sigma^{LL+} \sigma^{RR+}$	$\sigma^{LL+} \sigma^{RR-}$	$\sigma^{LL-} \sigma^{RR-}$	$\sigma^{LL-} \sigma^{RR+}$	Σ Biax	Σ Triax
Sample size [pcs]:	145	103	113	62	423	50
Minimum [-]:	0.02	0.00	0.00	0.30	0.00	0.00
Maximum [-]:	5.94	1.73	4.27	3.59	5.94	1.57
Median [-]:	0.70	0.19	0.15	1.30	0.60	0.00
Modus [-]:	0.40	0.00	0.00	1.25	0.00	0.00
Mean [-]:	1.14	0.38	0.47	1.38	0.81	0.11
SD ² [-]:	1.23	0.20	0.60	0.50	0.86	0.09
SD [-]:	1.11	0.44	0.77	0.71	0.93	0.30
CoV [%]:	97.6	115.3	165.5	51.5	114.4	259.3
Slope [-]:	2.14	0.85	2.92	0.97	2.18	3.45
Kurtiosis [-]:	4.75	-0.19	10.28	1.03	6.24	12.94

Table 3: Statistical evaluation of the failure prediction numbers (n) determined by the von Mises strength criterion. Results are presented for the four groups of the biaxial stress states, for all of the biaxial stress states, and for the triaxial stress states.

	$\sigma^{LL+} \sigma^{RR+}$	$\sigma^{LL+} \sigma^{RR-}$	$\sigma^{LL-} \sigma^{RR-}$	$\sigma^{LL-} \sigma^{RR+}$	Σ Biax	Σ Triax
Sample size [pcs]:	145	103	113	62	423	50
Minimum [-]:	0.40	0.46	0.56	0.48	0.40	0.67
Maximum [-]:	1.87	1.42	2.33	1.03	2.33	1.57
Median [-]:	0.80	0.70	0.80	0.70	0.77	1.04
Modus [-]:	0.72	0.65	0.70	0.66	0.76	1.03
Mean [-]:	0.87	0.75	0.88	0.71	0.82	1.05
SD ² [-]:	0.06	0.03	0.09	0.02	0.06	0.03
SD [-]:	0.25	0.18	0.31	0.14	0.25	0.17
CoV [%]:	28.2	24.4	35.0	20.1	30.3	16.1
Slope [-]:	1.48	0.85	2.86	0.29	2.32	0.85
Kurtiosis [-]:	2.86	0.77	9.68	-0.79	8.96	1.82

The differences among the failure prediction numbers determined by the failure theories can be seen easily in the box plots diagram (Figure 4).

