QUALITY AND PERFORMANCE OF STRUCTURAL TIMBER

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SUMMARY

Building contractors are generally not satisfied with the quality of sawn timber, primarily because of its excessive distortion. The grading regulations and standards do not prevent poor quality timber to reach the end-user. In this paper, a systematic analysis of the end user's expectations is presented and is illustrated using a product specification for floor joists. These set of requirements comprises of geometrical dimensions including tolerances, straightness values (for maximum twist, spring and bow), important mechanical properties (strength and stiffness utilization factors for common loading cases) and other general requirements. The proposed acceptance levels are based on interviews with contractors and derived from the requirements set for the floor. The current grading rules are more generous than our proposal. If timber is to hold its own as a building material, the forest and sawmill industry will have to produce products with properties which match the end user's requirements. Timber has to leave the old bulk era and enter the new product era. This also means that a more product-oriented grading system is needed. The current strength-related grading systems are not enough. Buying rules/standards for each type of product are needed in order to make it possible for the timber seller to fulfil the buyers demands.

1 INTRODUCTION

Timber has been, and still is, a widely used structural material. Its advantages include availability and renewability. The fact that it consumes less energy in its processing than other structural materials is a point of special relevance at the present time. Timber is therefore more environmentally-friendly than many other materials.

However, timber also has some important disadvantages. As a natural material, it does not possess consistent, predictable, reproducible and uniform behavioural properties.

2 WHAT IS QUALITY?

"Quality" is a term which everyone uses frequently without thinking about what it actually means. "Quality" is often used to mean "the right quality". The word quality can easily be misunderstood. People talk about a certain quality or grade of steel or concrete when what they actually mean is the strength class of the material. In the same way, people use terms such as high and low quality, the right or the wrong quality, quality products, all of which are diffuse terms if they are not related to anything. According to ISO, [1], quality can be defined as "All the properties and characteristics of a product which enable it to fulfil explicit or implicit requirements". Other definitions are: "Fitness for use"

and "Conformance to requirements". The first of these is aimed at the customer, whereas the second one should be seen first and foremost as internal guidance. None of the above descriptions of quality can be directly applied to the forest-sawmill-building chain, since they assume a knowledge of the properties which are necessary or desirable. When people describe timber quality, they often use substitute parameters; they register one property and think that this enables them to gauge another.

Timber quality is generally "formulated in negative terms" and means different things depending on the industry the user represents. When people describe timber quality, they tend to mention the properties and characteristics which should not be present. The timber should have no knots, no rot, no compression wood, no warp and so on - in other words, no defects. It is far less common for people to list the properties they require. The building industry often uses the word "quality" to mean "high quality"; this means that the timber has none of the defects which have a negative effect on the end product or the refining process. As far as the sawmill industry is concerned, "quality" means a raw material with no knots and with high density, even annual rings, little tapering, a high percentage of heartwood and straight fibres.

3 QUALITY GRADING AT SAWMILLS

The disadvantage of grading at sawmills according to some standards is that the final use to which the timber will be put is often selected at too early a stage. A general selection of logs at earlier stages is positive. However, in the case of poor grading rules, such a selection can be misleading. All the timber which is put into the highest quality classes will probably end up in the joinery industry. The other timber which contains defects of different types and is put into the lower classes when graded according to the standard may in fact end up in the highest quality group for structural timber when it is subsequently graded for strength. As a result, timber with many defects, which may often be large into the bargain, with varying density and sometimes even cracks, compression wood and pitch pockets, may end up in the building industry [2], [3].

4 THE BUILDING INDUSTRY'S PERCEPTION OF QUALITY

When purchasing building timber, the representatives of the building industry often apply quality criteria such as "this looks fine" and "this doesn't look too good". Apart from dimensions and strength, no requirements relating to quality are specified when ordering timber. Building contractors often complain that the timber is not dimensionally stable, in other words that it warps or deforms after being exposed to drying. The dimensions of the timber are not accurate, the moisture content is too high and the length has often not been adapted to match the application.

The sawmills often appear to ignore the existing standards for nominal dimensions unless the customer specifies this when placing his order. The thickness can vary depending on the delivery; panel thickness can, for example, vary from 21 to 22 to 23 mm. In general, no mention is made of the moisture content in conjunction with delivery.

