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Tomasz DOMAŃSKI

TIMBER MEMBER RESISTANCE TO SNOW AND WIND LOADS IN POLISH MOUNTAIN ZONES

The resistance of timber members in structures decreases over time. It depends on the type of load – permanent or variable- and the sort of timber. Strength reduction effects, often referred to as creep-rupture effects, due to long- term loading at high stress ratio levels, are well known for many materials such as aluminum and concrete. Wood materials are greatly affected by a reduction in strength with the duration of permanent and variable loads. The m*ethods for calculating these reductions and the data relevant for structural timber resistance are presented. Based on snow and wind measurements over 45 years from mountain zones in Poland (Zakopane, Świeradów, and Lesko), the reduction factors-* k_{mod} *for wood members, according to PN-EN – 1995, were estimated.*

Keywords: wood, reduction of resistance, variable load, reliability, safety index, creep rupture effects of wood.

Introducton

Timber-wood materials, such as glued solid timber, are greatly affected by a reduction in strength caused by the duration of a load over time [Toratti et al. 2007]. Therefore, the design of timber and glued timber [Vratusa et al. 2011] structures use the strength reduction factor to reduce the characteristic short-term strength of timber [Molier, Ranta-Manus 1998]. Characteristic values of the load duration and the load duration factors are calibrated using probabilistic methods. Three timber damage accumulation models are usually considered, that is, Gerhards model [1979], the Barret & Foschi model [1978] and the Foshi, Folz & Yao model [1989]. Reliability is estimated using representative short- and long-term limit states for timber elements. The time variants of the damage reliability

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Tomasz DOMAŃSKI (*doman@pk.edu.pl*) Cracow University of Technology, Cracow, Poland

aspects are taken into account using a simple representative limit state with time variant strength and a simulation of the whole lifetime load.

The parameters in these models are obtained by the Maximum Likelihood Method using data relevant to polish structural timber [Noskowiak, Szumiński 2009]. Data for the snow load over 45 years from the mountain zones in Zakopane, Świeradów, and Lesko [IMiGW Kraków, Wrocław, 2010] were analysed in terms of the impact on timber structures. The reliability was evaluated using representative short- and long-term limit states to obtain the load duration factor k_{mod} (k_{mod} factor also depends on the moisture content of the wood), which was obtained using the probabilistic models. Safety assessments [Ellingwood 1997] of timber structures built in the past require that many different parameters are considered. These parameters are mostly random and describe material characteristics, actions and the history of actions. Timber materials are greatly affected by this reduction in strength caused by the duration of a load [Wang et al., 2012]. Wind and snow are the primary variable loads acting on timber roofs in Poland, particularly in mountain areas. The main factor used in calculations of the safety of timber members in structures is the reliability index β, which is defined as follows:

$$\beta = \overline{g} / \sigma_g , \tag{1}$$

Where $\overline{g}$ is the mean value of the safety margin calculated as the difference between the mean value of timber resistance $\overline{R}$ and external loads $\overline{E}$. σ_g is the standard deviation of the safety margin g

$$\overline{g} = \overline{R} - \overline{E} . \tag{2}$$

The effect of prolonged stress on timber's bending strength has been recognized since at least 1840. Wood [Wood 1951] developed a time strength curve that was incorporated into the wood design procedure. This curve, often referred to as the "Madison curve" [Rosowsky, Bulleit 2002], is still in use. During the last decades, structural reliability methods have been further developed, refined and adopted and are now at a stage where they are being applied in practical engineering problems. Furthermore, basic knowledge concerning the actions carried out on structures and timber material characteristics has improved due to increased focus, better measuring techniques and international research co-operation. This knowledge has enabled designers to take into account uncertainties in material properties and actions in assessing the load-carrying capacity, serviceability and service life of timber structures and connections. Most building codes, national and international, are based on a probabilistic safety approach. The code formats are deterministic with connections to reliability design achieved through failure probability, partial safety factors and characteristic values. Partial safety factors are calibrated for standard cases and should meet the same safety requirements by means of probabilistic analysis and deterministic code. Hence, the required safety is usually not achieved by using probabilistic theories in the normal design process.

Materials and methods

The reference properties of structural timber are:

- bending strength $f_{m,k}$ in MPa
- bending modulus of elasticity $E_{0,mean}$ in MPa, both measured using short-term standard test specimens described in PN-EN 408 2012
- timber density ρ_k [kg/m^3], measured according to PN-EN 408 2012

The distribution parameters can be determined by the information given in table 1 [Faber et al. 2004], and table 2 [Sorensen et al. 2005].

