Högpresterande byggnadselement från svenskt lövträ

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Content

Summary

The overall aim of the project was to contribute to a reduced climate footprint from the construction industry and to strengthen the competitiveness of the Swedish forestry industry, through new knowledge about how future construction products can be designed. Through increased and efficient use of high-quality and further processed raw materials from our forests, the transition to a sustainable bio-based economy can be facilitated. Modern timber construction, is almost exclusively based on softwood species spruce and pine, while hardwood species are used only to a very limited or non-existent extent. Hardwood species such as birch and beech do however have great potential to for use in structural components and for development of high-performance products for structural purposes.

The one-year project *Högpresterande byggnadselement från svenskt lövträ* (supported by the ÅForsk Foundation) contributes to the completion of the project *Increased added value for Swedish hardwood – from forest to construction products* (supported by the Södra Research Foundation), carried out in collaboration between Skogforsk, Aalto University and the Division of Structural Mechanics, LTH Faculty of Engineering, Lund University. That project includes interdisciplinary research efforts along the entire value chain for hardwood building elements: from planting via felling, sawing, manufacturing building elements and finally a finished building. Within the project *Högpresterande byggnadselement från svenskt lövträ*, mainly two sub-areas have been studied: 1) fracture properties of different wood species and 2) dynamic properties of timber floors produced from different wood species.

Experimental and theoretical studies of fracture properties at tensile loading perpendicular to the fibre direction have been carried out. A governing material property for the load-bearing capacity of mechanical joints (e.g. screw and dowel-type joints) in timber structure is the fracture energy of the material, which describes the energy required to form a unit area of a traction-free crack during crack initiation and propagation. Fracture energy tests for birch material and spruce material have been carried out and the results suggest that birch has a higher fracture energy than typical softwoods used for structural timber and engineered wood products. Within the research work regarding fracture properties, development of the testing method itself has also been carried out, by examining the influence of the geometric shape of the specimens on the test results.

Floors with long spans are particularly sensitive to vibrations caused by footfalls. Timber-based floors, made of glulam or cross laminated timber (CLT), are in Sweden today almost exclusively produced from softwood species. Hardwoods such as birch and beech have higher stiffness and density, which can potentially improve the vibration performance of timber-based floors. Within the project, the vibrational performance of CLT panels made of beech and birch with different mechanical properties was investigated using finite element (FE) models calibrated via experimental modal analysis (EMA) tests. The study demonstrated that birch or beech laminations, compared with spruce ones, can provide a significant mitigation of vibrational responses, both for broadband (1–100 Hz) and footfall-induced vibrations.

1. Background and introduction

World-wide, and specifically northern Europe, softwood species such as spruce and pine are predominantly used in structural applications. However, hardwood species such as birch and beech, which potentially have higher strength and stiffness compared to softwood species, are also available. In Sweden, birch makes up roughly 15% of the stock forest population. As such, potentially improved wood-based products could be acquired by utilization of such species, as replacement of or in conjunction with, softwood species. Before introducing *new* materials in structural applications, it is however necessary to be able to predict the structural behaviour to allow for efficient and reliable structural design. This is very important, especially in relation to design with respect to material failure and fracture behaviour and knowledge of the mechanical behaviour of structural materials is highly important for the design process in general. Due to the historically widespread use of softwood species spruce and pine in the construction industry, such knowledge is significantly more prevalent for softwood species, compared to hardwood species, such as birch.

The interest for characterisation of the mechanical behaviour of hardwood species has increased in recent years and results suggest that birch in general possess superior mechanical properties for many structural applications, compared to spruce. For example, a significantly higher modulus of elasticity in bending for birch (compared to spruce) has been seen reported [1, 2]. Studies of birch wood loaded in compression parallel and perpendicular to grain loading, are also found in the literature, see e.g. [3]. The rolling shear stiffness, which is of important for the mechanical behaviour of Cross Laminated Timber (CLT), has also been examined in various studies, e.g. [2, 4]. In these studies, a significantly higher rolling shear modulus is reported, compared to typical values found for softwood species. Efforts have also been made to compile current knowledge of material parameters for various common wood species, see e.g. [5].