The attitude of too many sawmill industries could be summarised as follows "More or less anything can be used as building timber".   Anything that is left over is used as building timber. In recent years customer adaptation and market orientation have become popular terms in the timber products industry, but this has clearly not included building timber. It appears that the sawmill industry regards building timber as a bulk product and markets it as such.

The building industry's attitude can be summarised as follows: "Timber should be cheap and good". Many contractors regard the price as the most important parameter and are prepared to accept cheaper timber of inferior quality.

Many contractors assert that the quality of structural timber has steadily deteriorated in recent years. Excessive distortion (also called warp), Figure 1, is the main complaint. Consequently, market share has been lost to other materials, e.g. contractors have chosen straight steel studs rather than warped wooden ones.

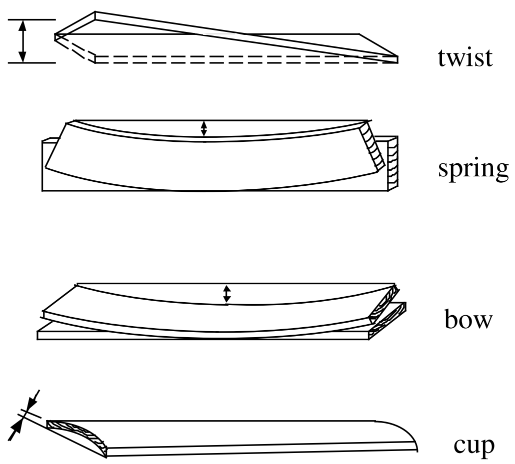

Figure 1 - Definition of different types of distortion.

5 PRODUCT SPECIFICATIONS - THE KEY TO QUALITY?

In order to improve and assure the quality of structural timber, a product specification system is needed. The implicit and explicit quality requirements that the end-user sets for building components must be specified for each product. A specification made up of measurable properties will define the product and will permit the application of Quality Assurance for timber products. The system should be designed in such a way that both producer and consumer benefit from it. When end-users order timber, they will know exactly which properties to expect, thereby enhancing the status of timber. The specifications will enable producers to make the optimum use of the timber at their disposal, thereby improving their image and their profitability.

Product specifications can benefit the manufacturers of timber elements, builders, sawmillers and silviculturalists by optimizing the entire process from forest to end-user. Products with the right properties should justify a higher price. Raw materials with the wrong properties for timber products should not be processed into sawn timber. Sawmillers will know what their customers require from their products and will try to obtain logs which can give the best yield to produce these products. Forest managers, on the other hand, will try to maintain the forest in order to produce logs of the required quality.

There are grading rules and standards which are intended to ensure that the products have acceptable properties. However, the grading criteria do not reflect the end user's needs. Many important properties are missing, the acceptance levels are too generous and some requirements are irrelevant. Furthermore, the rules are too general. Each end product has unique sets of requirements that could differ substantially.

The need for a consumer-adapted grading system is thus obvious. This system must be product-oriented in order fully to satisfy the end-user with respect to both properties and price. The current overly, general grading system forces the end-user to buy timber graded into an unreasonably expensive class for the purpose of obtaining straightness. A floor joist was chosen as an example of a well-defined product to set the requirements which could be incorporated in a product-oriented grading system.

6 FLOOR JOISTS [4].

A floor structure is a load-bearing horizontal component which demarcates different storeys in a building. 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, see Figure 2. 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. Beams, which are part of the loft ceiling structure, are usually fitted with spacing of 1200 mm and are often part of the roof-truss structure. The requirements for various types of floor structure can vary for different selfweight loads and live loads.

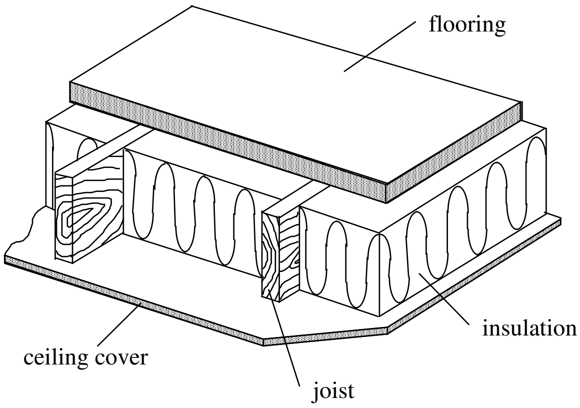

Figure 2 - A diagrammatic sketch of a floor structure.

