STABILITY OF WOOD COLUMNS LOADED IN BUCKLING.
PART 4. INFLUENCE OF MOISTURE CONTENT

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ABSTRACT

We carried out experiments with the influence of moisture content on critical stress for spruce columns. The issue was studied over the whole buckling range. We have derived functions $\sigma_{cr}(m)$ fitting the existing relations in the ranges of short, medium and long columns and determined the correction coefficients for conversion of the critical stress from the moisture content m_1 to moisture content m_2.

KEY WORDS: buckling, short, medium and long columns, spruce wood, moisture content

INTRODUCTION

In our previous works we studied the influence of several factors (slenderness ratio, way of end fastening, cross-section shape, load eccentricity, initial deflection, etc.) on stability of wood columns loaded in buckling (Kúdela 2002, Kúdela and Slaninka 2002, 2004, 2005).

However, in the case of wood, it is also necessary to consider additional factors (wood species, anatomic direction, density, internal stress, moisture content, defects in wood structure, etc.). All these factors can significantly influence the stability of a column loaded in buckling.

One of the most important factors is wood moisture content. Most of data on influence of moisture content has been provided for the range of short columns, i.e. for case of classic compression. As it follows from Leontiev (1960), Požgaj (1977), Gerhards (1982), Kúdela (1990, 1997) and some other authors, the compression strength limit parallel to grain, together with other stress characteristics (proportional limit, modulus of elasticity) are significantly decreasing with increasing moisture content – in the bound water range. The most conspicuous change to strength depending on change in moisture content was just observed in compression parallel to grain.

However, there only exists a small piece of information on moisture content influence on buckling strength, and there is a lack of coherence in this information. According to earlier-dated works by Roš and Brunner (Kollmann and Côté 1968), there is no significant influence of moisture content on the critical stress value when dealing with long columns. But these authors agreed that in the range of medium columns, buckling resistance significantly decreases with increasing moisture content and that this change is even more evident in case of short columns.

Also Tetmayer (Kollmann and Côté 1968) suggested that there is no important influence of moisture content on buckling strength. On the other hand, Fisher and Kühn (Dutko et al. 1976)

carried out extensive experiments aimed at experimental determination of buckling strength for columns from different wood species, with slenderness ratio λ ranging from 18.4 to 140, and moisture content values 0, 6, 12 and 18 %. The tests unambiguously confirmed the significant influence of moisture content on buckling strength. Požgaj et al. (1993) observed changes in critical stress depending on moisture content in the range of long columns. These authors also point out a change in slenderness ratio limit value $λ_L$ between the areas of long and medium long columns with the change in moisture content.

Kúdela and Slaninka (1999) carried out experiments with influence of moisture content at two moisture levels: m_1 = 9 % and m_2 > FSP. They showed that the critical stress was decreasing with increasing moisture content over the whole buckling range. The moisture influence was getting more pronounced with decreasing slenderness ratio. The authors also observed that with increasing moisture content, the medium columns expanded to the area of long columns.

Madsen (1992) points out differences in behaviour of wood columns in dependence on moisture content between eccentric compression and eccentric tension. In the case of eccentric compression were observed more conspicuous changes compared to eccentric tension.

However, none of the cited references contains functions expressing the dependence of $σ_{cr}$ on moisture content in the area of medium and long columns.

The goal of this paper has been set to verify experimentally the influence of moisture content on critical stress over the whole buckling range, to find out functions fitting the dependence $σ_{cr}(m)$ for the area of short, medium and long columns and to determine correction moisture coefficients for conversion of the critical stress values from moisture content m_1 to moisture content m_2.

MATERIAL AND METHODS

We have designed the experiment on the background of the results of our preceding research (Kúdela and Slaninka 1999). Our aim was to collect quantitative data about behaviour of wood columns loaded in buckling under variable moisture conditions. We prepared three series of spruce wood (*Picea abies* L., Karst) test specimens – representing short, medium and long columns. Each series was divided into seven sub-sets corresponding to seven values of moisture content in wood (0, 6, 12, 18, 24, 30 % and m > cell wall saturation limit – SL).

In the case of short columns, each moisture content value was provided with 15 specimens, 20 × 20 × 30 mm in size. In the case of medium and long columns, each of the sub-sets corresponding to the individual moisture values consisted of at least 12 specimens. Medium columns were represented by specimens with dimensions of 20 × 30 × 300 mm, long columns by specimens with dimensions of 15 × 25 × 600 mm and 20 × 30 × 800 mm.

