Mechanical properties of timber product required by end users

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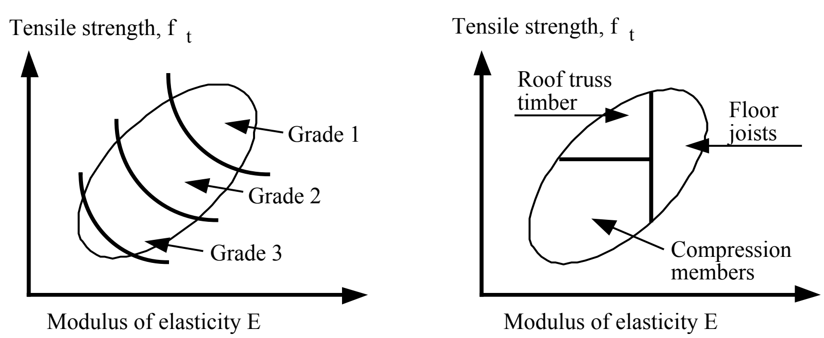
ABSTRACT

This paper deals primarily with the use of timber products in some common and general design applications (suggested by building contractors) and evaluates and propose some governing mechanical properties for each product. The design calculations on which the presented results were based should be regarded as a rough estimate. The main aim, however, was to obtain the utilization factors as a percentage of the strength/stiffness parameters for different timber products using just one code. Methodology is shown and based on a design calculation for floor joist timber. In similar way utilization factors were obtained for wall studs (external studs used in small buildings and multi-storey buildings), ground plates in wall structures, roof trusses, purlins in roof structures and formwork timber in some temporary gravity-loaded structures.

This study clearly demonstrated that stiffness is the governing property for many products, assuming that a certain level of bending strength is present for timber of high stiffness. It would be very desirable to produce some timber in fairly large sizes (dimensions > 45 x 195 mm) and a length of between 4 and 8 metres with a high stiffness class (> 12 GPa). When this timber dimension is graded in MOE classes, it could be differentiated in terms of the obtained shape. The most "straight" timber (spring < 8 mm and twist < 10 mm) should be classified as floor joists and ceiling joists in roof trusses. Less "straight" timber (spring < 20 mm and twist < 20 mm) can be used as purlins or in other applications. It is obvious that the bending strength of this timber should be verified and checked against the minimum requirements with regard to bending strength.

BACKGROUND AND OBJECTIVES

Strength and stiffness requirements differ considerably between timber products. Sawmills industries produce structural timber more or less as a bulk material without any consideration of end-user requirements. In order to improve the negative image of timber and to improve producers' profitability, a product-oriented grading system is required. To the knowledge of author, no such system for the timber used as a building material exists at present. An innovative system of this kind would make it possible to produce timber products which can easily be adapted to suit different customer requirements and which carry detailed quality specifications. This system should also enable end users to obtain technical specifications for each product, thereby enabling them to assess added value levels. A buyer would obtain a very well-defined product which would justify its choice and price on its own technical merits.



a) conventional grading system **b)** product-related classification

Figure 1. Use of raw material (Leicester 1992).