Table 1. Probability distributions of basic timber properties

Property	Distributions	COV		
		Solid timber	Plywood	LVL
Bending strength $f_{m,k}$	lognormal	0.25	0.17	0.11
Bending modulus of elasticity $E_{0,mean}$	lognormal	0.13	0.09	0.06
Timber density ρ_k	normal	0.10	0.07	0.05

Table 2. Expected values and coefficients of variation of timber members

Expected value Ex[X]	Coefficient of variation COV[X]
$Ex[f_{t,0,k}] = Ex[f_{m,k}]$	$COV[f_{t,0,k}] = 1.2COV[f_{m,k}]$
$Ex[f_{t,90,k}] = 0.015Ex[f_{m,k}]$	$COV[f_{t,90,k}] = 2.5COV[f_{m,k}]$
$Ex[E_{90,mean}] = Ex[E_{0,mean}]/30$	$COV[E_{90,mean}] = COV[E_{0,mean}]$
$Ex[f_{c,0,k}] = 5Ex[f_{m,k}]^{0.45}$	$COV[f_{c,0,k}] = 0.8COV[f_{m,k}]$
$Ex[f_{c,90,k}] = 0.007Ex[\rho_k]$	$COV[f_{c,90,k}] = COV[\rho_k]$
$Ex[f_{v,k}] = 0.2Ex[f_{m,k}]^{0.8}$	$COV[f_{v,k}] = COV[f_{m,k}]$
$Ex[G_{mean}] = Ex[E_{0,mean}]/16$	$COV[G_{mean}] = COV[E_{0,mean}]$

Damage models are usually used for the mathematical description of the long-term strength reduction as a function of the stress level and the duration of loading [Ellingwood, Rosowsky 1991]. In this paper, the damage model was fitted against data obtained from Polish structural timber subjected to constant loading [Domański 2010]. The characteristics of the damage model are that α is defined as the degree of damage, i.e. $\alpha = 0$ stands for no damage and $\alpha = 1$ stands for total damage or failure.

The damage accumulation model proposed by Barret and Foschi, [Barret, Foschi 1978] has the following expression:

$$\frac{d\alpha}{dt} = A(\frac{\sigma}{fo} - \eta)^B + C\alpha\,; \quad \frac{\sigma}{fo} > \eta$$

Where *A, B* and *C* are constants, σ is the stress, *fo* – short-term strength and η is the threshold ratio.

This expression was used in simulating timber damage due to load duration. When dealing with timber and wood-related product structures, in line with the requirements of PN-EN 1990, the design value of a resistance is R_d expressed in PN-EN 1995-1, as

$$R_d = k_{\mathrm{mod}} \frac{R_k}{\gamma_M}\,, \tag{3}$$

where k_{mod} (table 3) is the modification - reduction factor that takes into account the effect of the load duration and moisture content [Henijarvi 2000] in the timber , γ_M is the partial factor for a material property at the Ultimate Limit State (ULS) and R_k is the characteristic value of the load-carrying capacity at the ULS.

Table 3. Timber modification factor k_{mod}

Duration of load	Service classes		
	class 1 MC < 12%	class 2 12% < MC < 20%	class 2 MC > 20%
Permanent (> 10 years)	0.60	0.60	0.50
Long-term (6 months to 10 years)	0.70	0.70	0.65
Medium-term (1 week to 6 months)	0.80	0.80	0.70
Short-term (less than one week)	0.90	0.90	0.70
Instantaneous	1.10	1.10	0.90

Wind load

A stochastic model of the wind load in the Tatra mountain zone in Zakopane was established on the basis of meteorological data. The maximum wind velocity over the last 42 years [IMiGW Kraków, 2010] is shown in figure 1. The statistics of wind velocity for the values of wind speeds greater than 13 m/s were chosen due to the fact that these wind speeds are significant for the safety of timber roof structures.

