Hardwood - Softwood Combination in Glued Laminated Timber Cross-Section

Ivan BALÁZS[1], *Ondřej PEŠEK*[1], *Pavla BUKOVSKÁ*[1]

[1]Institute of Metal and Timber Structures, Faculty of Civil Engineering, Brno University of Technology, Veveří 331/95, Brno, Czech Republic

balazs.i@fce.vutbr.cz, pesek.o@fce.vutbr.cz, bukovska.p@fce.vutbr.cz

DOI: 10.35181/tces-2020-0002

Abstract. *Glued laminated timber (glulam), as one of the types of engineered wood products, is in our conditions most often made of coniferous, specifically spruce wood. In order to find optimal usage of material, some new configurations of cross-sections are being suggested. An advanced solution of glulam cross-section could be represented by cross-section formed from combination of hardwood (from deciduous trees) and softwood (from conifers). This paper deals with a possibility of combination of outer lamellas from a hardwood and inner lamellas from a softwood in glulam cross-section. The solution is focused on members suitable for a use in a skeleton frame. Attention is paid to two types of structural members: beam and column. Results of theoretical study are presented which arise from an analytical calculation and from a numerical modelling. For comparison, the calculations were carried out for a reference cross-section consisting of softwood lamellas only. By comparing the combined and reference cross-sections, it can be stated that the use of the combined cross-section can save material for both the compression member (column) and the member subjected to bending moment (beam, girder). The combined cross-section appears to be more advantageous than the reference cross-section, especially in cases of smaller beam depth.*

Keywords

Coniferous timber, deciduous timber, design resistance, glued laminated timber, hardwood, softwood.

1. Introduction

The choice of wood type for a production of structural timber members is given by the assortment available at the region of production. However, the timber production may be limited by weather conditions or by biological pests. Lack of a sawn timber together with a demand for quality building material leads to proposals of new cross-section arrangements that are optimal in terms of both material consumption and static function. Glued laminated timber, usually made from softwood, enables a variety in cross-section composition because it makes possible to use small diameters trees. Fast-growing and widely distributed species are searched for to be used for structural glulam products with a remarkable price to performance ratio. Nowadays, more attention is paid to hardwoods in order to complete missing information about glued laminated hardwoods in normative documents.

In the paper of Aicher et al. [1] utilization of the prevailing European hardwood species of chestnut, oak and beech is discussed. The paper reveals that the mechanical properties of glulam made of these hardwoods are at least equal and generally exceed the bending strength of the highest European softwood glulam strength classes. However, it is pointed out at the same time, that it is necessary to pay more attention to design of finger joints and lamination glue lines, as a result of increased density of hardwood (in comparison with softwood). In [2] results of an experimental investigation on full-scale glued solid timber beams made of oak timber for structural purposes are presented. It was confirmed that glued beams from hardwood are much more prone to breaking at the finger joints. Lanvin et al. [3] remind that the current producing procedures of finger joints are applicable for softwood (drying speed, test methods for resistance to delamination), so they should be adapted in case of hardwood application.

An interesting option of cross-section optimization is the combination of more species of wood. In [4] experimental results are presented for cross laminated timber (CLT) with use hardwoods (aspen and birch) as a cross layer and softwood (spruce, pine, fir) for outer layers. The results suggest that the used hardwoods improved the planar shear properties of CLT. Also investigations presented in [5] reveal the great potential of mixed softwood-hardwood CLT for structural members.

This paper discusses the possibility of using a combination of different wood species in a glulam cross-section. In case of glued laminated timber, combination of wood species could be convenient for the construction members which are subjected to bending or compression and bending so that they have not a stress distribution constant over the height of the cross-section. Different wood type lamellas are then set out in a cross-section according to the loading system and stress distribution. In this paper, combination of two species of timber is taken into consideration, inner lamellas of commonly used coniferous wood (spruce) and outer lamellas of hardwood (beech). A suitable cross-section configuration is sought for a column and a beam of a skeleton frame.

2. Assumptions and Methods

The cross-section of the glued laminated members subjected to the research is assumed to be a combination of certain number of lamellas of two types: coniferous timber and deciduous timber. The outer lamellas (top and bottom) are considered to be made of deciduous timber having higher moduli of elasticity while the coniferous timber is used for inner lamellas of the cross-section. The thickness of each lamella is 40 mm. The precise number of lamellas and therefore total dimensions of the cross-section is to be determined using static assessment depending on the presumed magnitude of applied load.

The material properties of the coniferous and deciduous timber were taken from the standard [6] and are summarized in Tab. 1. Strength classes C16 (coniferous timber) and D30 (deciduous timber) were considered.

Tab. 1: Material properties.