Zero moisture content was reached by drying at a temperature of 103 ± 2 °C. To reach the moisture content values of 6 and 12 %, the specimens were deposed in air-conditioning boxes. The moisture content values 18 and 24 % were obtained by exposing the specimens over saturated solutions of KCl and K_2SO_4. The moisture content above the fibre saturation point was a result of specimens wetting in water.

One half of the specimens (medium and long columns) from each set acclimated to the required moisture content were tested under pinned ending, the remaining were tested with both ends fixed. The critical stress was calculated according to the equation

$$σ_{cr} = \frac{F_{cr}}{A},$$

(1)

where F_{cr} is experimentally obtained value of the critical force, and A is the specimen area affected by the force.

The specimens representing short columns were tested for the critical stress identical with the strength limit – σ_{SL}. The strength limit was calculated according to the equation (1), in which we replaced F_{cr} by F_{max}.

After the buckling test, we took from each test specimen a sample for determining its actual moisture content during testing. The moisture content was determined by weighing following the Standard STN 49 0103.

We also assumed that wood density should be another factor significantly influencing wood strength in buckling – in a similar way as the strength in compression; consequently, we determined for each specimen its oven-dry density ρ_0 according to the Standard STN 49 0108, using the following equation:

$$\rho_0 = \frac{w_0}{V_0},$$ (3)

where w_0 is the weight and V_0 is the volume of an oven-dry specimen.

RESULTS AND DISCUSION

Because the tests confirmed a significant influence of moisture content on critical stress for all column types: short, medium and long, we tried to find functions $\sigma_{cr}(m)$ fitting these relations.

To express the dependence of critical stress on moisture content we issued from our former findings (Kúdela 1996a, b, Kúdela 2001). As the best fitting was found the equation:

$$\sigma = \sigma_{SL} + B(m_{SL} - m)^n,$$ (4)

where B, n are constants, m_{SL} is moisture content at the cell wall saturation limit whose value for spruce is according to Babiak and Kúdela (1995) 45.8 %, m is actual moisture content, σ_{SL} is stress value at the cell wall saturation limit.

The results were characterized with a high variability. Considering the fact that the values of critical stress were very variable also at constant moisture content – this variability was, to a considerable extent, a result of varying density of the experimental material; it became evident that it was necessary to remove the influence of this factor. To exclude as most as possible of the influence of wood density when determining the dependence $\sigma_{cr}(m)$, it was necessary to convert all the experimentally obtained values to those corresponding to a constant density. For this purpose, we arranged the equation (4) in such a way as to also consider the influence of wood density. In our case, the constant density was meant the average density of the concerned specimen set. That means that at first we evaluated the influence of moisture content and density by means of non-linear regression analysis, using the equation (5)

$$\sigma = (a_1\rho_0 + a_2) + (b_1\rho_0 + b_2)(m_{SL} - m)^c.$$ (5)

We have confirmed an important influence of the studied factors and also a very close correlation – the correlation indexes were high. The results for short, medium long and long columns, for both pinned and fixed end fitting are illustrated in Figs 1-5. As we can see, the

critical stress linearly increased with increasing density. This increase was more pronounced at lower moisture content values.

Considering the linear dependence of critical stress on wood density we have proposed the following equation for conversion of critical stress to a constant density value:

$$\sigma_{cr2} = \sigma_{cr1} - k(\rho_{01} - \overline{\rho}_0),$$
(6)

where σ_{cr1} is critical stress in the concerned specimen with a density of , is the mean density for the given set and k is correction coefficient obtained from equation (5)

$$k = a_1' + b_1'(m_{SL} - m)^c.$$
(7)

After conversion of the experimentally obtained values σ_{cr} to the values corresponding to the mean density, we used the equation (4) to express the dependence $\sigma_{cr}(m)$. The obtained values for all the examined parameter combinations are summarised in Figs. 6-10. The parameters of regression equations for short, medium and long columns, for both pinned and fixed end fastening are summarised in Tab. 1.
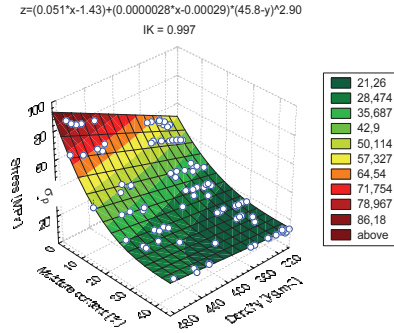