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 apartments 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.

The requirements for floor structures vary depending on different environmental loads and live loads. The crawl-space foundation usually has very high relative humidity, especially during the summer. As a result, the floor structure above the crawl-space foundation differs from the intermediate floor.

The specific requirements for a beam which is used in the floor structure can be traced back to the requirements for the entire floor. A building contractor has to fulfil the structural design requirements set for the floor structure in question. In addition, a building contractor needs joists with certain properties that permit the effective and rational assembly of the specific floor structure.

7 BUILDABILITY REQUIREMENTS OF FLOOR JOISTS

7.1 Dimensions

Length The length of timber beams used in a floor structure should be adjusted to the actual span of the structure, in order to avoid expensive splices. Beams which span the entire width of the house are desirable. Finger joints in larger cross-sections are difficult to produce. The tolerance of beams that are cut exactly to length should be ± 1.5 mm.

Thickness The thickness of timber is determined by the strength and stiffness requirements and by the need for sufficient support for splicing the flooring. Tolerance: ± 1 mm.

Width The width of timber is usually based on the stiffness requirements, but the insulation required in the structure over the crawl space, for example, can also have a decisive effect. An acceptable tolerance between beams and within an individual beam is ± 1 mm.

7.2 Distortion

Uneven floor surfaces are often caused by distortion in the floor joists. The curvature and inclination requirements specified in various Codes of Practice relate to the floor structure. Curvature consists of the deformation in the beams and the deformation in the flooring. Deformations caused by moisture conditions can be reduced if the components which are included in the floor structure are conditioned to match the expected climate.

Cup Cup causes the flat sides to bend and makes the edge sides no longer parallel, see Figure 3. The bend in the flat sides produces gaps in the insulation, thereby reducing the thermal resistance of the floor. The inclination in the edge sides results in incomplete contact between the flooring and the joist. This can lead to creaking in the floor and to problems in the glued joints in those cases in which there is interaction between the flooring and the joist. An acceptable tolerance when it comes to cup is 2% of the width.

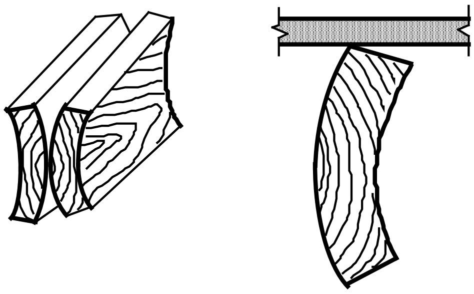

Figure 3 - Difficulty in splicing and reduced contact as a result of cup.

Bow The design recommendations in the National Codes often assume that the lateral deflection will not exceed the span divided by some number. In normal situations, bow is adjusted when the flooring is fitted or when herringbone strutting is incorporated in the structure. These adjustments can be avoided if the requirements for bow are set at a maximum of 10 mm for the entire beam. Joists with finger joints can be S-shaped with bow in two different directions. This is difficult to adjust. The requirement should be more rigorous for timber with finger joints.

Spring Spring can often be used to produce camber in the floor structure. The beams are laid with the “spine” upwards, so to speak. When a load is imposed, the beams bend in such a way that the floor is flat or somewhat deflected. Provided that crook is turned in the right direction, the tolerances can be made fairly generous; 5 mm measured over 2 metres, but a maximum of 8 mm measured over the entire beam.

Twist   Twist creates a lateral displacement which is difficult to adjust. Contact with the flooring is poor because the cross-section is twisted along the beam. Twist could be limited to 2% of a width of 2 metres and a maximum lateral displacement of 10 mm in the entire beam.