Properties, indications and units		Strength class C16	Strength class D30
Modulus of elasticity (fifth percentile value)	$E_{0.05}$ [GPa]	5.40	9.20
Modulus of elasticity (mean value)	$E_{0,\mathrm{mean}}$ [GPa]	8.00	11.00
Characteristic compressive strength along the grain	$f_{c,0,k}$ [MPa]	17.00	24.00
Characteristic bending strength	$f_{m,k}$ [MPa]	16.00	30.00

As the behaviour of a member differs depending on type of applied load, the process of determination of required dimensions of the cross-section was divided into two separate types of members: a compression member (column) and a beam. The design values of material properties were calculated under assumptions of a medium-term load and service class No 1 or 2 which results in value of the modification factor $k_{\mathrm{mod}} = 0.80$. The partial factor for material properties was considered as $\gamma_M = 1.25$ [7].

The static assessment of the proposed cross-sections was performed in accordance with currently valid standards taking into account the specific composition of the cross-section combining two materials with different properties and using theoretical and numerical analysis. The calculation of the design resistance of the cross-sections was performed under assumption of the magnitude of the design axial (normal) compressive load up to 100 kN (column) and design uniformly distributed load up to 6 kN/m (beam). These magnitudes of loads can be realistically expected for structures of usual timber multi-storey buildings under normal conditions.

The obtained results were compared with results of static assessments of conventional glued laminated timber members consisting of lamellas of coniferous timber only (strength class C16) to quantify the differences and finding possible benefits resulting from combination of materials.

3. Compression Members

3.1. Analytical Approach

1) Adaptation of the standard procedure

The analysis of the compression member is performed for a member of a length of 3.8 m (the height of a storey). A square section is considered (Fig. 1). The boundary conditions at both ends of the member in both perpendicular directions comply with the assumption of a simply supported member. The critical lengths for both buckling modes (about y-axis and z-axis) are therefore equal to the length of the member.

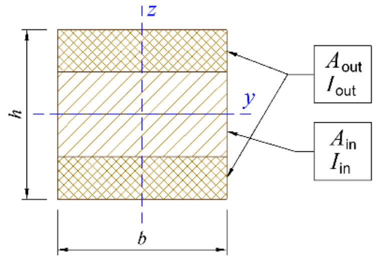

Fig. 1: Cross-section of a compression member.

The determination of design buckling resistance of the compression member was based on provisions given in standard [7] taking into account specific rules for composite members according to [8]. It is possible to express the design buckling resistance of a compression member as Eq. (1):

$$N_{b,Rd} = k_{\mathrm{mod}} \cdot \frac{N_{b,Rk}}{\gamma_M}, \tag{1}$$

where $N_{b,Rk}$ is characteristic buckling resistance. It can be formulated by Eq. (2):

$$N_{b,Rk} = k_c \cdot \left(A_{\mathrm{out}} \cdot f_{c,0,k,\mathrm{out}} + A_{\mathrm{in}} \cdot f_{c,0,k,\mathrm{in}}\right), \tag{2}$$

where k_c is the minimum instability factor, A_{out} is area of the outer lamellas, A_{in} is area of the inner lamellas and $f_{c,0,k,out}$ and $f_{c,0,k,in}$ are characteristic compressive strengths along the grain of the timber of outer or inner lamellas, respectively. The calculation of the instability factor k_c follows the usual procedure according to [7] but considering the relative slenderness as Eq. (3).

$$\lambda_{rel} = \sqrt{\frac{N_{Rk}}{N_{cr}}} = \sqrt{\frac{A_{out} \cdot f_{c,0,k,out} + A_{in} \cdot f_{c,0,k,in}}{N_{cr}}}, \quad (3)$$

where N_{cr} is elastic critical load of a composite member which can be expressed as Eq. (4) with effective flexural stiffness $(E \cdot I)_{eff}$ according to Eq. (5) with I_{out} being second moment of area of the outer lamellas, I_{in} being second moment of area of the inner lamellas and respective moduli of elasticity.

$$N_{cr} = \frac{\pi^2 \cdot (E \cdot I)_{eff}}{L_{cr}^2}, \quad (4)$$

$$(E \cdot I)_{eff} = E_{0.05,out} \cdot I_{out} + E_{0.05,in} \cdot I_{in}. \quad (5)$$

The effective flexural stiffness and respective elastic critical load should be calculated for both possible buckling modes (about y-axis and z-axis). The minimum resulting instability factor k_c calculated according to the standard procedure is used to determine the characteristic buckling resistance $N_{b,Rk}$ and subsequent design buckling resistance $N_{b,Rd}$ used for the final assessment. The straightness factor β_c is taken equal to 0.1 (glued laminated timber) [7]. For the presented composition of the cross-section, the elastic critical load for the flexural buckling about z-axis is lower than the elastic critical load for the flexural buckling about y-axis due to less favourable distribution of the portions of the cross-section with higher moduli of elasticity related to the principal axes. Using this analytical procedure, minimum required dimensions of the column cross-section were determined provided square cross-section is preferred. The results are summarized in Tab. 2.

Tab. 2: Column cross-sections and compositions.