Fig. 1: Dependence of critical stress on moisture content and density – short columns
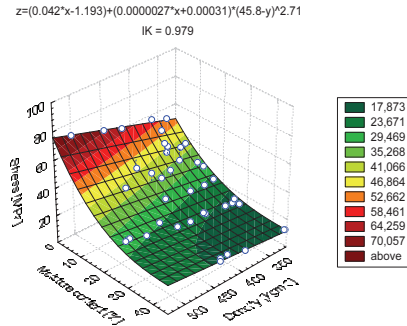

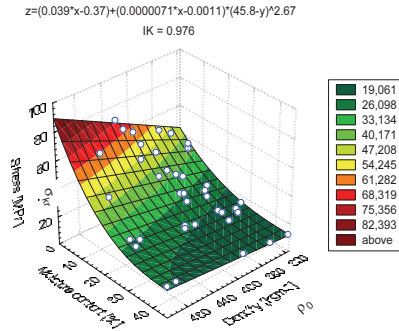*Fig. 2: Dependence of critical stress on moisture content and density – medium columns with pinned ends*

$$z=(0.039*x-0.37)+(0.0000071*x-0.0011)*(45.8-y)^{2.67}$$

IK = 0.976

Fig. 3: Dependence of critical stress on moisture content and density – medium columns with fixed ends

$$z=(0.029)*x+0.775)+(2.7e-8*x+0.0000053)*(45.8-y)^{3.43}$$

IK = 0.849

Fig. 4: Dependence of critical stress on moisture content and density – long columns with pinned ends

$$z=(0.031*x-0.511)+(0.000035*x-0.0058)*(45.8-y)^{1.85}$$

IK = 0.920

Fig. 5: Dependence of critical stress on moisture content and density – long columns with fixed ends

Fig. 6: Dependence of strength limit in compression parallel to grain on wood moisture content

Fig. 7: Dependence of critical stress on moisture content – medium columns with pinned ends

Fig. 8: Dependence of critical stress on moisture content – medium columns with fixed ends

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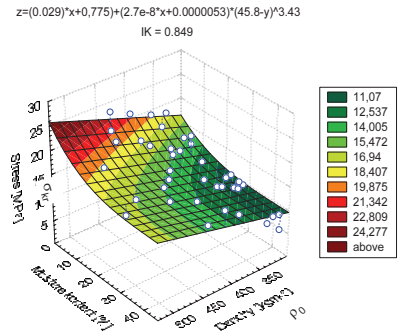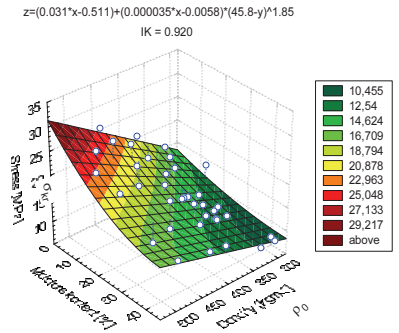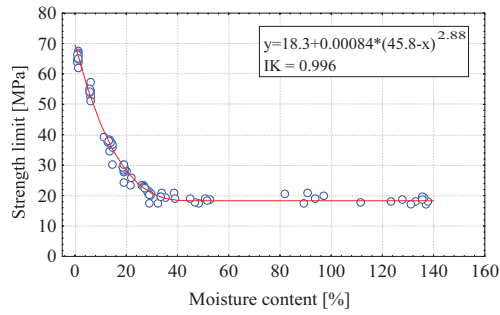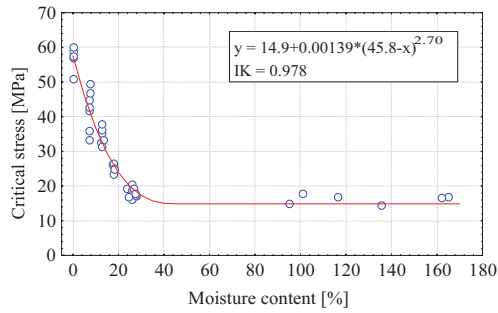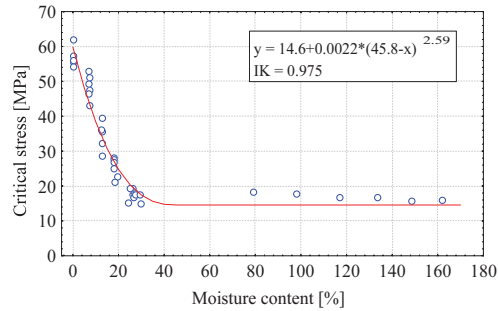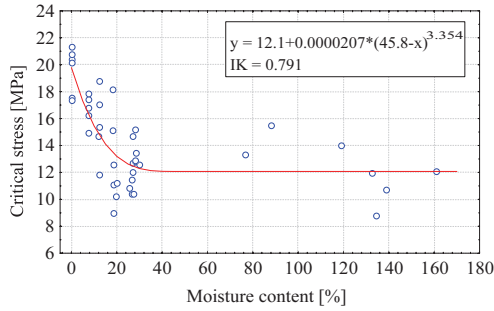*Fig. 9: Dependence of critical stress on moisture content – long columns with pinned ends*
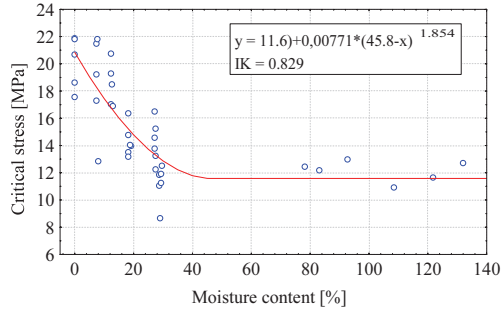