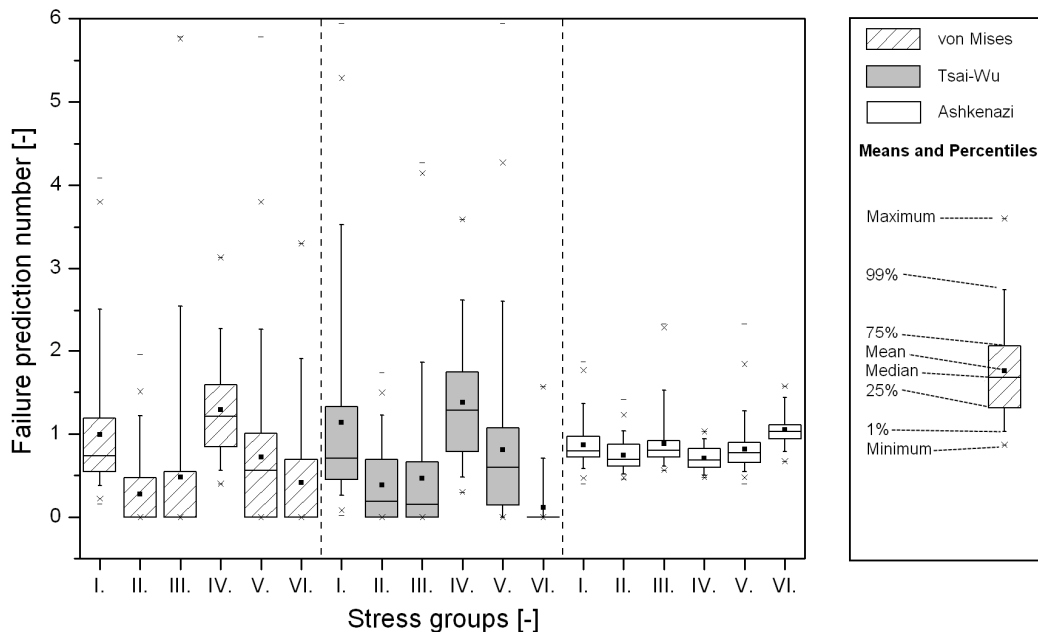


Figure 4: Box plots of the failure prediction numbers according to the von Mises, the Tsai-Wu, and the Ashkenazi strength criteria. Stress groups are the following: I – $\sigma^{LL+} \sigma^{RR+}$; II – $\sigma^{LL+} \sigma^{RR-}$; III – $\sigma^{LL-} \sigma^{RR-}$; IV – $\sigma^{LL-} \sigma^{RR+}$; V – Σ Biax; VI – Σ Triax.

The box plots represent the mean, the median, the percentiles (1, 25, 75, 99%), the minimum, and as well the maximum values of the failure prediction numbers in the given stress group. It is remarkable that those significant amounts of failure prediction numbers with negative signs were determined by the von Mises and the Tsai-Wu strength criteria. This can be explained by the fact that the graphical demonstration of the biaxial stress point is absolutely out of the strength surface. The stress point according to the normal stresses is out of the projection of the strength surface onto the base surface. This phenomenon is similar in a triaxial stress state but a graphical explanation is difficult to make due to the higher dimensions.

Hence, the failure prediction numbers with negative signs mean that the given failure theory cannot accurately describe the failure. Therefore, failure prediction numbers with negative signs were evaluated as zero. Zero for a prediction number means absolutely no fitting of the criterion. Failure prediction numbers according to the Ashkenazi strength criterion were never zero.

Moreover, failure prediction numbers according to the von Mises and the Tsai Wu strength criteria do not represent the accurate failure of the wood. Although there are several stress groups where the failure prediction numbers are near 1 but the variation is not similar to the variance of the mechanical properties of wood. However, failure prediction numbers according to the Ashkenazi strength criterion are near 1 and the deviation is similar to the mechanical properties of wood.

6. Conclusion

According to the results, among the von Mises, the Tsai-Wu, and the Ashkenazi failure theories, only the Ashkenazi strength criterion accurately describes the failure of the wood. Based on the theoretical investigations (Szalai 1994, 2008) and the experimental studies, the reasons for suitability of the Ashkenazi strength criterion are the following:

- The Ashkenazi strength criterion is the most suitable to estimate the strength in a uniaxial stress state. (In several circumstances the difference among the three criteria is not relevant.)

- The von Mises and the Tsai-Wu strength criteria are theoretically not sufficient, because the theories state that failure occurs at the same energy level at every orientation. However this statement is contradicted by the practical observations.
- Significant amount of failure prediction numbers were calculated with negative signs for the von Mises and the Tsai-Wu strength criteria. It means that the failure theory cannot accurately describe the failure of wood.
- Failure prediction numbers determined by only the Ashkenazi strength criterion were near 1 in all stress groups. Moreover, the variance of the failure prediction numbers was similar to the variance of the mechanical properties of the wood.

7. Theses

1. Thesis

I prepared a method to compare strength criteria for wood based on experimental results. I introduced the failure prediction number (n), which compares the experimental stress state (resulted at the failure) to the theoretical stress state predicted by the strength criteria.

The failure prediction number can be applied to linear, biaxial, and triaxial stress states.