It is however clear, that the complete characterization of birch as a structural material is insufficient. The current availability of material property parameters is mainly related to elastic stiffness parameters and strength parameters at tension parallel to the grain and compression parallel and perpendicular to the grain. The mentioned parameters are all of great importance for the structural design of load-bearing structures. For design and prediction of load-bearing capacity of mechanical joints (e.g. screw and dowel-type joints) and beams with irregular geometries (e.g. beams with holes or notches) fracture mechanical properties are also needed for reliable determination of the load-bearing capacity. The present work aims to characterise the fracture behaviour of birch in terms determination of the specific fracture energy and the softening behaviour. This characterisation was carried out by conducting experimental tests and numerical simulations of birch material loaded in tension perpendicular to the grain.

Previous research indicates that wood-based structural products, such as CLT, may have superior mechanical properties if hardwood species such as birch and beech are utilised for the laminations instead of traditionally used softwood species such as spruce and pine. Within the project, computer models for numerical simulations of the dynamic behaviour of CLT floors were developed and used in applied analysis in order to quantify the potential benefits.

2. Fracture energy at tension perpendicular to the grain

Data for fracture mechanical properties of birch is scarce in the research literature. Studies of the fracture behaviour of compact tension specimens made of birch and spruce have been presented by Tukiainen and Hughes [6, 7]. In this study, higher values of the fracture energy G_f were in general found for the birch material (compared to spruce). For accurate and reliable evaluation of the fracture energy from this type of testing, a stable response in terms of the load versus crack-mouth opening displacement (CMOD) response is needed. This was not always the case for the reported tests and the birch material showed in many cases an unstable response, giving unreliable results for the evaluated fracture energy.

Experimental tests concerning the fracture energy at tension perpendicular to grain for birch and Scots pine have been presented by Forsman et al [8]. This study was focused on the effects of wood modification by acetylation of the two species and tests were performed on specimens conditioned in different climates regarding relative humidity (RH). A 3-point-bending test configuration according to the Nordtest-method [9] was used for loading of Single-Edge Notched Beam (SENB) specimens with geometry according to Figure 1. However, two modifications of the specimen geometry compared to the description in [9] were introduced: All specimen sizes were scaled to a = 20 mm and b = 20 mm and notch lengths of 0.5a were used. For the birch material, the shape of the notch was also altered to achieve a triangular shape of the fracture area of size $0.5h_cb$, following the suggestion of specimen geometry given in [10], in order to promote a stable load versus displacement response. These tests however still suffered from some difficulties regarding stability of the response.

For test series conditioned at 20 °C and RH 75%, the mean values of the fracture energy were determined as 460 Nm/m^2 and 387 Nm/m^2 for unmodified birch and unmodified pine, respectively.

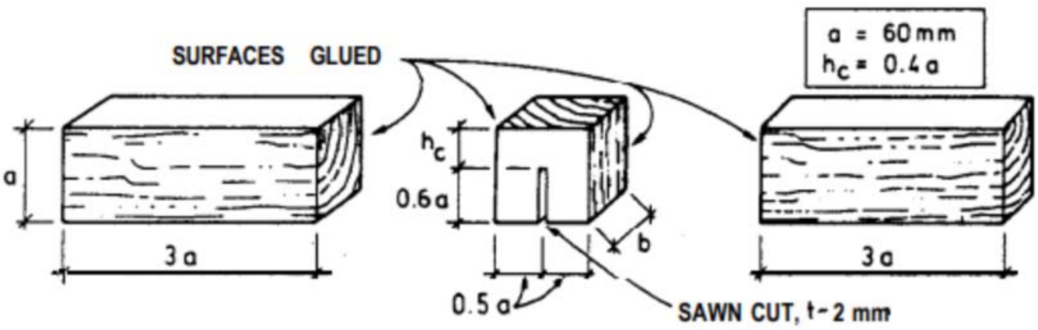

Figure 1: Geometry of specimen for testing of fracture energy according to the Nordtest-method [9].

2.1 Test method

Experimental tests were conducted at the Division of Structural Mechanics, Faculty of Engineering LTH, Lund University, during the spring of 2023. A 3-point-bending test configuration according to the Nordtest-method [9] was used for all tests, with specimen dimensions according to Figure 2. Two materials were tested, silver birch originating from southern Finland and Norway spruce of strength class C24. The specimens were produced with the middle piece made from either birch or spruce, while the two side pieces were made from spruce for all tests. The specimens were conditioned at 20 °C and RH 60% before testing.

Two types of notches were used for the tests: a rectangular notch (giving a rectangular fracture area) and a chevron notch (giving a triangular shaped fracture area), see Figure 2. The choice of using chevron notches was made based on considerations of instabilities reported for previous tests of birch material, see above. Numerical simulations were also performed in order to investigate suitable specimen geometries in order to obtain stable responses for both birch and spruce.