Fig. 10: Dependence of critical stress on moisture content – long columns with fixed ends

Tab. 1: Parameters of regression equation fitting the dependence of critical stress on moisture content

Columns and their end fastening	Parameter				Correlation index	Number of measurements
	σ_{SL} [MPa]	m_{SL} [%]	B	n		
Short columns	18.31	45.8	0.00084	2.881	0.996	107
Medium columns						
Pinned ends	14.88	45.8	0.00139	2.702	0.978	43
Fixed ends	14.56	45.8	0.00222	2.595	0.975	41
Long columns						
Pinned ends	12.07	45.8	0.000021	3.354	0.791	42
Fixed ends	11.58	45.8	0.00771	1.854	0.829	39

The experimental results for all model variants confirmed that the highest values of critical stress were obtained at zero moisture content and they decreased with increasing moisture content up to the saturation limit. The high values of correlation indexes in the case of short and medium columns demonstrate a very close dependence σ_{cr} on moisture content described by equation (4). In these columns, the decrease in critical stress corresponding to moisture change from 0 % to m_{SL} can reach 75 %.

Somewhat lower correlation coefficients were attained for long columns, however, also in this case was the dependence $\sigma_{cr}(m)$ significant on the highest significance level, and the critical stress decrease over the whole bound water range represented 40 %. As in the case of long columns, the values of σ_{cr} were low, consequently, the influence of additional factors that was not possible to exclude was more conspicuously reflected on the variance of the critical stress values.

Important influence of moisture content on σ_{cr} in range of long columns also follows from the Euler's equation itself. The general form of this equation is:

$$\sigma_{cr} = \frac{C\pi^2 E}{\lambda^2} \ . \tag{8}$$

As it follows from equation (8), σ_{cr} increases linearly with increasing modulus of elasticity. With increasing moisture content, the modulus of elasticity decreases, and, proportionally to this decrease, also decreases σ_{cr}. We have confirmed the hypothesis that if we have recognized the dependence of modulus of elasticity on moisture content, we can calculate with a high precision σ_{cr} in case of long columns for each moisture content value.

From the results it further follows (Figs 12-13) that with increasing moisture content, the differences in critical stress values between short, medium and long columns are getting smaller. At zero moisture content is the difference σ_{cr} between short and long columns 70 %; at the cell wall saturation limit, it is only 35 %.

Because σ_{cr} is changing with changing moisture content in all cases: for short, medium and long columns, the practical use requires converting the strength value from the moisture content m_1 to m_2. For this reason, we tried to find the most suitable way of conversion σ_{cr} from the value corresponding to m_1 to the one corresponding to m_2. In our country, the value of strength for all natural wood species and for all loading modes (compression, tension, shear, bending) is in most cases determined using the equation

$$\sigma_{12} = \sigma_m \left[1 + \alpha(m - 12) \right], \tag{9}$$

where σ_m and σ_{12} are strength values corresponding to the actual moisture content and a moisture content of 12 %, respectively, α is the correction moisture coefficient.

