System effects of structural elements - determined for bending and tension

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Summary

The system effect of continuous connected, parallel members of spruce (*picea Abies*) has been the topic of the current research work. First, emphasis was taken on overview of the system effect supported by literature study and current national and international regulations. Second step was to proof the system behaviour by testing samples of doubled and fourfold finger jointed structural lumber (KVH®) as rigid connected systems in tension and bending. The reduced scatter of strength and stiffness was objected which resulted in an increase of the 5 % quantil of *MOR*. Emphasis was taken on statistical evaluation to define best fitted model to represent the data sets of the samples. In addition bending tests of horizontal arranged 2x2 and 2x3 structures named as 'Balkenbinder' (BB) were carried out with two different cross sections of the single components KVH®, 60/200 mm and 80/160 mm. The results obviously reflect the interaction of system effects and size effects.

1. Introduction

Wood as a raw material, naturally grown, is characterised by its linear elastic plastic behaviour in dependence of species and load situation, its anisotropy, creeping and its high in-homogeneity compared to other substituting construction materials.

By arrangement of components to systems which work like one unit, e.g. edgewise loaded, the reduced scatter of the mechanically properties strength and stiffness can be objected. Another kind of arrangement is the combination of load distributing structures and load bearing structures. The whole system appears like one unit too, but the load bearing components are not directly linked together, the load distributing structure serves as indirect connector.

In both kinds of systems added values by mechanically properties can be generated in comparison to single components. One is the increase of the certainty of parameters strength and stiffness; another is the valuable shift of the 5 % quantil of *MOR* (Mtenga et al., 1995, Cramer et al., 2000, Rosowsky and Yu, 2004, Hansson and Isaksson, 2001). This shift is in current standards expressed as 'system factor' or as 'load sharing factor'. The factor itself serves as multiplier for the referring characteristic strength values, e.g. bending and tension, based on the mechanical potential of single components. Application of the system factor depends on the national standards and reaches from laminated decks for bridges or floors to beam structures like Duolam or Trilam, or systems like floor-, roof- or wall constructions.

But nevertheless the factor itself is a conglomerate of a variety of effects resulting from interacting behaviour between elements, components and systems.

2. State of the Art

The term 'system' is defined as compilation, a combination of interacting elements. Parts of a system can be structured in elements, components or subsystems. For further work elements are defined as the basically unit, the increment of components. Elements can be single molecules of cellulose, lignin, hemicelluloses, or a functional unit as cluster of mentioned molecules combined in percentage of appearance in wood. An element can also be the smallest testable unit or a reference unit of every wood property, e.g. knot, to describe its characteristics. Components consist of preferred serial but also parallel arranged elements to form a structural unit like a lamella, a board, or a beam. Systems are defined as structures, built up of parallel components. Consequently systems can be best described as parallel acting sub-serial structures (see Fig 1).

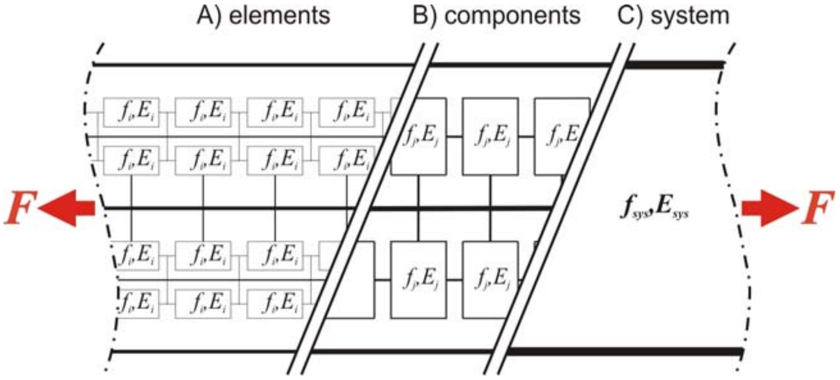

Fig 1 Structure of systems

There exist system effects in and between components. The effects in components, caused by elements, are well known as size effects and result of preferred serial arrangement of the elements. The effects between components and in systems reflect principal parallel interactions.