A total of four test series were included in the test programme: Norway spruce with rectangular notches, Norway spruce with chevron notches, silver birch with rectangular notches and silver birch with chevron notches.

The tests were performed in displacement control using an MTS-machine, see Figure 3 (left), with a constant rate of loading of 0.75 mm/min. The applied load and the crosshead movement was measured during loading. The fracture energy G_f was then determined from the recorded test data according to Figure 3 (right), as the work done by the midpoint force *F* during the complete course of loading.

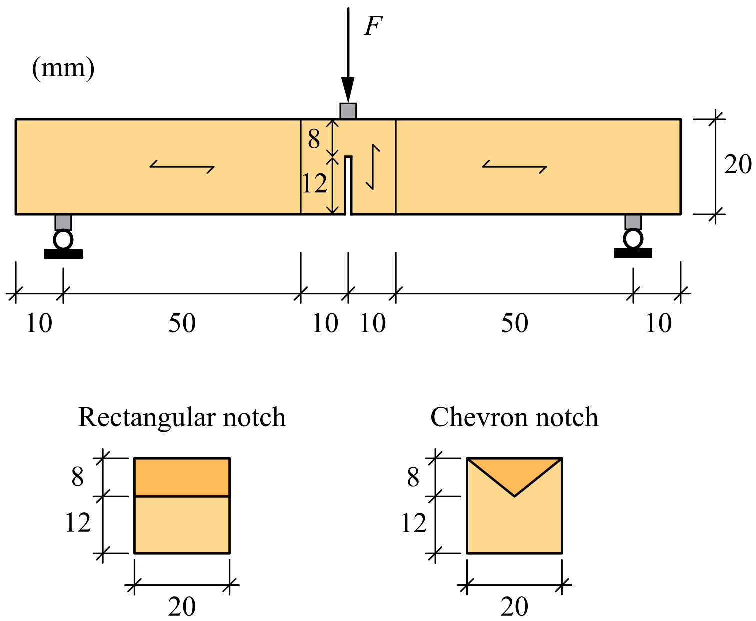

Figure 2: Test setup and specimen geometry for testing of fracture energy.

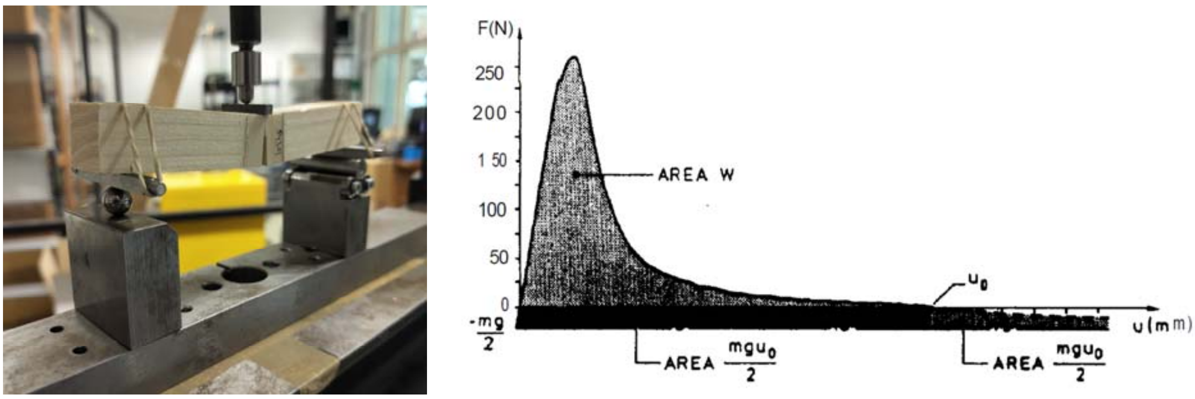

Figure 3: Specimen during loading (left) and illustration of load vs displacement response from [9] (right)

2.2 Test results

The preliminary test results suggest that the fracture energy obtained from the birch specimens is significantly greater than the fracture energy obtained from the spruce specimens. Detailed analysis of test results is currently carried out and a manuscript is being prepared for submission to a scientific journal.

Ongoing analyses concern evaluation of fracture energy based on the nominal fracture area, according to dimensions given in Figure 2, and evaluation based on the fracture area based from a detailed measurements of photos taken of the actual fracture area of each specimen. Further analyses also include general comparison of the presence of instabilities in the load versus displacement response for the different materials and for the two different notch shapes.