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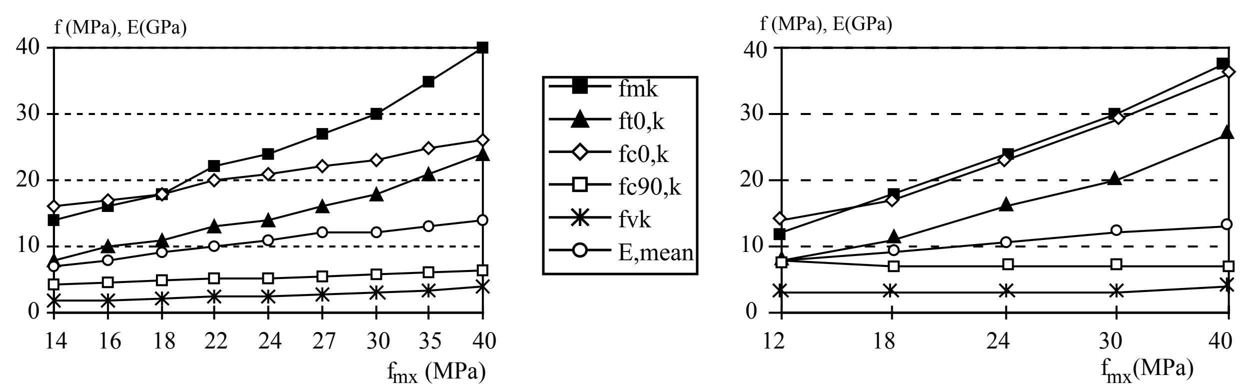
Current grading systems are too general and do not utilize the potential of wood resources. In the current grading system the raw material is divided into grading classes according to Figure 1a. A product specification system aims at a principal subdivision according to Figure 1b.

In the earlier projects shape and deformation requirements for various timber products has been assessed, see Johansson et al. 1994 or Kliger et al. 1994. The earlier work was based on geometrical studies to formulate the requirements for different products. The requirements were assessed by contractors, carpenters, consulting engineers and so on through interviews and through grading at building sites. A very similar methodology to the one used previously was applied in this project which focused more on the commonly used engineering parameters/properties such as strength and stiffness. The design calculations produced which formed the background to this study should be regarded as rough estimates, as the examples were not accurately defined from a geometrical viewpoint and partial coefficients for action and material characteristics vary between different building codes.

One important aim of this project was to identify the most vital product properties for end-user satisfaction and to formulate these requirements in measurable wood properties. The main aim, however, was to obtain the utilization factors as a percentage of strength/stiffness parameters for different timber products using just one code. The trends for the utilization factors as a percentage of the strength/stiffness parameters for different timber products will produce the same tentative results, regardless of the building code and as this project has been produced in a collaboration with a group of Swedish building contractors, it was decided to carry out the design calculations using the Swedish code (BKR 94). The timber products discussed in more details in this paper with regards to the mechanical properties were floor joist timber, wall studs (external studs used in small buildings and multi-storey buildings) and ground plates in wall structures. Furthermore, timber used in roof trusses, purlins in roof structures and formwork timber in some temporary structures was also briefly discussed.



a) Eurocode 5 **b)** Swedish building code BKR 94.

Figure 2. Characteristic values for mechanical strength (stiffness) for different strength classes (f_{mx}). The characteristic values for strength class 40 in BKR94 apply to glulam, L40.

Mechanical properties (stresses and modulus of elasticity) vary with different strength classes expressed as bending strength fmk, see Figure 2. There are nine strength classes in the Eurocode 5 and five classes in BKR94. Each class is denoted as C14 for Eurocode 5, for example or K18 for BKR94, for example and figures after letters C or K are the characteristic bending strength (5-percentile) fmx with values from 14 MPa to 40 MPa. Bending strength fmk increases the most (by 186%), while the modulus of elasticity E0, mean increases by 100% within the interval of strength classes C14 to C40 (Eurocode 5). Shear strength (fvk) and compression perpendicular to the grain (fc90,k) increase by only about 70% within the same interval. This is one of the main reasons for the difficulty involved in optimizing the utilization of structural timber.

FLOOR JOIST TIMBER

A floor structure is a load-bearing horizontal component which demarcates different storeys in a building. Depending on its position in the building, a structure of this kind can be designated as an intermediate floor, loft ceiling structure or floor above a crawl space. Floor joists are made of lumber or EWT, I-beams for example, with spacing which is usually 400 mm or 600 mm, with or without thermal insulation. In certain floor structures, the spacing between the beams can vary between 300 and 1200 mm depending on the type of floor structure, type of building and other criteria. Flooring is applied on top of the joists and a ceiling cover under the joists. The flooring can be made of wood or any wood-based sheet material, provided that it fulfils the safety and functional requirements. In Sweden, flooring is frequently made of 22 mm thick particleboard. The requirements for various types of floor structure can vary for different selfweight loads and live loads. Requirements set for floors in multi-storey buildings become much more rigorous when compared with one-family dwellings. The serviceability requirements for floor structures separating two different apartaments in particular must fulfil the requirements relating to deflection, vibration, sound transmission and fire resistance, apart from the mechanical requirements. The literature on floors is very extensive and in this paper only general information and information related to the requirements set for timber is given.