Design axial load	Dimensions		Number of lamellas		
	Width (mm)	Depth (mm)	Outer		Inner
			Top	Bottom	
Up to 50 kN	120	120	1	1	1
50 to 100 kN	160	160	1	1	2

For further analysis and comparison with different methods of determination of the design resistance, a square cross-section with following dimensions was selected. The section consists of two outer lamellas (one top and one bottom) made of deciduous timber and two inner lamellas made of coniferous timber. Both dimensions of the cross-section (width, depth) were 160 mm. The length of the column was 3.8 m. Simply supported member (for both buckling modes) is considered. For these dimensions and boundary conditions, flexural buckling about z-axis is decisive as it gives lower value of the critical load ($N_{cr,z} = 272.49$ kN). The design buckling resistance of this cross-section calculated using the above described procedure $N_{b,Rd}$ is 157.62 kN.

2) Second order theory analysis

The lateral displacement of the compression elastic member depending on the load level can be described using Eq. (6) and respective additional bending moment using Eq. (7) [9] where N_{cr} is the critical load for buckling about z-axis which was determined using Eq. (4) and e_0 is amplitude of the initial bow imperfection. Its value is considered to be equal to $L/500$ (recommended value for glued laminated timber [7]) which results in the value of 7.6 mm. For the case selected for the analysis, the critical load $N_{cr,z}$ is 272.49 kN (see above).

$$u = e_0 \cdot \frac{N}{N_{cr} - N} \quad (6)$$

$$M = N \cdot e_0 \cdot \frac{N_{cr}}{N_{cr} - N} \quad (7)$$

Knowing given load level (axial force N) and respective effect of the second order (additional bending moment M), it is possible to calculate the normal stress with the use of the theory of ideal cross-section (the cross-section consists of material with different characteristics) with appropriate cross-section characteristics and modular ratio [8]. Resulting diagrams of the lateral displacement and the maximum normal stress at the outer and inner lamellas depending on the load level are shown in Fig. 2 and Fig. 3.

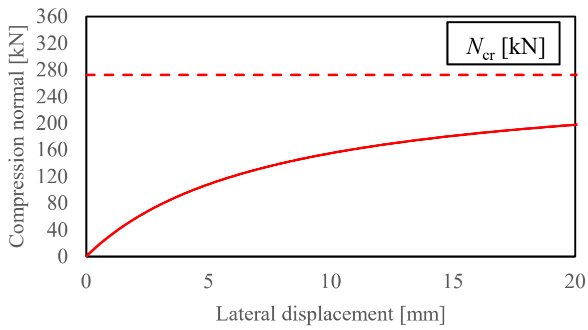

Fig. 2: Lateral displacement.

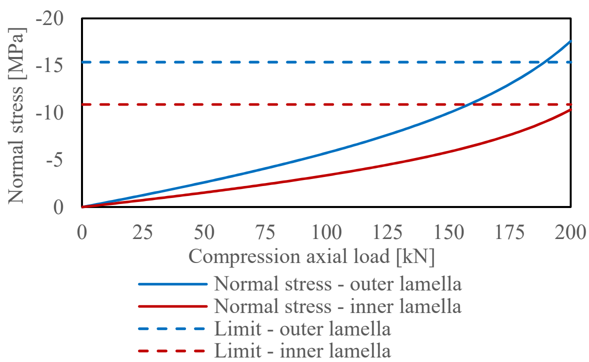

Fig. 3: Normal stress and limit values (outer and inner lamellas).

This relationship between the applied axial load and respective normal stress was used to find the load at the level of maximum allowable stress. The outer lamellas appeared to be decisive as the maximum allowable stress was reached there first (design compression strength along the grain of the outer lamellas $f_{c,0,d}$ = 15.36 MPa, for inner lamellas $f_{c,0,d}$ = 10.88 MPa). The respective maximum allowable load which can be considered as design resistance is therefore 188.75 kN.

3.2. Numerical Approach

To verify the analytical calculations, numerical analysis was performed using ANSYS 19.1 software based on the finite element method [10]. For comparison with the above mentioned calculations, a square cross-section of the column was selected with characteristics identical to those used for the analytical solution described above.

For creation of the numerical model of the column, volume finite elements SOLID186 were used. The assumption of no slip between the lamellas of the cross-section was considered which is in reality presumed to be ensured by using of suitable structural adhesive. Maximum length of the edge of an element was set to 0.02 m. The total number of finite elements was 12160, total number of nodes was 79336. The numerical model is in Fig. 5.

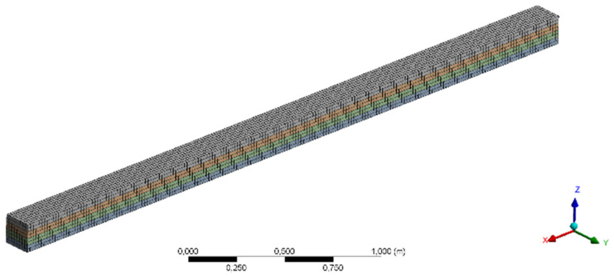

Fig. 4: Numerical model.