2.1. Characterisation and differentiation of system effects and aspects of sited literature

Systems in wood structures can be divided into combined load distributing and load bearing structures, like roof, floor, or wall systems, or as directly continuous connected parallel structures like Duolam or Triolam, pre-stressed deck plates. In both kinds components and elements interact resulting in mechanically and statistically based effects.

The mechanically effects can be subdivided into 'load sharing', 'load redistribution', and 'partial composite action' (Rosowsky and Yu, 2004). The term 'load sharing' describes the distribution of load between components and elements in a system according to their stiffness. Generally stiffer members attract more load than limber members (Mtenga et al., 1995, Cramer et al., 2000, Rosowsky and Yu, 2004, Liu and Bulleit, 1995, Douglas and Line, 1996, Hansson and Isaksson, 2002, Gromala and Sharp, 1988, Faherty and Williamson, 1999). 'Load redistribution' defines the potential of components to carry increased load after single failures. The potential of 'load redistribution' depends on the load sharing rule (between local- and global load sharing), the post-yield behaviour, and further on the species, kind and direction of load, and fracture mechanics (Mtenga et al., 1995, Cramer et al., 2000, Liu and Bulleit, 1995, Lynch, 1999, Kim and Kvam, 2004). A perfect brittle material does not allow any redistribution of load in case of partial failure (Liu and Bulleit, 1995, Thelandersson and Larsen, 2003). Even wood in tension parallel to grain demonstrates share of plasticity.'Partial composite action' terms the interaction of the load distributing and load bearing structure.

A variety of effects which are mainly based on the redundant structures of the systems are statistically describable. Out of experiments most obvious is the decreased scatter of mechanically features based on homogenisation processes, whereas the mean seems to stay constant (Liu and Bulleit, 1995, Reece, 1949, Nemeth, 1967), irrelevant reduced (Williams et al., 1994, Bohnhoff et al., 1991), or depending on the material characteristics (Bakht and Jaeger, 1991). It follows an increase of the 5 % quantil. The standardization and the added values are additional results of the reduced likelihood of having a weak element in a high stressed region (Mtenga et al., 1995, Hansson and Isaksson, 2002). But with the increasing quantity of components in a system the probability of a weak one also rises. Also statistically express able is the positive correlation of strength and stiffness values which enables the 'load sharing' as described above. But all in all "… load sharing in wood assemblies is both a structural phenomenon and a statistical phenomenon …" (Cramer et al., 2000).

The system factor k_{sys} is defined as ratio of the 5 % quantil of *MOR* of the system ($f_{05,\text{n}}$) and the components ($f_{05,1}$), expressed in [1], with *n* components acting in the system.

$$k_{sys} = \frac{f_{05,n}}{f_{05,1}} \qquad [1]$$

In this study emphasis is taken on systems of continuous and rigid connected components. Nevertheless most of the described sub-effects are applicable for both kinds of system structures.

2.2. Current regulations in international standards

According to the task of this research only regulations concerning continuous, parallel, directly and rigid connected systems are taken into consideration.

Generally the European standards contain linear functions of the system factor as multiplier, applicable for shear and bending strength. The German standard DIN 1052 and the EN 1995-1-1 defines the system factor in dependence of the quantity (*n*) of acting lamellas and kind of connection, with a maximum of $k_{\text{sys}} = 1.2$ at $n \geq 8$. The DIN 1052 includes an additional passage with a $k_{\text{sys}} = 1.2$ for $n \geq 4$ edgewise loaded glulam lamellas. The EN 1995-2 enables supplementary to the EN 1995-1-1 and DIN 1052 the application of the k_{sys} for block-glued or pre-stressed glulam with a maximum of $k_{\text{sys}} = 1.1$ at $n \geq 8$. The Swiss standard SIA 265 defines the system factor as function of quantity of components (not lamellas!), kind of connection, and in dependence of the properties of the components. A $k_{\text{sys}} = 1.2$ is applicable for shear and bending for $n \geq 4$. The enBR, as Austrian answer to the EC 5 combines the content of the SIA 265, the EC 5, and the DIN 1052. The standard also defines the system factor $k_{\text{sys}} = 1.2$ for $n \geq 4$ components, like SIA 265, but includes the passage of DIN 1052 for vertically loaded glulam lamellas and the application for block-glued or pre-stressed glulam of EN 1995-2.