There are three basic criteria, i.e. strength, deflection and vibration, for floor joists when it comes to the mechanical properties of timber. Wooden flooring on top of floor joists functions as a compression flange. This flange is rigidly connected to timber joists and both parts become a T-joist. Like most timber structures, floor joists have to satisfy two basic requirements: safety requirements, usually expressed in terms of load-bearing capacity, and serviceability requirements, expressed in terms of limited deflection and limited vibration. The rigid connection between floor joist and compression flange can be utilized in serviceability limit state design only. Safety design does not permit the utilization of the glue joint between floor joist and flooring in structural interaction, due to the uncertainty of gluing on site. The maximum shear strength at the support was calculated without reduction as a result of the depth of the joists. However, it was assumed that shear strength was not the governig property for floor joists and, as a result, it was calculated on the safe side without any reduction in the shear force.

According to the Swedish building code BKR 94 or Eurocode 5, for residential floors with a fundamental frequency higher than 8 Hz, the basic serviceability requirement is that the deflection in the middle of the span should not exceed 1.5 mm for a concentrated load of 1 kN. It is important to take account of the percentage of the concentrated load expressed as the load distribution factor k, which depends on the equivalent plate bending stiffness in both major directions. This simple model corresponds to the floor vibration level when taking account of the expected stiffness of the floor and the modal damping ratio. As a result, this criterion is called “vibration criterion” in this paper. The design calculations should be regarded as rough design estimations of two types of floor joist: T-joist - solid timber beam with structural particleboard (in composite action at the serviceability limit state) or solid timber beam with wooden boards connected non-rigidly. The aim of this exercise was to obtain the utilization factors for mechanical properties expressed in per cent. In order to obtain utilization values for different structural timber classes of the same dimension, the span had to vary for different classes when the vibration criterion was utilized to 100% (the design factor for residential wooden floors). This could be achieved by varying the load distribution factor k for different timber classes in order to obtain the same deflection. Different structural classes expressed in Kxx (xx is the characteristic strength) are used in Figures 3, 4 and 6.

The methodology will be illustrated on the the simply-supported floor joist (dimensions 45 x 220 mm, strength class K24, Em = 10500 MPa, service class 1, load duration classes medium-term and long-term) in a residential house at intermediate floor structure with joist spacing of 0.6 m the design value of actions was 1.8 kN/m.

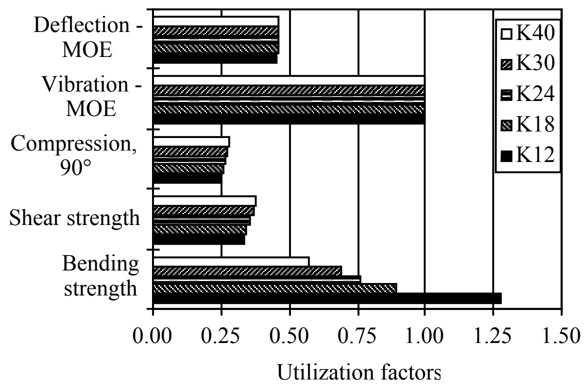
Concentrated load criterion for T-joist (timber and 22 mm structural particleboard)
Deflection U in the middle of the simply-supported T-joist has Ulimit of 1.5 mm for P = 1 kN.