Linear elastic material models were used for both strength classes of the timber with moduli of elasticity according to Tab. 1. It was necessary to assign the Poisson ratio to the materials in the model. In literature, results of a number of experimental investigations of material properties of timber are available. The values of the Poisson ratio naturally slightly differ from each other. Based on [11], [12], [13], it was concluded to consider the value of the Poisson ratio equal to 0.4 which seemed to be reasonable for considered materials (coniferous and deciduous timber of common types of lumber, e.g. spruce and beech).

The first phase of the numerical modelling was verification of the magnitude of the critical normal load N_{cr} which is a crucial value necessary for calculation of the buckling resistance. For the square section of the column, two possible buckling modes can occur: flexural buckling about y-axis or flexural buckling about z-axis. The boundary conditions of the model comply with the assumption of a simply supported member (related to the respective axis of bending) for both possible buckling modes. At one end of the member, the support conditions preventing displacements in longitudinal as well as both transversal directions were assigned in the numerical model. At the opposite end of the member, the longitudinal displacement was enabled. At this end, normal force of a magnitude of 1 kN was assigned. The support conditions were assigned to the line corresponding to the centroidal axis of the cross-section for the evaluation of the respective buckling mode.

First, linear static analysis (first order) was performed. In the frame of the subsequent step, linear buckling analysis (LBA analysis) was performed to obtain the buckling modes and eigenvalues (critical loads). Both possible buckling modes were evaluated. The critical forces were compared with analytically calculated ones obtained using Eq. (4). The comparison is summarized in Tab. 3. Good agreement between the results obtained using two different methods confirms correctness of the analytical approach of calculation of the critical loads. Both buckling modes are shown in Fig. 5 and Fig. 6. It can be seen that buckling about z-axis is decisive for structural design of a column as it gives lower critical load.

Tab. 3: Comparison of critical loads.

	Method		Difference [%]
	Analytical calculation	Numerical analysis	
$N_{cr,y}$ [kN]	325.68	323.85	0.56
$N_{cr,z}$ [kN]	272.49	271.50	0.36

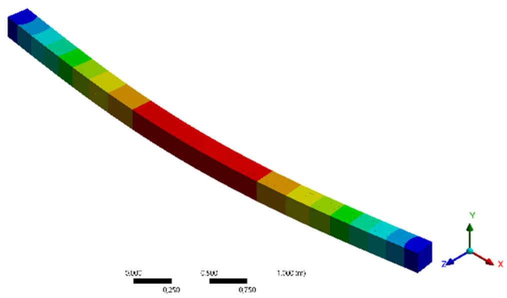

Fig. 5: Buckling mode about y-axis.

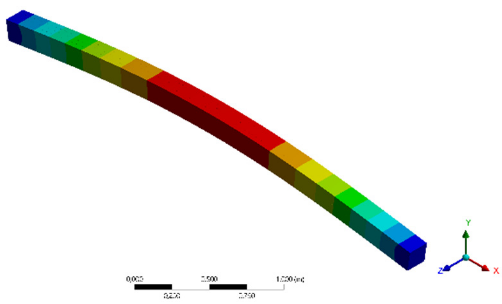

Fig. 6: Buckling mode about z-axis.

The next step of the numerical analysis was static geometrically nonlinear analysis (second order theory) of the member with imperfections (GNIA analysis). To assign the initial imperfection, the geometry of the member was updated complying with the decisive buckling mode for global buckling about z-axis with given amplitude equal to 7.6 mm ($L/500$). Once geometrically nonlinear analysis (maximum applied axial load 200 kN, 50 steps) was completed, the normal stress of the member was checked. The maximum stress was found at midspan of the member with decisive value at the outer lamellas. The maximum allowable stress at the level of $f_{c,0,d}$ was reached at 45th step of the nonlinear analysis. The respective value of the applied axial force was 180.00 kN. The normal stress distribution at midspan cross-section is displayed in Fig. 7. Little asymmetry in the stress distribution might indicate possible minor influence of torsion on the stress magnitudes.

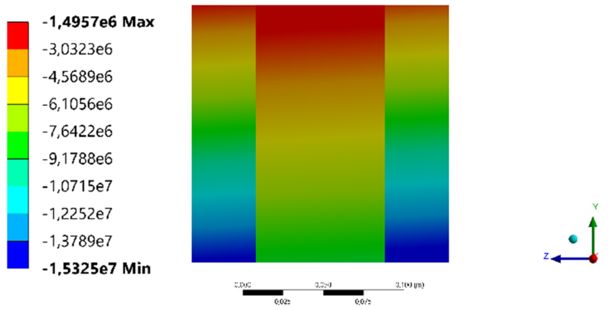

Fig. 7: Normal stress distribution.