The OHBDC contains regulations concerning the 'load sharing', based on research work of Bakht and Jaeger, 1991. The defined functions for the load sharing factor are in dependence of the scatter of *MOR*, nonlinear, degressive, with a maximum at $n \geq 20$ lamellas. Bakht and Jaeger, 1991 defined the scatter of *MOR* as the main parameter influencing the load sharing behaviour of wood systems and enabled the inclusion of this parameter by definition of a relative function of the scatter F_σ in addiction to *n*. This function obviously reflects a conservative approach, according to the probabilistic concept, by shifting the well known general function of scatter σ_{m} of the normal distribution in dependence of *m* samples (see, with δ as shift factor acc. fitting to function of Bakht and Jaeger, 1991).

$$F_\sigma = \sqrt{\frac{2}{n+1}} \rightarrow COV_n = COV_1 \cdot \sqrt{\frac{2}{n+1}} = \frac{COV_1}{\sqrt{n+1}} \cdot \sqrt{2} \approx \sigma_m = \frac{\sigma_1}{\sqrt{m}} + \delta \qquad [2]$$

The Australian standard AS 1720.1 defines strength sharing factors and takes into consideration both kinds of systems, continuous connected, and interaction of load sharing and load bearing structures. If only considering the continuous connected components a degressive function with $k_{\text{sys}} = 1.33$ at $n \geq 10$ as maximum can be determined.

Obviously the variety of regulations concerning rigid and continuous connected systems reflects the uncertainty and different view and the complexity of defining the increased potential without reducing the safety of engineered constructions.

3. Experiments

Four series of KVH® of spruce (*picea Abies*) were tested to failure, one in tension and three in 4 point bending test arrangement. First emphasis was taken on determining k_{sys} for bending and tension with series B_80-160 and T_60-78 with systems of doubled and fourfold components of *b*/*h*/*l* = 80/160/3200 and 78/60/5500 mm. The next step was to determine the system potential of horizontal arranged 2x2 and 2x3 structures based on doubled components, by series BB_80-160 and BB_60-200 (see Fig 2).

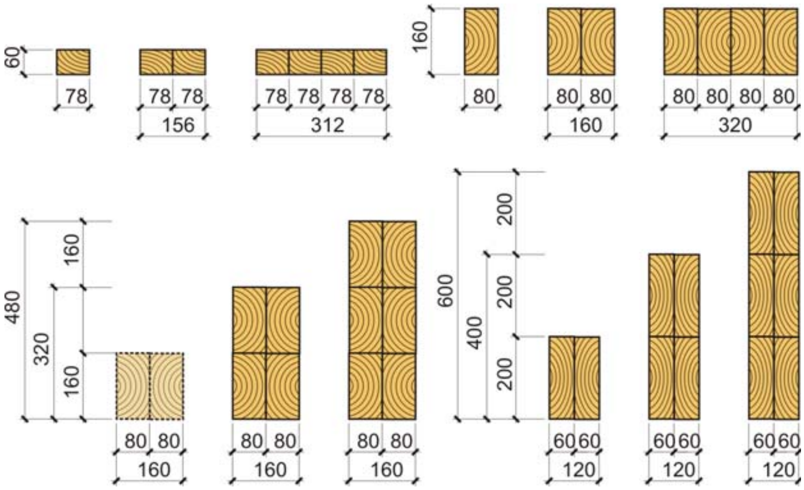

Fig 2 Cross sections of samples series T_60-78 (left above), B_80-160 (right above), BB_80-160 (left below) and BB_60-200 (right below)

The components of visual grade ≥ S10, according to DIN 4074-1 (strength class ≥ C24, acc. to EN 338) were glued together with adhesive based on polyurethane, which was also used for finger joints.

Tension tests were done with free testing length of 4860 mm. The distortion was measured over the whole testing length by inductive measuring device after checking the accuracy of this arrangement concerning slipping. The 4 point bending tests were carried out according to EN 408 with span of 18x*h* and third point loading. Measurement of distortion for determining the *MOE* was done locally over a length of 5x*h* in middle third section.