$$U = k \frac{P\,L^3}{48\,EI_x} \quad \text{where: } k = 0.9 + 0.27 \times \log\beta \text{ (load distribution factor) and } \quad \beta = \frac{EI_x}{sD_y}\left(\frac{s}{L}\right)^4 \text{ with } D_y = \frac{E\,t^3}{12}$$

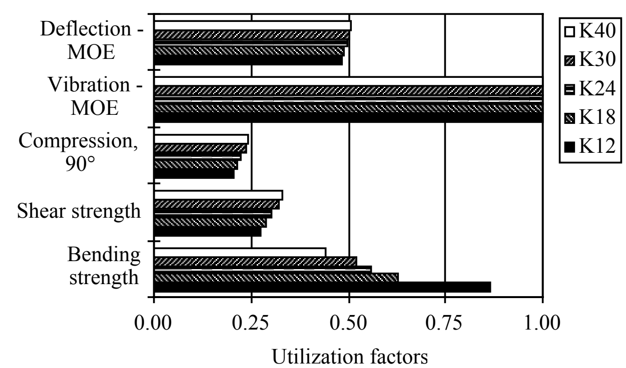
Span L can be calculated for Ulimit = 1.5 mm. As β is dependent on span L, it is necessary to find L which fulfils both criteria. By iterated calculations it was found that L = 4.28 m for β = 0.34. The span L varies for different structural classes due to the fact that the characteristic values of the modulus of elasticity for timber joists vary. In the same way as shown above, the following spans were obtained: for K12, L = 4.023 m, for K18, L = 4.131 m, for K30, L = 4.409 m and for L40, L = 4.490 m. Now, for each timber class and the coresponding maximum span which fulfils the “vibration criterion” all bending and shear stresses, compression stress perpendicular to the grain and the maximum deflection for the simply-supported joist in combination of different actions with different durations were calculated. All these calculated values were compared with the design resistance of joist and deflection limits in the generally-accepted common design manner.

Utilization values for floor joists 45 x 220

It was very clear that the vibration criterion expressed as the middle deflection of a joist of 1.5 mm exposed to a concentrated load of 1 kN was the governing design parameter for the floor joist. The mechanical properties which govern the vibration criterion are the modulus of elasticity of short-term duration. However, it was interesting to know how much the other mechanical parameters were utilized when calculated for two different cases, i.e. joists with particleboard with a certain stiffness in the longitudinal direction and joists with wooden boarding with no stiffness in the longitudinal direction. It appears that, in both cases, the bending, shear and compression strength were utilized to a maximum of 60%, Figure 3. The same thing applied to the middle deflection limited to L/300. Bending strength is the governing property only for the lowest strength class K12.



a) T-joists with particleboard of 22 mm.
L vary from 4 m for K12 to 4.5 m for K40



b) Joists with boarding of 22 mm and no interaction between particleboard and timber joist.
L vary from 3.3 m for K12 to 3.95 m for K40.

Figure 3. Utilization factors for floor joists 45 x 220 mm. The span L had to vary as showed above to obtain the same governing vibration criterion.

Requirements for floor joist timber products

The mechanical requirements which are set for floor joists of different sizes are totally dominated by the vibration requirement expressed in different design values for the modulus of elasticity for each structural class. This conclusion is based on the “normal” load action and “normal span” of domestic floors, cf. Nilsson (1995). Different design loads were also tested. For a design load of 3.8 kN/m per joist, the utilization of bending strength exceeded the vibration criterion. A large floor load of this kind can occur in buildings used for special purposes; i.e. premises where people gather, such as cinemas, theatres, stands at sporting arenas, corridors and so on.