3.3. Comparison with Reference Section

The analytical procedure was used for dimensioning of the cross-section of the column consisting of a combination of materials (strength classes C16 and D30) and assessment of its design buckling resistance for magnitudes of design normal load N_{Ed} up to 100 kN. The resulting cross-section dimensions are presented in Tab. 2 together with the respective load level (120/120 mm for loads up to 50 kN, 160/160 mm for load levels from 50 kN to 100 kN). A glued laminated cross-section of the same dimensions consisting of coniferous timber lamellas only was considered for comparison with the combined one. The process of the buckling resistance assessment followed the standard procedure [7]. The graphical interpretation of the comparison is shown in Fig. 8 using percentage utilization of the cross-section.

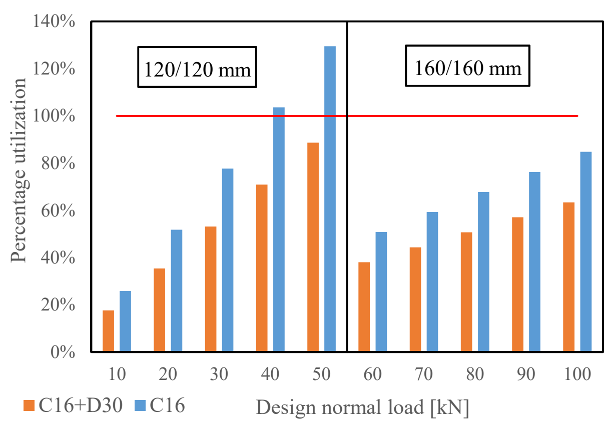

Fig. 8: Graphical comparison of results.

For some load levels, the conventional cross-section does not fulfil the reliability condition given by Eq. (8). Cross-section of greater dimensions should be used in that case.

$$\frac{N_{Ed}}{N_{bR,d}} \leq 1 \tag{8}$$

It can be seen that the combined cross-section is more economical as it gives lower utilization level than the conventional one. The average decrease of the unit utilization is approx. 21%.

4. Beams

The analysis of the member subjected to bending moment was performed for a wide range of span (from 3.0 to 6.0 m) and uniformly distributed load (from 1.0 to 6.0 kN/m) as it can be seen in Tab. 4 and Tab. 5. The static behaviour of a simple beam was considered. The analysis was performed for simple bending (without lateral torsional buckling) in ultimate limit state and for vertical deformation in serviceability limit state.

4.1. Analytical Approach

The analysis of the beam was performed for members of the length and load described above. Rectangular sections of dimensions b/h: 80/120; 80/160; 100/160; 100/200; 120/200; 120/240; 120/280; 120/320; 140/280; 140/320; 140/360; 140/400 were considered. In Fig. 9 the beam of depth of 280 mm and width of 120 mm is illustrated. The upper and bottom lamella of each cross section was made of deciduous timber and all inner lamellas were made of coniferous timber. The thickness of each lamella was 40 mm. The material properties of coniferous and deciduous timber are listed in Tab. 1.

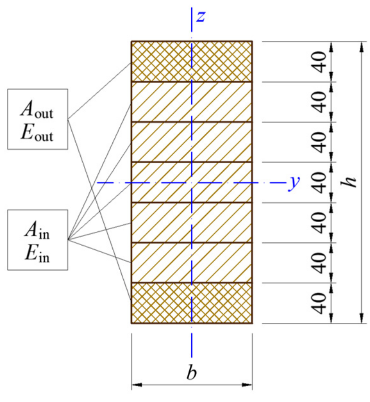

Fig. 9: Example of cross-section of a beam.

The determination of design bending resistance of the beam was based on provisions given in standard [7] taking into account specific rules for composite members according to [8]. The possible influence of lateral-torsional buckling effect was neglected, because the expected application of the investigated members are floor beams in buildings where the lateral-torsional buckling is usually prevented by the adjacent ceiling construction. The ultimate limit state is reached when normal stress in any lamella is equal to the design bending strength of that lamella. The bending resistance M_{Rd} is equal to the bending moment which causes the normal stress. It is possible to express the design bending resistance of a beam as Eq. (9):

$$M_{\mathrm{Rd}} = M_{\mathrm{Ed}} \quad \text{if} \quad \sigma_{\mathrm{Ed,i}} = \frac{M_{\mathrm{Ed}}}{I_{\mathrm{y,eff}}} \cdot z_{\mathrm{i}} = f_{\mathrm{md,i}} \tag{9}$$

where M_{Ed} is design bending moment, I_y is second moment of area, z_i is distance from centroid to the extreme fibres of i-th lamella, i is inner or outer lamella and $f_{\mathrm{md,i}}$ is design bending strength of outer or inner lamellas.

The serviceability limit state was limited by vertical deformation reaches the limit value which is considered as $L/300$. It is possible to express it as Eq. (10):

$$u_{\mathrm{z}} \leq u_{\mathrm{z,lim}} = \frac{L}{300} \tag{10}$$

Within the serviceability limit state analysis only instantaneous deformations were evaluated, because the considered characteristic load was not differentiated to permanent or variable action.