This equation serves first of all for conversion of a wood strength value at a given moisture content m to the value corresponding to 12 % moisture content. The same equation also frequently serves for conversion to the value corresponding to other different moisture content – namely by means of transition through that corresponding to 12 %. The range of moisture content in which we can use equation (9) for conversion is in general considered 8–18 % (Požgaj 1987, Dubovský et al. 1998). The concerned conversion of the σ_{cr} value corresponding to moisture content m_1 to the value corresponding to m_2 (both in the just specified moisture range) requires to estimate correction moisture coefficients because these have not been specified yet. Our experimental values of correction moisture coefficients are summarized in Tab. 2.

In Tab. 2 we can see that the values of correction moisture coefficients are very similar for short and medium columns and also for the two modes of end fastening. For this reason, we recommend a common correction moisture coefficient – $\alpha = 0.046$ for both areas: short and medium columns. The value of this correction moisture coefficient is higher compared to the value set for compression parallel to grain by the Standard STN 49 0110. According to the Standard, $\alpha = 0.04$, and this value is recommended for all wood species. It is an over-simplification at costs of precision – which has already been pointed out by Kúdela (1997).
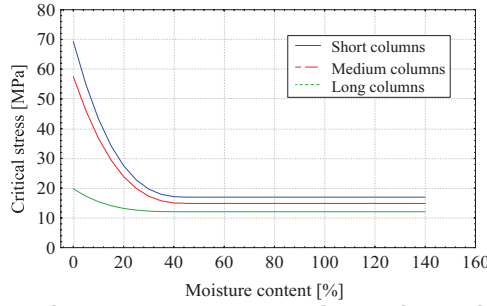
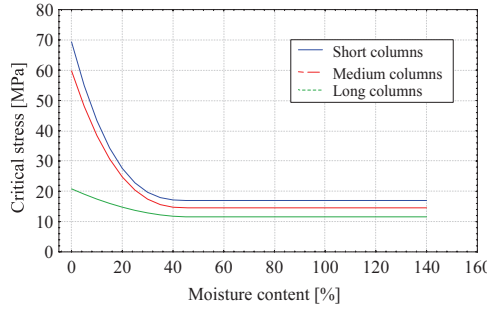*Fig. 11: Dependence of critical stress on moisture content – short, medium and long columns with pinned ends*

Fig. 12: Dependence of critical stress on moisture content –short, medium and long columns with fixed ends

Tab. 2: Correction moisture coefficients for short, medium and long columns

Correction coefficient	Short columns	Medium columns		Long columns	
		Pinned ends	Fixed ends	Pinned ends	Fixed ends
α	0.047	0.0455	0.0461	0.0181	0.0172

The value of correction moisture coefficient α for long columns is lower. Because we have not confirmed any significant difference between the two modes of end fastening, we recommend to use a common correction moisture coefficient α = 0.018. It is necessary to call attention to the fact that these correction coefficients are only suitable to use in equation (9) for the moisture range 8–18 %.

For the conversion of σ_{cr} from m_1 to m_2 over the whole moisture range (0 %– m_{SL}) we recommend to use the equation

$$\sigma_{m_2} = \sigma_{m_1} + B\left[\left(m_{SL} - m_2\right)^n - \left(m_{SL} - m_1\right)^n\right], \tag{10}$$

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obtained by arranging the equation (4), consequently, the meaning of symbols and regression parameters in the equation (10) is the same. The values of parameters B and *n* necessary for conversion σ_{cr} are listed in Tab. 1. The equation (10) ensures sufficient accuracy for conversion of σ_{cr} over the whole moisture area.

CONCLUSIONS

Based on analysis of the results we can draw the following conclusions:

Moisture content in the range of bound water significantly influences critical stress values over the whole buckling area. For all variants of buckling, the critical stress was the highest at zero moisture content and decreased with increasing moisture content up to cell wall saturation limit. For fitting the dependence $\sigma_{cr}(m)$ we recommend equation (4), appropriately expressing the given change.

For the case that the conversion of critical stress value from moisture content m_1 to moisture content m_2 is performed using equation (9) as set by the Standards STN, there have been established correction moisture coefficients for moisture content range 8–18 %. For short and medium columns we recommend a value of $\alpha = 0.046$, for long columns $\alpha = 0.018$.

For conversion of σ_{cr} from moisture content m_1 to m_2 over the whole moisture range ($0-m_{SL}$) we recommend equation (10).

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