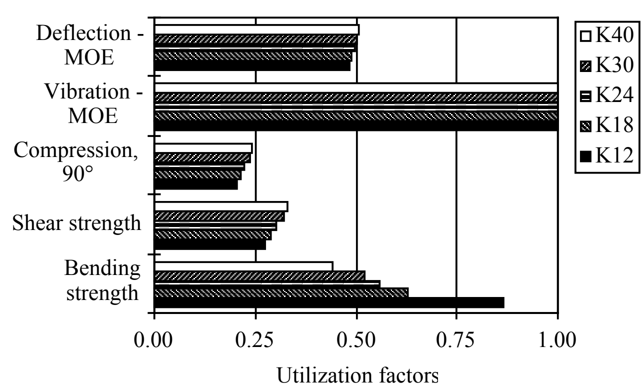
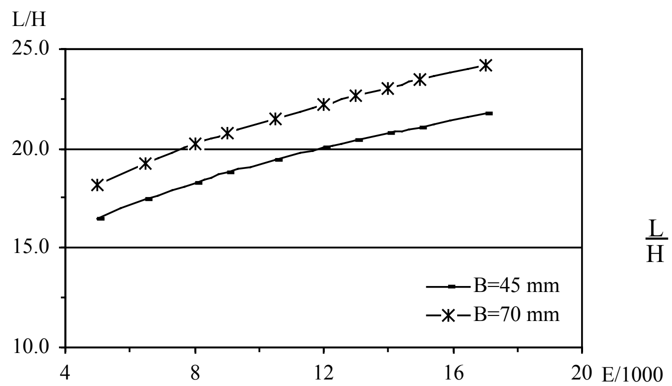


Figure 4. Utilization factors for floor T-joists (45 x 220 mm) with particleboard of 22 mm. Timber joists are calculated with an average E of 14 GPa independent of strength class. The span is 4.57 m for timber and 4.5 m for glulam L40 (here K40 as E = 13 GPa for glulam was taken from the Code) to obtain the same governing vibration criterion.

The design calculations showed very clearly that the present grading system does not permit the optimization of floor joists when it comes to mechanical properties. The decisive parameter is the short-term modulus of elasticity for the corresponding strength class of timber higher than K18. The other mechanical parameters are utilized to a very low extent. As a result, timber with the lowest strength class and with a high modulus of elasticity value should be the ideal timber for use as floor joists, assuming it is reasonably “straight”, see Table 1. If it were possible to grade timber for floor joists in a high stiffness class, i.e. short-term stiffness of 14 GPa, for example, the floor span could be increased by 10% from 4.15 m to 4.6 m, which would utilize a bending strength of about 20 MPa (based on the example with particleboard as flooring), cf. Figure 4.

The vibration criterion for a limited deflection of 1.5 mm due to a concentrated load of 1 kN in the middle of a single span can be expressed as a ratio L/H (span/height), which is a function of the product E x B (MOE times breadth), see Eq.1 and Figure 5. From this almost linear relationship, it can be concluded that for MOE which increases from 8 GPa to 12 GPa (50% increase), the corresponding increase of L/H is approximately 10% only. One could argue that it is as effective to increase the breadth of a joist (instead of increasing the MOE) and to obtain the same effect on L/H. However, increasing the breadth of a joist increases the volume and weight of timber and, as a result, the cost of handling and transportation will increase correspondingly. It is therefore proposed that we should aim at the highest possible MOE and grade timber for floor joists in a high MOE class (while maintaining a certain level of bending strength) instead of many strength classes, which is the normal procedure at present.