The calculation of normal stresses σ_{Ed} in lamellas and vertical deformations u_z follows the usual procedure for elastic composite beams according to [8] with considering no slip between lamellas.

4.2. Numerical Approach

To verify the analytical calculations, numerical analysis was performed using ANSYS 19.1 software based on the finite element method [10]. For comparison with the above mentioned calculations, a rectangular cross-section 140/400 of the beam was selected with characteristics identical as those used for the analytical solution described above.

The numerical model is shown in Fig. 10. The settings of numerical model (material models, finite elements size) was the same as for compression member described above. In Fig. 11 normal stress on the half of the beam is displayed. Normal stresses are concentrated in upper and bottom lamellas made of hardwood which is consistent with analytical solution.

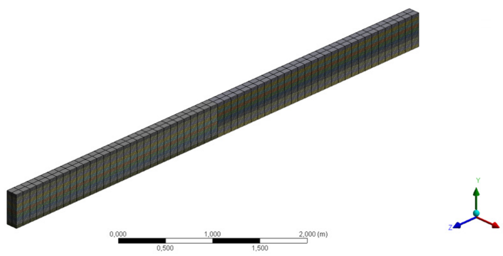

Fig. 10: Numerical model of beam of 140/400 cross section.

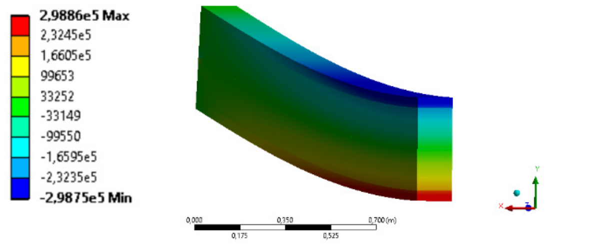

Fig. 11: Normal stress distribution on the beam of 140/400 cross-section.

4.3. Comparison with Reference Section

The analytical procedure was used for dimensioning of the cross-section of the beam consisting of a combination of softwood and hardwood (strength classes C16 and D30) and assessment of its design bending resistance for range of span (from 3.0 m to 6.0 m) and load (from 1.0 kN/m to 6.0 kN/m). The same principle was used for vertical deflections in ultimate limit state which is decisive in the considered range of span and load range.

Tab. 4: Table of minimal dimensions of combined section.

Uniformly distributed load [kN/m]	Span [m]						
	3.0	3.5	4.0	4.5	5.0	5.5	6.0
1.0	80/120	80/160	80/160	100/160	100/200	100/200	120/240
1.5	80/160	80/160	100/200	100/200	120/200	120/240	120/240
2.0	80/160	100/160	100/200	120/200	120/240	120/240	120/280
2.5	80/160	100/200	100/200	120/240	120/240	120/280	120/280
3.0	100/160	100/200	120/200	120/240	120/280	120/280	140/280
3.5	100/200	100/200	120/240	120/240	120/280	140/280	120/320
4.0	100/200	100/200	120/240	120/280	120/280	120/320	140/320
4.5	100/200	120/200	120/240	120/280	140/280	120/320	140/360
5.0	100/200	120/240	120/240	120/280	140/280	140/320	140/360
5.5	100/200	120/240	120/240	120/280	120/320	140/320	140/360
6.0	100/200	120/240	120/280	120/280	120/320	140/360	140/360

Tab. 5: Table of minimal dimensions of coniferous section.

Uniformly distributed load [kN/m]	Span [m]						
	3.0	3.5	4.0	4.5	5.0	5.5	6.0
1.0	80/160	80/160	100/160	100/200	100/200	120/240	120/240
1.5	80/160	100/160	100/200	120/200	120/240	120/240	120/280
2.0	80/160	100/200	100/200	120/240	120/240	120/280	120/280
2.5	100/160	100/200	120/200	120/240	120/280	120/280	120/320
3.0	100/200	100/200	120/240	120/240	120/280	140/280	120/320
3.5	100/200	120/200	120/240	120/280	120/280	120/320	140/320
4.0	100/200	120/240	120/240	120/280	140/280	120/320	140/360
4.5	100/200	120/240	120/280	120/280	120/320	140/320	140/360
5.0	100/200	120/240	120/280	140/280	120/320	140/360	140/360
5.5	120/200	120/240	120/280	140/280	140/320	140/360	140/400
6.0	120/200	120/240	120/280	120/320	140/320	140/360	140/400

The resulting minimal cross-section dimensions are summarized in Tab. 4. A glued laminated cross-section of the same dimensions, load and span consisting of coniferous timber lamellas only (softwood) was considered for comparison with the combined one. The process of the bending resistance assessment followed the standard procedure [7]. Deflections at both cases (combined and non-combined section) are calculated without influence of creep. The resulting minimal cross-section dimensions of reference full coniferous beam are in Tab. 5. In those tables the minimal cross-section dimensions resulting from serviceability limit state (which is decisive) are summarized.