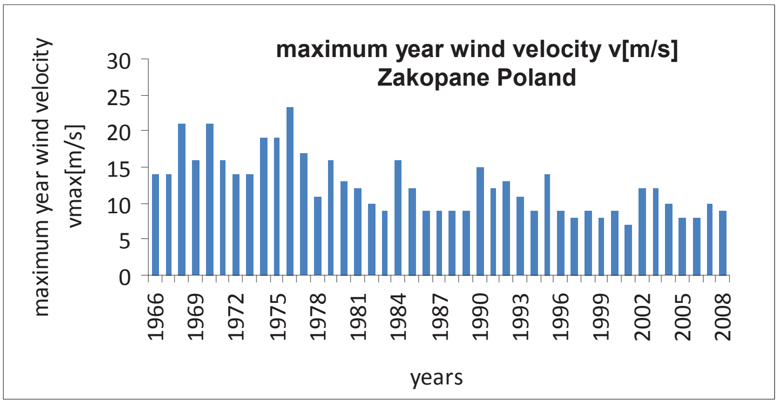

Fig. 1. Maximum annual wind velocity. Zakopane –Tatry

The wind velocity was modeled using sensors typically placed at a height of 10 m above ground. Measurements were made over a period of 42 years. Based on the wind data recorded over 42 years in Zakopane, in the Tatra mountains, the parameters of the wind model were established, figure 2, 3, 4.

Snow load

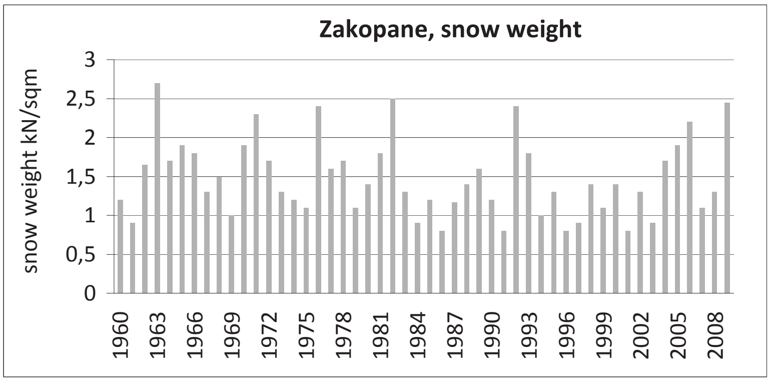

Fig. 2. Snow weight: Zakopane – Tatry

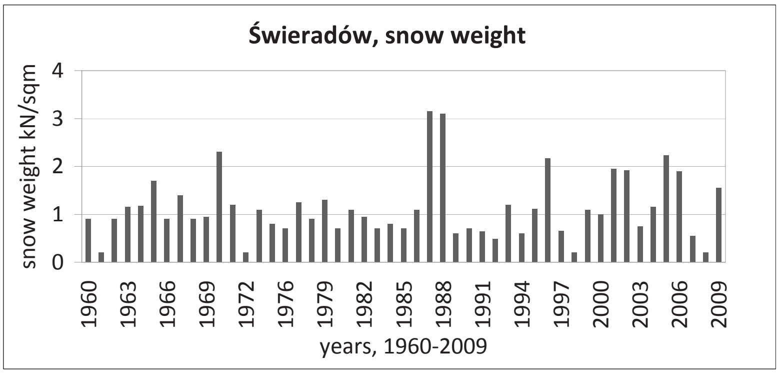

Fig. 3. Snow weight: Świeradów – Karkonosze

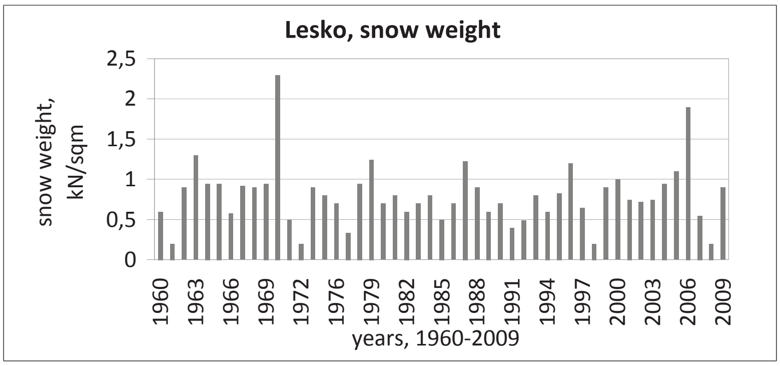

Fig. 4. Snow weight: Lesko – Bieszczady

The duration of snow package T was modelled by X_TP_m, proportional to the maximum snow load of snow package X_T – the exponential is distributed with the expected value μ_{XT} (table 4) [IMiGW Kraków, 2010], [IMiGW Wrocław, 2010].

Table 4 shows the probabilistic parameters of the snow packets in Zakopane (Z), Swieradów (S) and Lesko (L).