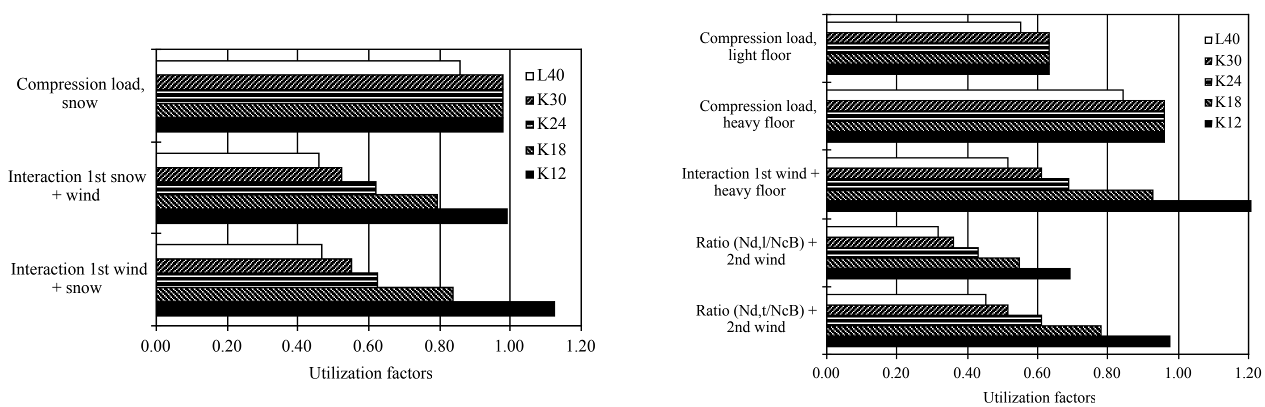
$$\frac{L}{H} = \sqrt[3]{0.006\,\frac{E}{1000} \times \frac{B}{k}} \qquad (1)$$

Figure 5. Relationship between L/H (span/height) and MOE for two different breadths (in mm) in a joist in a floor structure which fulfils the criterion of a limited deflection of 1.5 mm due to a concentrated load of 1 kN in the middle of a single span.

STUDS AND GROUND PLATES IN WALL STRUCTURES

The requirements in terms of mechanical properties are govern by the interaction between axial load and a moment acting on an external load-bearing wall stud and utilization factors for a single mechanical property is not as straight forward as for floor joist. However, in this study it was shown that the mechanical requirements for an external load-bearing wall stud are compression strength parallel to the grain and to some extent bending strength. As an example the utilization factors for dimensions of 45 x 120 mm and for different strength classes are shown in Figure 6. The compression perpendicular to the grain acting on the horizontal ground plate is utilized to the largest degree for all classes superior to K12, Figure 6a. The interaction between wind load (first load) with a characteristic value and a medium-heavy-weight floor produced a too large stress combination for strength class K12, Figure 6b. Properties such as shear strength and stiffness in the serviceability limit state have virtually no effect on the load-bearing capacity of wall studs. Nor is bending strength usually a critical parameter in a load-bearing wall stud. In some calculated examples, a very large wind load was chosen (for the coastline of Sweden in an open, flat area). However, the thickness of the external walls is often governed by the thermal insulation and is therefore usually not a problem for studs with a spacing of 0.6 m, exposed to bending stresses. If larger spacing were used, e. g. 0.9 to 1.2 m, combined with a large axial load, it would then be a question of structural optimization when it comes to the dimension and magnitude of the characteristic strength of a stud. High strength parallel to the grain is the main mechanical property required for a load-bearing wall stud in a timber-framed, multi-storey building. Eccentricity in a stud caused by too much spring (more than 8 mm) reduces the load-bearing capacity of a wall due to buckling. However, the shape requirements for a stud must apply to ensure that L/300 (≈8 mm) applies in service.

The only mechanical requirement for a ground plate in a load-bearing external wall is compression strength perpendicular to the grain. However, the transverse compression load in ground plates (also bottom and top plates) cannot cause failure, but it will lead to large deformation, especially when it is combined with shrinkage in the plate. Deformation at each floor level can be as large as 10 mm (Thelandersson, 1995). Adding the deformation from each floor in a multi-storey building can result in very large total deformation in the upper part of the building. The moisture- and load-induced displacement in the structural system (mechano-sorptive deformation) may affect the serviceability of the entire building. As a result, one possible structural solution is to avoid using horizontal members made of soft timber such as bottom and top plates in load-bearing walls, i.e. transmit the vertical loads via vertical members only or use plates made of steel, for example. Another solution is to produce dry horizontal members with much higher compression stiffness perpendicular to the grain than E90,k=300 MPa (for K24) with high long-term stiffness to avoid deformation perpendicular to the grain. The optimal stiffness should be at least 5 to 10 times higher than it is for K24 grade. However, the solution building contractors would probably choose is to use a multiple number of vertical studs (to increase the area under load) or a ground plate made of steel or steel-sheet material in order to reduce large, long-term deformation which occurs in the corresponding plate made of timber when loaded perpendicular to the grain.