Charts on Fig. 12 and Fig. 13 show characteristic bending resistances M_{Rk} and flexural stiffness $(E \cdot I_y)_{eff}$ for all the cross-sections made of combined softwood-hardwood and reference softwood section. The increase of bending resistance and flexural stiffness of combined cross-section compared to reference one is expressed in percentage at Fig. 14.

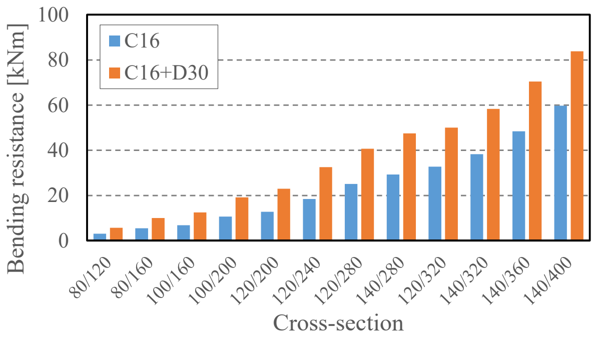

Fig. 12: Bending resistance.

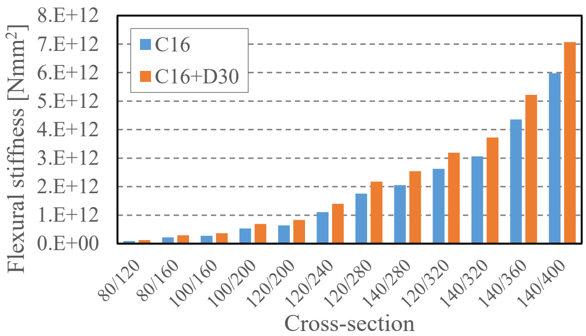

Fig. 13: Flexural stiffness.

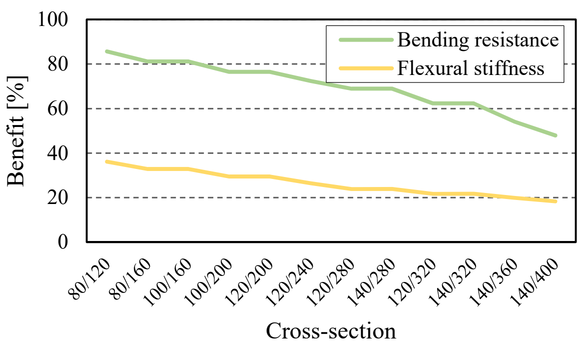

Fig. 14: Benefits of combined cross-section over to reference coniferous cross-section

5. Conclusion

In this paper, a possibility of combination softwood and hardwood in glulam cross-section is investigated. Results of theoretical study are presented which arise from an analytical calculation and from a numerical modelling. A suitable cross-section configuration was found for a column and a beam of a skeleton frame, for range of span (from 3.0 m to 6.0 m) and load (from 1.0 kN/m to 6.0 kN/m) and the height of 3.8 m. The results presented in tables can be used for preliminary timber structural design.

Comparison was performed between proposed cross-section and a reference cross-section consisting of softwood lamellas only. By comparing the combined and reference cross-sections, it can be stated that the use of the combined cross-section can save material for both the compression member (column) and the member subjected to bending moment (beam). The combined cross-section appears to be more advantageous than the reference cross-section, especially in cases of smaller beam depth.

In terms of bending resistance and flexural stiffness of beams, it can be concluded that the benefit of using of hardwood lamellas in combined cross-section decreases with increasing of section depth. Another conclusion is that serviceability limit state (represented by limit vertical deformation) is decisive than ultimate limit state (represented by bending resistance) for whole range of span and load which is usual in timber constructions for buildings and engineering structures.

The design buckling resistance of the compression member was determined using different methods. The result of the analytical second order calculation was fairly comparable with the result of the numerical geometrically nonlinear analysis performed using finite element method-based software (for the investigated case the difference did not exceed the value of 5%). The calculation complying with the currently valid standard provided slightly lower value of the design buckling resistance of the selected member (the difference was approx. 16% compared to the analytical analysis). This difference can be explained by the process of the standard calculation of the design buckling resistance of timber members where the straightness factor (representing initial bow imperfection) is adjusted to give results on the safe side. This assumption was confirmed by the exact numerical analysis of the selected member.

Based on the presented results it can be stated, that hardwood-softwood combination in glued laminated timber has a potential to be a good alternative in timber construction designing. The research will be followed by experimental verification of reached results and by verification of failure mode at finger joints and at lamination glue lines.

Acknowledgements

The paper was elaborated in the frame of the project No TJ02000171 of the Technology Agency of the Czech Republic.