If $n < 1$,

the strength criterion predicts no failure but the material is damaged,

if $n = 1$,

the strength criterion describes the failure,

if $n > 1$,

the strength criterion predicts failure but the material remains intact.

2. Thesis

I deduced the relations of the determination methods of the failure prediction numbers according to the von Mises, the Tsai-Wu, and the Ashkenazi strength criterion based on experiments.

The determination of the failure prediction numbers according to the strength criteria is the following:

von Mises strength criterion:

$$n_{von\ Mises} = a_{ijkl} \sigma^{ij} \sigma^{kl}, \quad i, j, k, l = L, R, T$$

Tsai-Wu strength criterion:

$$n_{Tsai-Wu} = a_{ij} \sigma^{ij} + a_{ijkl} \sigma^{ij} \sigma^{kl}, \quad i, j, k, l = L, R, T$$

Ashkenazi strength criterion:

$$n_{Ashkenazi} = \frac{a_{ijkl} \sigma^{ij} \sigma^{kl}}{\sqrt{I_1^2 - I_2}}, \quad i, j, k, l = L, R, T$$

where,

$n_{von\ Mises}$, $n_{Tsai-Wu}$, $n_{Ashkenazi}$ – failure prediction number according to the strength criteria,

a_{ij} , a_{ijkl} – components of the strength tensor according to the strength criteria,

σ^{ij} – components of the stress tensor,

I_1 and I_2 – the first and the second stress invariants.

3. Thesis

I presented the relations to transform the stress states on given anatomical main planes into the main anatomical directions of wood. Moreover, I introduced the transformation method of triaxial stress states when the longitudinal (L) direction is obvious in the board.

4. Thesis

I determined the failure prediction numbers according to the three fundamental strength criteria in the biaxial stress state. I did the evaluation for the comparison of the strength criteria. The results are presented in the following table according to the stress groups separated by the sign of the normal stresses:

Table 4: Statistical evaluation of the failure prediction numbers (n) according to the von Mises, the Tsai-Wu, and the Ashkenazi strength criteria in the biaxial stress state. Results are presented in the stress groups organized by the sign of the normal stresses.

Stress states		$n_{von\ Mises}$		$n_{Tsai-Wu}$		$n_{Ashkenazi}$	
Stress groups	Sample size [pcs]	Mean [-]	CoV [%]	Mean [-]	CoV [%]	Mean [-]	CoV [%]
$\sigma^{LL+} \sigma^{RR+}$	145	0.99	72.1	1.14	97.6	0.87	28.2
$\sigma^{LL+} \sigma^{RR-}$	103	0.27	155.1	0.38	115.3	0.75	24.4
$\sigma^{LL-} \sigma^{RR-}$	113	0.48	215.5	0.47	165.5	0.88	35.0
$\sigma^{LL-} \sigma^{RR+}$	62	1.29	44.8	1.38	51.5	0.71	20.1
All biaxial stress states	423	0.73	114.5	0.81	114.4	0.82	30.3

5. Thesis

Based on the statistical evaluation of the biaxial investigations, only the Ashkenazi strength criterion can accurately describe the failure of the spruce wood in the biaxial stress state.

6. Thesis

I determined the triaxial compression strength of the spruce wood by my experiments. Using the results, I determined the failure prediction numbers according to the three strength criteria in the triaxial stress state. The results of the evaluation are summarized in the following table:

Table 5: Statistical evaluation of the failure prediction numbers (n) according to the von Mises, the Tsai-Wu, and the Ashkenazi strength criteria in the triaxial stress state.

	$n_{von\ Mises}$	$n_{Tsai-Wu}$	$n_{Ashkenazi}$
Sample size [pcs]	50	50	50
Mean[-]	0.42	0.11	1.05
CoV [%]	170.2	259.3	16.1

7. Thesis

Corresponding to the failure prediction numbers based on the new experiments, only the Ashkenazi strength criterion can accurately describe the strength of wood in the triaxial stress state.