a) Characteristic snow load (1 kN/m^2) and wind (0.7 kN/m^2)

b) Loaded by either a medium-heavy weight floor or a light floor and wind (0.7 kN/m2) with characteristic values and snow (1 kN/m2)

Figure 6. Examples of utilization factors for wall studs including ground plates (45 x 120 mm) in a 4-storey timber-framed house.

ROOF TRUSS TIMBER

The mechanical requirements set for roof truss timber are very difficult to summarize due to the fact that there are a very large number of roof trusses and end-users set requirements for roof trusses and not for timber. In the normal circumstances, in addition to the axial forces, there are bending moments in the top rafters. Special attention must be paid to the joints in the ceiling joists. These joints are stressed axially due to loads from the roof, transversally due to loads from the ceiling and from the attic floor and, finally, rotationally due to unavoidable eccentricities in the connection members. However, the principal requirements for truss timber from the mechanical viewpoint must be strength criteria such as tensile strength parallel to the grain, bending strength and density.

The end-user requirements for the entire roof truss include a stable, straight, stiff truss with a minimum of deflection. Large deflections cause serviceability problems and can also cause large secondary stresses in continuous rafters. Deflection in a truss is a combination of stiffness of timber, stiff slip characteristics in fasteners and a minimum number of mechanically-jointed splices. According to Ozelton and Baird (1976), one possible way of minimising truss deflections is to use timber of lower strength and consequently larger member sizes. The reason for it is that the ratio between stiffness and strength increases with lower strength classes, as shown in Figure 7.

The mechanical performance of roof trusses results from the optimization of various sizes of timber, various strength classes and size and qualities of nail plates in the connections. As an example of this optimization, it can be mentioned that the use of lower strength classes may appear uneconomical, since the necessary dimensions of the cross-section increase. However, since the fastener spacing and distances often determine the size of the cross-sections, the choice of a high strength class frequently does not lead to material savings. The load-bearing capacity of connections using mechanical fasteners such as nail plates depends on the density of the timber (Whale et al. 1989). The ratio between density and strength increases with lower strength classes, Figure 7. As a result, it can be more economical to use timber of lower strength classes, when the necessary mechanical connections determine the dimensions of the cross-section.

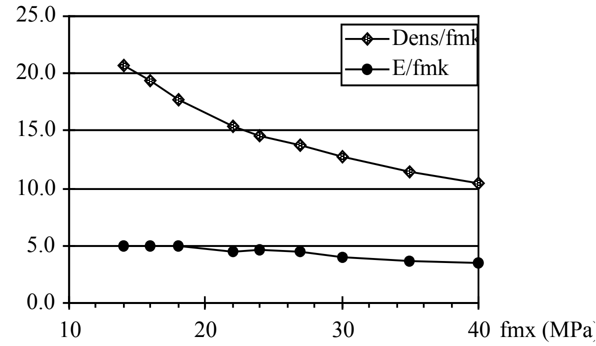


Figure 7. Ratio between density and strength and modulus of elasticity (in GPa) and strength versus strength, fmx (MPa).

CONCLUSIONS AND A SUMMARY OF QUALITY REQUIREMENTS

This paper briefly illustrates the methodology based on a practical design of load-bearing floor joist member made of sawn timber to determine requirements in terms of strength and stiffness. In the same way requirements in terms of strength and stiffness for other timber products such as: wall studs (external studs used in small buildings and multi-storey buildings), ground plates in wall structures, purlins in roof structures and formwork timber in some temporary gravity-loaded structures have been determined (Kliger 1998). Interest focused primarily on the use of these products in some common and general design applications (suggested by the building contractors) and on evaluating the governing mechanical properties for each product. The main aim was to obtain the utilization factors as a percentage of the strength/stiffness parameters for different timber products using just one code. The Swedish Building Code BKR 94 was applied in order to facilitate the discussions in the working group which, in addition to researchers from Chalmers, also included building contractors and designers from companies in the western part of Sweden. Between 5 to 15 different design cases with varying loads and design solutions for each timber products were studied. The summary of the requirements is shown in Table 1.