References

[1] AICHER, S., Z. CHRISTIAN and G. DILL-LANGER. Hardwood glulams – emerging timber products of superior mechanical properties. In: *Proceedings of the World Conference on timber Engineering (WCTE).* Quebec City, Canada: Curran Associates, 2014, pp. 287–296. ISBN 978-1-5108-5820-6. ISSN 00002014.

[2] TRAN, V.-D., M. OUDJENE and P.-J. MÉAUSOONE. Experimental investigation on full-scale glued oak solid timber beams for structural bearing capacity. *Construction and Building Materials*. 2016, vol. 123, iss. 1, pp. 365-371. DOI: 10.1016/j.conbuildmat.2016.07.002. ISSN 0950-0618.

[3] LANVIN, J.D., G. LEGRAND, F. SIMON, C. FAYE, C. PRINCE, and J. LEMAIRE. Strength Assessment and Potential for Use as Glulam of French Chestnut Lumber. In *Proceedings Of The 5Th International Scientific Conference On Hardwood Processing 2015*, Quebec City, Canada: FPInnovations, 2015, pp. 131–138. ISBN 978-0-86488-571-5.

[4] GONG, M., D. TU, L. LI and Y.H. CHUI. Planar Shear Properties of Hardwood Cross Layer in Hybrid Cross Laminated Timber. In *Proceedings of the 5th International Scientific Conference On Hardwood Processing 2015*, Quebec City, Canada: FPInnovations, 2015, pp. 85–90. ISBN 978-0-86488-571-5.

[5] AICHER, S., M. HIRSCH and Z. CHRISTIAN. Hybrid cross-laminated timber plates with beech wood cross-layers. *Construction and Building Materials*. 2016, vol. 124, iss. 15, pp. 1007–1018. DOI: 10.1016/j.conbuildmat.2016.08.051. ISSN 0950-0618.

[6] ČSN EN 338. *Konstrukční dřevo – Třídy pevnosti (Structural timber – Strength classes)*. Praha: Úřad pro technickou normalizaci, metrologii a státní zkušebnictví (Czech Office for Standards, Metrology and Testing), 2016.

[7] ČSN EN 1995-1-1. *Eurokód 5: Navrhování dřevěných konstrukcí – Část 1-1: Obecná pravidla – Společná pravidla a pravidla pro pozemní stavby (Eurocode 5: Design of timber structures – Part 1-1: General – Common rules and rules for buildings)*. Praha: Český normalizační institut (Czech Normalization Institute), 2006.

[8] ČSN EN 1994-1-1. *Eurokód 4: Navrhování spřažených ocelobetonových konstrukcí – Část 1-1: Obecná pravidla a pravidla pro pozemní stavby (Eurocode 4: Design of composite steel and concrete structures – Part 1-1: General rules and rules for buildings)*. Praha: Český normalizační institut (Czech Normalization Institute), 2006.

[9] BŘEZINA, V. *Vzpěrná únosnost kovových prutů a nosníků (Buckling resistance of metal members)*. Praha: Nakladatelství Československé akademie věd (Czechoslovak Academy of Science Publishing), 1962.

[10] ANSYS® Multiphysics, Release 19.1.

[11] KUMPENZA, C., P. MATZ, P. HALBAUER, M. GRABNER, G. STEINER, F. FEIST and U. MÜLLER. Measuring Poisson's ratio: mechanical characterization of spruce wood by means of non-contact optical gauging techniques. *Wood Science and Technology*. 2018, vol. 52, iss. 6, pp. 1451–1471. ISSN 0043-7719. DOI: 10.1007/s00226-018-1045-7.

[12] HERING, S., D. KEUNECKE and P. NIEMZ. Moisture-dependent orthotropic elasticity of beech wood. *Wood Science and Technology*. 2012, vol. 46, iss. 5, pp. 927–938. ISSN 0043-7719. DOI: 10.1007/s00226-011-0449-4.

[13] NIEMZ, P. and D. CADUFF. Untersuchungen zur Bestimmung der Poissonschen Konstanten an Fichteholz (Research into determination of the Poisson ratio of spruce wood). *Holz als Roh- und Werkstoff*. 2008, vol. 66, iss. 1, pp. 1–4. ISSN 0018-3768. DOI: 10.1007/s00107-007-0188-2.

About Authors

Ivan BALÁZS was born in Brno, Czech Republic. He received his Ph.D. from Brno University of Technology, Faculty of Civil Engineering in 2017. His research interests include problems of stability of steel structures, thin-walled members and numerical simulations of load-bearing structures.

Pavla BUKOVSKÁ was born in Valtice, Czech Republic. She is a Ph.D. student at Brno University of Technology, Faculty of Civil Engineering. Her research interests include steel and timber composite members.

Ondřej PEŠEK was born in Vysoké Mýto, Czech Republic. He received his Ph.D. from Brno University of Technology, Faculty of Civil Engineering in 2018. His research interests include designing of steel, glass and GFRP structures and numerical simulations of load-bearing structures.