The moisture content was determined according to EN 13183-1. The measurement of the dimensions, weight, and calculating of density, *MOE* and *MOR* was done according EN 408. The calculated stiffness and density values were transformed to reference moisture u = 12 %, according to EN 384. During testing breaking events were recorded and the initial reason for failure was determined.

4. Results

Tab 1 summarises the data of series T_60-78 and B_80-160 and include the 5 % quantil of *MOR* and the related k_{sys} factors, which are calculated according to [1] (the evaluation of the series of product 'Balkenbinder' is not yet finished and will be published later). Emphasis was taken on computing of the 5 % quantil because of the sensibility of the k_{sys} as ratio value. Empirical data gained from testing was compared to statistical models like normal distribution (ND), 2 and 3 parametric logarithmic normal distributions (LND), and 2 and 3 parametric Weibull distributions (WD). To determine the best fitted distribution model analysis, based on quantitative and qualitative aspects was carried out. Tools like QQ-plots and least square method were applied.

Tab 1Series T_60-78 and B_80-160 - key values

T_60-78	**T_1_xx** *b* / *h* = 77.4 / 59.5 mm			**T_2_xx** *b* / *h* = 151.0 / 55.8 mm			**T_4_xx** *b* / *h* = 306.6 / 55.6 mm		
	ρ_{12} 1) [kg/m³]	$E_{t,0,12}$ 1) [N/mm²]	$f_{t,0}$ [N/mm²]	ρ_{12} 1) 2) [kg/m³]	$E_{t,0,12}$ 1) [N/mm²]	$f_{t,0}$ [N/mm²]	ρ_{12} 1) 2) [kg/m³]	$E_{t,0,12}$ 1) [N/mm²]	$f_{t,0}$ [N/mm²]
quantity	46 #	46 #	46 #	41 #	41 #	41 #	29 #	29 #	30 #
mean	460	11900	23.0	453	11750	24.6	457	12380	28.3
COV [%]	6.4 %	11.6 %	26.8 %	4.5 %	8.4 %	17.7 %	3.6 %	7.3 %	14.6 %
5 % qu. (3p WD) 3)	--	--	14.4	--	--	16.9	--	--	20.9
k_{sys}	**--**	**--**	**1.00**	**--**	**--**	**1.17**	**--**	**--**	**1.45**

B_80-160	**B_1_xx** b / h = 80.3 / 159.8 mm			**B_2_xx** b / h = 150.0 / 155.7 mm			**B_4_xx** b / h = 306.3 / 154.6 mm		
	ρ_{12} 1) [kg/m^3]	$E_{m,l,12}$ 1) [N/mm^2]	f_m [N/mm^2]	ρ_{12} 1) 2) [kg/m^3]	$E_{m,l,12}$ 1) [N/mm^2]	f_m [N/mm^2]	ρ_{12} 1) 2) [kg/m^3]	$E_{m,l,12}$ 1) [N/mm^2]	f_m [N/mm^2]
quantity	74 #	72 #	74 #	49 #	49 #	49 #	29 #	29 #	29 #
mean	442	11560	33.2	457	13290	38.8	444	12070	37.1
COV [%]	8.6 %	24.2 %	23.2 %	5.6 %	17.0 %	16.9 %	5.2 %	13.4 %	11.5 %
5 % qu. (3p WD)3)	--	--	20.5	--	--	28.4	--	--	30.5
k_{sys}	--	--	**1.00**	--	--	**1.39**	--	--	**1.49**

1) values of density and stiffness are adjusted acc. to EN 384 to reference moisture content u = 12 %

2) density values are calculated as mean of the density of each component per system

3) 5 % quantil of *MOR* calculated by use of best fitted statistical distribution model in brackets

The k_{sys} was calculated as ratio of 5 % quantils, not characteristic values. The standard deviation and the mean of a data set are expected values for the population, the 5 % quantil, based on them, reflects the best point estimation. The data sets of T_60-78 and B_80-160 reflect the reduced scatter of the mechanical properties. In addition the mean of *MOR* also increased. Consequently the 5 % of *MOR* increased too, reflected in growing system potential expressed as k_{sys}.