Table 1. Requirements in terms of the mechanical properties (a) and of shape (cup, bow, spring and twist) and moisture content (b), including an indication of the most probable level for the governing properties. Values in brackets indicate a subordinate property.

(a) Property **Product**	E_0 (GPa)	f_m (MPa)	f_{t0} (MPa)	f_{c0} (MPa)	E_{90} (GPa)	f_v (MPa)
Floor joist	≥ 12	(18)				
Multi-storey:						
Load-bearing stud		≥ 15		≥ 15		
Ground plate					>> 0.3	
Roof truss:						
Ceiling joist	≥ 12	(18)				
Rafter	≥ 10	(18)		(≥ 17)		
Tension rail			> 15			
Roof purlin	(≥ 12)	≥ 24 (≥ 30)				
(b) Property	**L (m)**	**Cup**	**Bow**	**Spring**	**Twist**	**mc (%)**
Product		**in mm on the entire length**				
Floor joist	4-8	2%	max 10	5/2 m	2%/2 m	15%±2%
		max 5		max 8	max 10	(12%±2%)
Load-bearing stud		2%	max 6	max 4	4%/2 m	15%±2%

It was virtually impossible to produce general structural requirements for each product which would apply in every situation. The strength and stiffness requirements specified in the code must be fulfilled when required by structural designers for each specific case. However, the applications studied here for different products showed very clearly which strength or stiffness requirements were important, Table 1. By improving or adjusting grading methods, it should be possible to produce a more optimal mixture of products from our forest resources.

This study clearly demonstrated that stiffness is the governing property for many products, assuming that a certain level of bending strength is present for timber of high stiffness. It would be very desirable to produce timber in fairly large dimensions [≥ (45 x 195)] and a length of between 4 and 8 metres with a high stiffness class (≥ 12 GPa). When this timber dimension was then graded in MOE classes, it could be differentiated in terms of the obtained shape. The most "straight" timber (spring ≤ 8 mm and twist ≤ 10 mm) should be classified as floor joists and ceiling joists in roof trusses. Less "straight" timber (spring ≤ 20 mm and twist ≤ 20 mm) can be used as purlins. It is obvious that the bending strength this timber represents should be verified and checked against the minimum requirements with regard to bending strength. Load-bearing wall studs in a multi-storey building, the rafters in a roof truss or shores in temporary structures are examples of products in which compression stress parallel to the grain is the governing property. Ground plates in a load-bearing wall structure are an example of a product in which stiffness perpendicular to the grain should be much higher than 300 MPa. It is important to keep the shrinkage/swelling property as low as possible, i.e. no juvenile wood or compression wood should be present in timber used as a ground plate. Truss timber is an example of a product in which high density is an important property with respect to the mechanical connections used to produce a roof truss. One important issue, which has not previously been mentioned in this paper with regard to mechanical properties, is the main weakness of structural timber, i.e. tensile stress perpendicular to the grain. Improving this property, which has caused many failures in timber structures in the past and utility problems for building commissioners, should be a challenge for tree geneticists and silviculturalists.

Building contractors and building commissioners may set additional requirements with regard to the mechanical properties for sawn timber when the official code requirements do not apply. In order to succeed with the overall optimization of the forest-wood-chain, it is crucial that the governing requirements of the end user are defined. Current grading systems are too general and do not utilize the potential of wood resources. It is vital that research and development within the forestry and processing industries is driven by the needs of the end user. One important result of this project is therefore to identify the most vital product properties for end-user satisfaction and to formulate these requirements in measurable wood properties.

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