2.3 Discussion and conclusions

The collected test results are very useful for further research work relating to the use of birch and other hardwoods for structural applications. The fracture energy is an important material property for analysis of structural elements and joint where of load-bearing capacity is limited by crack initiation and propagation. For such applications, rational models for analysis include Linear Elastic Fracture Mechanics (LEFM) and approaches based on nonlinear fracture mechanics, e.g. cohesive zone modelling.

The data from the test described above will be used for calibration of material models to be used numerical simulations of structural elements and joints. An outline for such a calibration approach was presented at the conference *CompWood*, held in Dresden during September 2023. Further analysis of the test data is ongoing, and the results are expected to be presented as a paper in a scientific journal during the spring of 2024.

3. Dynamic behaviour of cross laminated timber panels

The vibrational performance of CLT panels made of beech and birch has been analysed within the project, in order to investigate and quantify the potential performance of such CLT panels compared to traditional panels made from softwood laminations.

Floors made by wood-based structural elements can be sensitive to footfall induced vibrations and this issue is a critical concern in the design of such floors. Using hardwood species, such as birch and beech, in CLT floors may improve the vibrational performance since these species generally have a greater stiffness and higher density compared to softwood species spruce and pine.

CLT of different species and with different mechanical properties was investigated using finite element (FE) models, calibrated via experimental modal analysis (EMA) tests. Based on a literature review concerning stiffness and density properties for birch and beech, two sets of material properties were defined for each species, see Table 1 and [11]. Material property sets denoted "high" and "low" refer to upper and lower limits, respectively, of values found from the literature review.

Results of numerical simulations for these four sets of material properties were compared to results considering material property values for spruce, considering mean stiffness values for the softwood strength class C24 according to EN 338 [12] as a reference.

Table 1. Mechanical properties used in the investigation. Moduli in MPa and density in kg/m^3.

	E_L	E_R	E_T	G_{LT}	G_{LR}	G_{RT}	ρ
Spruce C24	11 000	370	370	690	690	49	420
Birch, low	13 000	1 100	620	850	850	175	510
Birch, high	16 500	1 260	650	850	850	180	830
Beech, low	10 000	1 310	460	1 240	940	350	540
Beech, high	18 000	1 510	730	1 240	940	380	910

3.1 Numerical model

The CLT panels were modelled in 3D using the FE method and the software Abaqus. A python script was developed in order to formulate the models and conduct the numerical investigations. Each layer in the CLT plates was modelled as homogeneous solid and full interaction was assumed between the layers. Quadratic brick elements with reduced integration were used for all models.

The FE model was calibrated to experimental results from measurements of a 5-layer CLT plate of length 1500 mm, width 1000 mm, and thickness 120 mm [11]. The CLT panel was suspended by elastic straps and accelerations excited by an impact hammer were measured. The experimentally obtained natural frequencies and the corresponding modes shapes of the first nine modes were then used in a calibration process according to Newton's method. The calibration process involved the metrics normalized relative frequency difference (NRFD) and the modal assurance criteria (MAC).

In the next step, the vibrational response of CLT panels composed of layers of different wood species was studied. Three different panel sizes and CLT lay-ups were studied:

- Small panel: L = 5 m, b = 2.4 m and t = 150 mm, CLT lay-up 30-30-30-30-30
- Medium panel: L = 7 m, b = 2.4 m and t = 280 mm, CLT lay-up 40+40-40-40-40-40+40
- Large panel: L = 9 m, b = 2.4 m and t = 315 mm, CLT lay-up 45+45-45-45-45-45+45

The CLT panels were modelled as simply supported along the short edges (2.4 m) and the spans were hence 5 m, 7 m and 9 m for the three panel sizes, respectively. The numbers given for the CLT lay-ups above refer to the thickness of the individual layers, where the medium and the large panel had two layers of laminations in the same direction on the top and bottom side of the panel.

The vibrational performance of the panels was evaluated considering natural frequencies, accelerance frequency response functions (FRFs) and response to transient footfall loading. The effects on natural frequencies were evaluated using normalized relative frequency differences (NRFDs). The FRFs were evaluated by calculating the steady-state acceleration response under harmonic loading of a unit force (1 N) at frequencies in the range 1–100 Hz and comparing the root mean square (RMS) values of the acceleration.