5. Discussion

The system effect was determined in bending and tension. It has to be differentiated between the share of reduced scatter and the share of increased mean of *MOR* which both leads to higher 5 % quantils. The reduced scatter seems logical from the point of view of homogenisation and as part of interacting of serial and parallel systems in dependence of n. According to the basically idea of Bakht and Jaeger, 1991 emphasis was taken on defining a more general function to describe the relative change of *COV* of *MOR* in relation to n. For that, all test results, added by past data sets of edgewise loaded glulam lamellas and current tests with 'Brettsperrholz' BSP (plywood of boards) (see Tab 2 and Fig 3), were plotted with COV_1 = 100 % and COV_n related to this value.

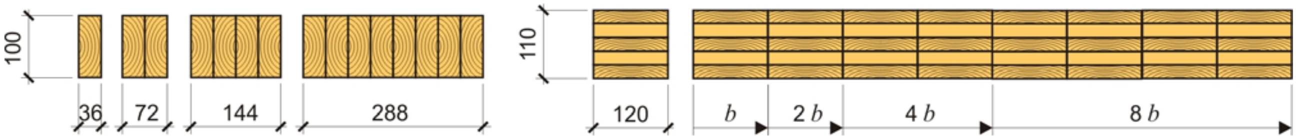

Fig 3 Cross sections of glulam (lamellas), Schickhofer, 2004 (left), and BSP, Jöbstl, 2006 (right)

Tab 2Additional data sets of Schickhofer, 2004 (left) and Jöbstl, 2006 (right)

additional data sets		data set of edgewise loaded glulam lamellas at 4 p. bending tests acc. EN 408, b/h = 36-288/100 mm, strength class C16/C24 acc. EN 338				data set of 4 p. bending tests of BSP acc. EN 408, b/h = 120-960/110 mm, strength class C24 acc. EN 338			
n	[--]	1	2	4	8	1	2	4	8
quantity	[--]	20 #	9 #	9 #	9 #	37 #	16 #	14 #	10 #
$f_{m,mean}$	[N/mm^2]	36.8	38.5	37.5	38.1	38.0	39.1	39.3	37.2
COV_{fm}	[%]	**36.7 %**	**23.9 %**	**14.7 %**	**7.9 %**	**16.1 %**	**14.3 %**	**12.5 %**	**7.6 %**
$f_{m,05}$ (2p LND1), ND2))	[N/mm^2]	20.8 1)	23.3 1)	27.5 1)	31.4 1)	27.9 2)	29.9 2)	31.2 2)	32.5 2)
k_{sys}	[--]	**1.00**	**1.12**	**1.33**	**1.51**	**1.00**	**1.07**	**1.12**	**1.17**

Based on empirical observation and the goal to define a general function by including the parameter COV_1 the function of [3] was defined. Fig 4 includes the test values mentioned in comparison to the gained function of [3]. It seems to be an appropriate application representing trends of $COV_{n,rel}$ when bearing in mind the statistical uncertainty caused by the limited sample scales.