Table 4. Probabilistic parameters of snow load in mountain zones

Variable	Zakopane	Świeradów	Lesko
μ_P [kN/m^2]	1.47	1.12	0.80
σ_P [kN/m^2]	0.49	0.65	0.37
μ_{XT}[days/(kN/m^2)]	65.58	40.97	53.62
λ	1.43	1.85	1.64

The short-term conditions design and the limit state equation formulas can be described as follows:

$$\frac{zf_k}{\gamma_m} - [(1-\kappa)\gamma_G G_k + \kappa(\gamma_Q Q_{S,k} + \psi_0 Q_{W,k})] = 0\,, \tag{4}$$

$$g = zf_o - [(1-\kappa)G + \kappa(Q_S + Q_W)] \tag{5}$$

Where z is design parameter, f_o – short-term strength, G – permanent load, Q_{S} snow variable load, Q_{W} wind variable load,

The reliability indexes β were calculated by simulation according to the FORM method on the basis of equations (4) and (5), and the stochastic model is presented in table 5.

Table 5. Stochastic model for Zakopane (Z), Świeradów (S), and Lesko (L)

Variable	Distribution	Expected value	Coefficient of variation
f_o timber strength	Lognormal	1	0.18
G permanent load	Normal	1	0.10
Q_{S} snow load	Gumbel	1	0.34/0.44/0.46 (Z/S/L)
Q_{W} wind load	Gumbel	1	0.65

By utilizing the Monte Carlo simulation for generating random variables, the modification factor k_{mod} was determined according to the procedure proposed by Sorensen et al. [2005].

In the code format PN-EN 1995-1, the load duration effect is represented by a modification factor k_{mod}. The following design equation for the long-term situation can be described as follows:

$$\frac{zf_k k_{\mathrm{mod}}}{\gamma_m} - [(1-\kappa)\gamma_G G_k + \kappa(\gamma_Q Q_{S,k} + \psi_0 Q_{W,k})] = 0\,, \tag{6}$$

where z is the design variable, f_k is the characteristic value for short-term strength (5% quantile) , $Q_{S,k}$ and $Q_{W,k}$ are the characteristic values of the variable – snow and wind loads (2% quantile), G_k is the characteristic value of the permanent load (mean value), γ_G is the partial safety factor for the permanent load (= 1.35), γ_{Q} is the partial safety factor for the load (= 1.5), γ_{m} is the partial safety factor for solid timber (= 1.3), ψ_0 is the load combination factor for wind and κ , the coefficient which represents the proportion between permanent and variable (snow and wind) loads. The corresponding long-term limit state equation is:

$$g = z(1-\alpha)f_o - [(1-\kappa)G + \kappa(Q_W + Q_S)]\,, \tag{7}$$

Where α is the damage state variable of the timber member, f_o is the short-term timber strength, G *and* Q are the permanent and variable – snow and wind – loads.

Then the k_{mod} factor can be estimated as follows:

$$k_{\mathrm{mod}} = \frac{\gamma_m^S(\beta s)}{\gamma_m^L(\beta L)}, \tag{8}$$

where $\gamma_m^S(\beta s)$ is the short-term partial safety factor as a function of β and $\gamma_m^L(\beta L)$ is the long-term partial safety factor as a function of β [Svensson, Thelandersson 2003].

Results and discussion

Figure 5 shows the relations between the reduction coefficient of timber strength k_{mod} and parameters κ – part of the variable (snow, wind) loads to the total loads for different kinds of wood – LVL, plywood and solid timber.

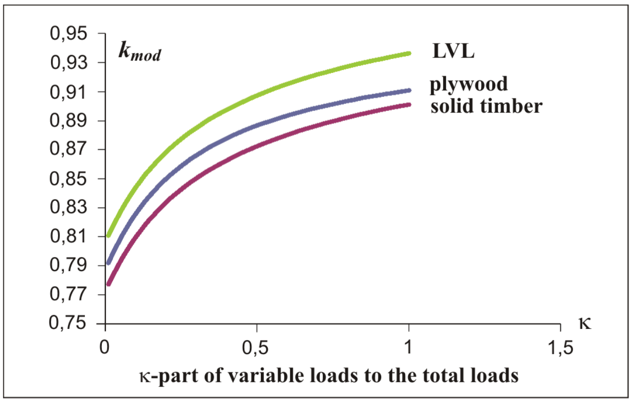

Fig. 5. The dependence of timber reduction factor k_{mod} on coefficient κ for solid timber, plywood, and LVL

The reduction parameter k_{mod} increased faster for the small values of κ. This means that k_{mod} was smaller for small snow and wind loads. Figure 6 presents the relations between the reduction coefficient of timber strength k_{mod} obtained for different mountain locations, such as Zakopane in the Tatry mountains, Świeradów in the Karkonosze mountains and Lesko in the Bieszczady mountains.