For footfall induced loading, the effect of using birch or beech laminations was investigated by computing the acceleration from a transient analysis of five consecutive walking steps in the direction of the panel length, see Figure 4. Walking frequencies f_s from 1.5 to 2.4 Hz were considered, in frequency steps of 0.01 Hz and the mass of the walker was 75 kg. The shape of the footfall force $F(t)$ was assumed according to [13], as a function of the walking frequency and the mass of the walker. The stride length l_s was determined from the relation $l_s = v/f_s$, with the walking velocity v (m/s) defined as a function of the walking frequency f_s according to [14].

Modal decomposition, considering 12 retained modes, and implicit time-integration with a time step of 1 ms were used for the analyses of footfall induced loading. The results were analysed considering the transient out-of-plane acceleration at the midpoint of the panel, over a period of 5 s to capture the entire response including the decay after the last footfall. For comparison of the response for different material property values (spruce/birch/beech), RMS values of the acceleration for the worst second within the 5 s time period was determined using a 1 s window sweeping over the entire time period for the analyses.

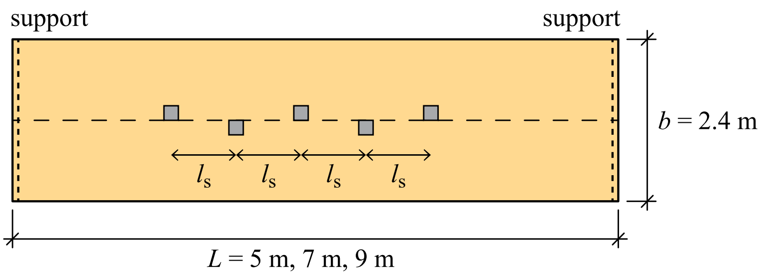

Figure 4: Panel geometry, panel supports and load positions for footsteps.

3.2 Numerical results

Using material properties for birch and beech, considering both "low" and "high" values, the natural frequencies increase for most modes of all three panel sizes (small/medium/large) compared to the reference case of material properties of strength class C24. The NRFDs were in general greater for the higher modes than for those of the lower modes. The fundamental frequency (the lowest natural frequency) was however reduced considerably (about 10%) for both sets of material properties of beech and for the high values of birch. The most significant NRFD (about 30%) were found for higher modes and for low values of birch and beech.

Regarding the FRFs, differences could be seen both regarding the magnitudes of the peaks and regarding the frequencies for both sets of material property values of birch and beech. The RMS values of the acceleration for the considered frequency range (1–100 Hz) was found to be significantly lower for birch and beech compared to the reference of strength class C24, with reductions of RMS values to about 40% of the reference value.

The analyses of footfall induced loading showed that the acceleration response is highly influenced the walking frequency, which can be explained by matching of the fundamental frequency of the panel with the harmonics of the applied load. Overall, the investigation showed that using birch and beech laminations in CLT may lead to substantial mitigation of footfall-induced vibrations compared with the reference case of spruce from strength class C24. Birch gave the most consistent reduction of the acceleration response for the CLT panel sizes, CLT layups and walking frequencies included in the investigations, with reductions of RMS values to about 30% of the reference value. For beech, even greater reduction of the vibration response was achieved for many cases. However, also considerable increase of the vibration response was found for certain cases for low-quality beech.

3.3 Discussion and conclusions

A main conclusion from the investigation is that the use of birch or beech laminations in CLT (instead of spruce laminations), may improve the floor performance regarding the dynamic behaviour. Significant mitigation of the vibrational response, both for broadband (1–100 Hz) and footfall-induced vibrations, were found from the numerical investigations of CLT panels.

The investigation of the dynamic behaviour of cross laminated timber panels made from different wood species is expected to be published in a scientific journal during the spring of 2024. A manuscript [15] is currently under review.

4. General conclusions and further studies

The project has contributed to increased knowledge of hardwood species and their mechanical properties relevant for structural use, specifically the fracture energy at tensile loading perpendicular to the grain. The potential benefits of using hardwood species for laminations in CLT floor has also been investigated. The results suggest that the vibration response, and hence the comfort of the occupants, can be significantly improved using hardwood laminations compared to traditionally used softwood laminations.

The investigations conducted within the project *Högpresterande byggnadselement från svenskt lövträ* are parts of the larger research project *Increased added value for Swedish hardwood – from forest to construction products*. That project continues during 2024 and further research related to the work presented in this report will be carried out.

The work carried out within the project *Högpresterande byggnadselement från svenskt lövträ* has also inspired new research applications and funded research projects relating to the use of structural elements from hardwoods.

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