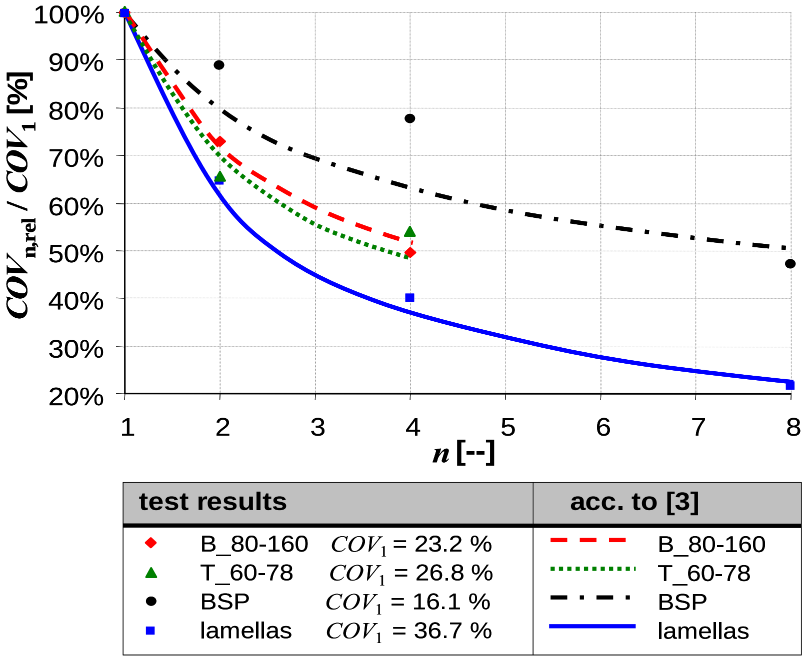

Fig 4 Comparison of relative $COV_{n,rel}$ values of MOR of data sets to the defined function of [3]

The tendencies increased mean of *MOR* seems to be the result of load sharing and load redistribution between elements and components, in combination with statistical effects, but appears to be too progressive. It is a fact that the strength we measure in test like tension reflects the strength of the weakest section, like a minimum, and the *MOE* represents a mean value over the reference length. If we assume that the weakest section in a system of two or more components is not situated at the same location in length direction, which is very probable, we have also to assume that the weak sections are supported by e.g. elements with higher mechanical potential in e.g. *MOE* and *MOR*. In that case load sharing at one cross section results in general higher *MOR* and leads also to increased mean of *MOR*.

$$COV_{n,rel} = n^{-2 \cdot COV_1} \qquad [3]$$

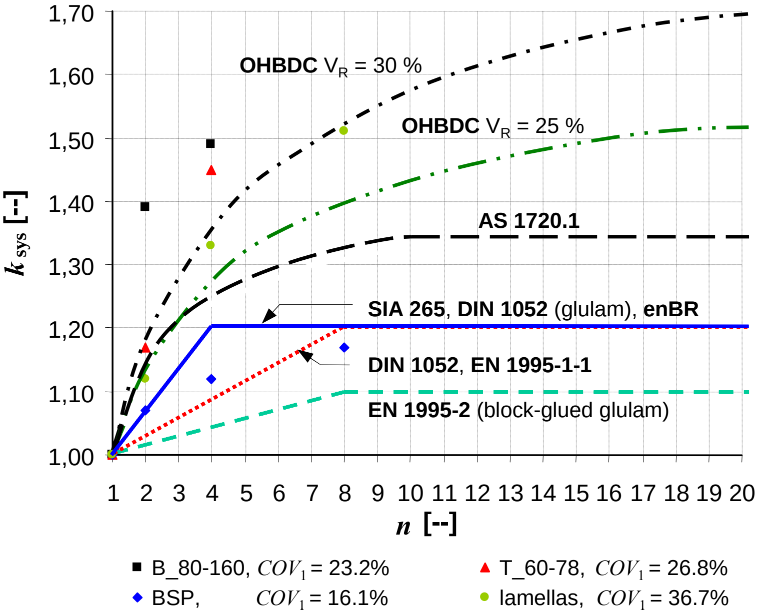

Fig 5 Comparison of international standards concerning system factor k_{sys} of continuous, directly, rigid connected components (lines) with test results of given reference COV_1 (symbols)

Because of the fact that we can not measure all this values in appropriate way a simulation procedure has been started to gain deeper insight into the system effect of rigid connected components by examining related parameters. Results will be published.

Generally, based on the assumption of a constant mean, as conservative approach and according to the ideas of Bakht and Jaeger, 1991, the determination of system effects can be determined by assuming an appropriate distribution to describe the data set, with scatter acc. to [3].

Nevertheless, system factor increase also the assurance of *MOE* and the 5 % quantil, which would be relevant if we have the intention to introduce classes of stiffness instead of strength. This would lead to a further progress in thinking based on the knowledge that stiffness is in case of engineer couple more relevant than strength and also measurable in contrast to strength values which are estimated by parameters like stiffness, density, and on insecure assumptions of data sets and a multiple regression function.

Based on the increased potential of aimed and intelligent combination of single components to systems it is possible to compete successful with substituting construction materials, to ensure the profitability and purposeful use the natural resource wood.

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