Main references

1. Ashkenazi, E.K., 1966: *Protschnost' anisotropnüh drevesnüh i sintetitscheskih materialov* [English title: *Strength of Anisotropic Wood and Synthetic Materials*]. Isdaniia Lesnaya Promishlennost. Moscow, 223 pp.
2. de Boer, R., 1982: *Vektor- und Tensorrechnung für Ingenieure*. Springer-Verlag, Berlin-Heidelberg-New York, 260 pp. (in German)
3. Eberhardsteiner, J., 2002: *Mechanisches Verhalten von Fichtenholz – Experimentelle Bestimmung der biaxialen Festigkeitseigenschaften*. Springer-Verlag. Wien-New York, 174 pp. (in German)
4. Garab, J., Reihnsner, R., Eberhardsteiner, J., 2012: Mechanical behaviour of spruce under triaxial compression, *Wood Research*, in press
5. Szalai, J., 1994: *A faanyag anizotrop rugalmasságtana. I. rész. A mechanikai tulajdonságok anizotrópiája* [English title: *Anisotropic strength and elasticity of wood and wood based composites*]. Hillebrand nyomda. Sopron, 398 pp. (in Hungarian)
6. Szalai, J., 2008: Festigkeitstheorien von anisotropen Stoffen mit sprödem Bruchverhalten, *Acta Sylvatica et Lignaria Hungarica* 5:61-80 (in German)
7. Tsai, S.W., Wu, E.M., 1971: A general theory of strength for anisotropic material, *Journal of Composite Materials* (5): 58-80
8. von Mises, R., 1928: Mechanik der plastischen Formänderung von Kristallen, *Zeitschrift für Angewandte Mathematik und Mechanik* 8 :161-185. (in German)

Publications in the topic of the thesis

Papers in peer-reviewed scientific journals in foreign language

1. Garab, J., Reihnsner, R., Eberhardsteiner, J., 2012: Mechanical behaviour of spruce under triaxial compression, *Wood Research*, in press
2. Garab, J., Szalai, J., 2010: Comparison of anisotropic strength criteria in the biaxial stress state, *Drewno Wood* 53 (1):51-66

Papers in peer-reviewed scientific journals in Hungarian

3. Garab, J., Szalai, J., 2012: Tönkrementeli elméletek alkalmazhatóságának vizsgálata térbeli feszültségállapot esetén (English title: Investigation the usability of strength criteria in the triaxial stress state), *Faipar*, in press
4. Garab, J., Polgár, R., Szalai, J., 2011: Térbeli feszültségállapotok átszámítása a faanyag anatómiai főirányainak rendszerébe (English title: Transformation of triaxial stress states into the anatomical coordinate system of wood), *Faipar* 59(1):12-17
5. Garab, J., Szalai, J., 2010: Tönkrementeli elméletek alkalmazhatóságának vizsgálata síkbeli feszültségállapot esetén, (English title: Examination of strength criteria in complex stress state) *Faipar* 58(3-4):5-11

Oral presentations, Posters

6. Garab, J., 2010: A faanyag és faalapú anyagok anizotrop tönkrementeli elméleteinek vizsgálata alkalmazhatóságuk szempontjából (English title: Investigation the usability of strength criteria applied to wood and wood based materials). *PhD. Student Conference*, Sopron, Hungary, 4th June 2010 (oral presentation and proceedings)
7. Szalai, J., Garab, J., 2007: Anizotrop tönkrementeli elméletek összehasonlítása faanyagon végzett kísérletek eredményei alapján (English title: Comparison anisotropic strength criteria based on experiments). *X. Magyar Mechanikai Konferencia*, Miskolc, Magyarország, 2007. augusztus 27. (szóbeli előadás és konferenciakiadvány)

Publications in other topics

Papers in peer-reviewed scientific journals in foreign language

8. Garab, J., Keunecke, D., Hering, S., Szalai, J., Niemz, P., 2010: Measurement of standard and off-axis elastic moduli and Poisson's ratios of spruce and yew wood in the transverse plane, *Wood Science and Technology* 44(3): 451-464
9. Garab, J., Tóth, Á., Szalai, J., Bejő, L., Dívós, F., 2010: Evaluating glued laminated beams using a nondestructive testing technique, *Transactions of Famena* 34(4):33-46