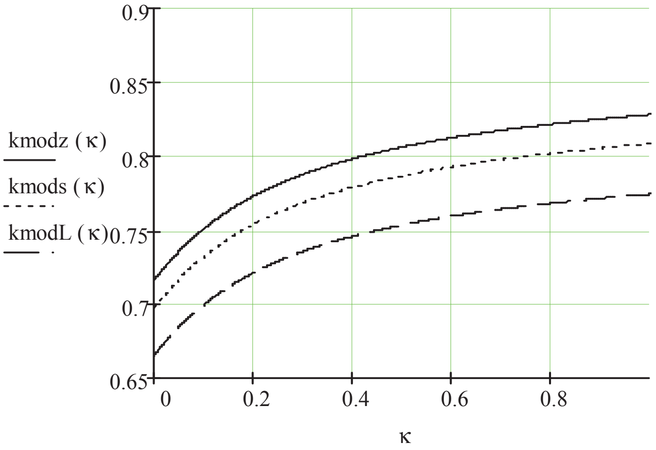

Fig. 6. The dependence of timber reduction factor k_{mod} on coefficient κ for Zakopane kmodz, Świeradów kmods, and Lesko kmodL

It can be observed that for the places of high altitude, the values of the modification factor for timber k_{mod} were greater, and for this reason, the locations for timber building design should be taken into account.

Finally, it is possible to suggest a new diagram and tables for k_{mod} reduction – modification factor k_{mod} for the Polish mountain zones, as follows: figure 7 and table 6. The above calculations were made on the assumption that the moisture is of the second service class (12 % < MC < 20%).

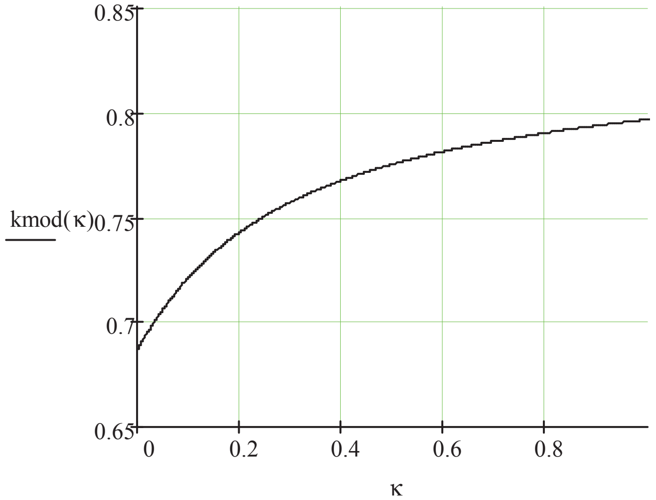

Fig. 7. The dependence of timber reduction factor k_{mod} on coefficient κ Polish montain zones

Table 6. .Suggested new timber modification factor k_{mod} for Polish mountain zones

Type of material	Loads				
	Permanent	Long-term	Medium	Short	Instantaneous
Solid timber	0.65	0.70	0.78	0.82	1.10
Plywood	0.70	0.72	0.82	0.84	1.10
LVL	0.71	0.80	0.84	0.86	1.10

Conclusions

The statistical assessment of timber material properties was considered with special emphasis on the modeling of the effects of timber strength reduction in time due to permanent and variable loads. The probabilistic model for timber reduction factor k_{mod} was formulated in such a way that it may be readily applied in structural reliability analysis. It is noted that a significant effect of the time variation of snow and wind impulse-packages on the timber damage model was found. Stochastic models were presented for wind and snow loads in accordance with load and damage models. The reduction factors k_{mod} for different combinations of permanent and variable (snow, wind) loads were almost the same as those found in PN-EN 1995-1-1 [2010]. More research is needed on the variance parameters of snow package loads as found in practice, and the assumption that the distribution of the duration of snow packages is exponential should be verified. The factor k_{mod} value greatly depends on the ratio between permanent and variable (snow, wind) loads.

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