Oral presentations, posters

10. Karácsonyi, Zs., Garab, J., 2011: Optical systems application to determine deformations – orientation method application to determine shear modulus - *The 17th International Nondestructive Testing and Evaluation of Wood Symposium*, Sopron, Hungary (oral presentation and proceedings)
11. Tolvaj, L., Kánnár, A., Barta, E., Karácsonyi, Zs., Garab, J., 2010: A légköri széndioxid koncentráció növekedésének hatása a faanyag fizikai és mechanikai tulajdonságaira (English title: Influence of the increased carbon-dioxide emission on the physical-mechanical properties of wood). *The wood as the material of the sustainable development Conference*, 10th September 2010, Sopron, Hungary (oral presentation)
12. Keunecke, D., Garab, J., Hering, S., Szalai, J., Niemz, P., 2010: Elastic parameters of softwoods loaded in transverse compression at varying growth ring angles. *The 6th International Symposium Wood Structure and Properties '10*, 6-9th September 2010, Podbanské, Slovakia (oral presentation and proceedings)
13. Garab, J., Karácsonyi, Zs., Kánnár, A., 2010: Influence of the carbon dioxide emissions on selected mechanical properties of wood. *YSESM*, 7-10th July, Trieste, Italy (poster presentation)
14. Kánnár, A., Karácsonyi, Zs., Garab, J., 2010: Influence of climate change on mechanical properties of wood. *The 4th Conference on Hardwood Research and Utilisation of Europe*, 17-18 May 2010, Sopron, Hungary (oral presentation and proceedings)

15. Karácsonyi, Zs., Garab, J., 2010: Determination the shear modulus of European ash (*Fraxinus excelsior L.*). *The 4th Conference on Hardwood Research and Utilisation of Europe*, 17-18 May 2010, Sopron, Hungary (poster presentation)
16. Garab, J., Karácsonyi, Zs., 2010: Engineering strength of European ash (*Fraxinus excelsior L.*), *The 4th Conference on Hardwood Research and Utilisation of Europe*, 17-18 May 2010, Sopron, Hungary (poster presentation)
17. Divós, F., Szalai, J., Garab, J., Tóth, Á., 2009: Glued timber structures evaluation. *The 16th International Nondestructive Testing and Evaluation of Wood Symposium*, 11-13th October 2009, Beijing, China (oral presentation and proceedings)
18. Divós, F., Szalai, J., Garab, J., Tóth, Á., 2009: Glulam beam evaluation based NDT technologies. *26th Danubia-Adria Symposium on Advances in Experimental Mechanics*, 23-29th September 2009, Leoben, Austria (poster presentation)
19. Garab, J., Keunecke, D., Niemz, P., 2009: Einfluss der Belastungsrichtung auf die elasto-mechanischen Eigenschaften von Fichte und Eibe in der RT-Ebene. *3. Kolloquium "Aktuelle Fragen der Holzforschung"*, 14th September 2009, Zurich, Switzerland (oral presentation) [in German]
20. Garab, J., 2008: Examination of the suitability of anisotropy deterioration theories based on experimental data. *International Student Scientific Conference*, 30th May 2008, Brasov, Rumania (oral presentation)

Other publications

21. Garab, J., 2008: *Élőfák mechanikai vizsgálata*. (English title: Investigation of the mechanical properties of the living trees) Research report. Magyar Faápolók Köre. [In Hungarian]
22. Tolvaj, L., Barta, E., Kánnár, A., Karácsonyi, Zs., Garab, J., 2011: A légköri szén-dioxid hatása a faanyag tulajdonságaira (English title: Influence of the carbon-dyoxid in the climate on the properties of wood), *Magyar Asztalos és Faipar* 21(9):76-78 [In Hungarian]