7.3 Moisture content

When delivered, the floor joists should be conditioned to match the expected climate in the structure in order to prevent excessive drying. The beams in an intermediate floor structure should have the same equilibrium moisture content as studs used in partition walls, i.e. 8-14% depending on the time of year. A moisture content of 15% should be low enough for timber beams not to warp extensively when dried to a moisture content of 8-10% in the intermediate floor structure.

8 DESIGN PRINCIPLES FOR FLOOR JOISTS [5].

There are three basic criteria, (strength, deflection and vibration) for floor joists when it comes to the mechanical properties of timber. Wooden flooring on top of floor joists often functions as a compression flange. Like most 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.

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. 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 chapter.

9 EXAMPLE, SIMPLY-SUPPORTED FLOOR JOIST

The calculations presented in this section 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 is to obtain the utilization factors for mechanical properties expressed in per cent. It is well known that the vibration criterion is the design factor for residential wooden floors.

As a result, 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%. This could be achieved by varying the load distribution factor k for different timber classes in order to obtain the same deflection in the middle of a joist of 1.5 mm from a concentrated load of 1 kN.

Assume a simply-supported floor joist (45 x 220 mm) with spacing 0.6 m in a residential house, 22 mm particle board. Strength class K24, service class 1, load duration classes medium-term and long-term. The design loads are 1.8 kN/m for strength and 0.75 kN/m for deflection. The deflection in the middle of the simply-supported joist caused by a concentrated load is

$w = k (P L3/48 E I)$ (1)

where k is the load distribution factor

With the deflection limitation 1.5 mm for P = 1 kN the governing span length is 4.28 m and the load distribution factor k = 0.77 for strength class K24. 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.

The maximum deflection, w, for a simply-supported joist together with wooden boarding is calculated. The bending stiffness for three different load durations is as follows: EIP = 386 x 10^9 Nmm^2, EIA = 470 x 10^9 N mm^2 and EIB = 596 x 10^9 N mm^2. The total deflection, for joist 45 x 220, quality K24, span of 4.28 m, together with a structural particleboard, is as follows :

$w = 5 \times 4.284 (0.15/386 + 0.3/470 + 0.3/596) \times 10^3 / 384 = 6.6$ mm.

10 DESIGN RESISTANCE OF JOISTS AND DEFLECTION LIMITS. COMPARISONS

Down below some results from design calculations of the joist 45 x 220 are shown. The calculations are conducted for five different strength classes according to BKR 94. Similar results will be obtained using any different timber design code. The calculations are conducted both in the ultimate limit state design and in the serviceability limit state design.

Timber	Modulus of elasticity		
quality	short	medium	long
K12	4.4	5.2	6.4
K18	4.95	5.85	7.2
K24	5.77	6.82	8.4
K30	6.6	7.8	9.6
K40	7.15	8.45	10.4
Timber	Design stresses		
quality	bending	shear	fc90d *
K12	7.85	1.64	3.82
K18	11.78	1.64	3.82
K24	14.84	1.64	3.82
K30	17.45	1.64	3.82
K40	21.82	1.64	3.82

* fc90d - compression perpendicular to the grain

Table 1 - Modulus of elasticity (in GPa) and design stresses (in MPa) for different timber classes.

The design capacity for compression perpendicular to the grain, fc90d, is calculated using a magnifying factor of 1.12 , due to the width of 95 mm at the support. The design stresses and design modulus of elasticity for different timber classes are shown in Table 1.

Deflection in the middle of the joist as a result of permanent action and imposed actions should be limited to L/300 This value is not in the code, but it was obtained from a reference group consisting of building contractors. The limitation corresponds to 14.3 mm for joists (45 x 220 mm, K24, with 22 particleboard with a span of L = 4.28 m) and to 12.2 mm for joists without interaction with the boarding (45 x 220 mm, K24, with a span of L = 3.65 m).

11 UTILIZATION VALUES FOR THE MECHANICAL PERFORMANCE OF TIMBER JOISTS IN FLOOR STRUCTURES

The results from calculations of two different joists are shown below, joists with interacting particleboard and joists without interacting wooden boarding.

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, joists with interacting particleboard and joists without interacting wooden boarding. It appears that, in both cases, the bending, shear and compression strength were utilized to a maximum of 60%, Figures 4 and 5. The same thing applied to the middle deflection limited to L/300.

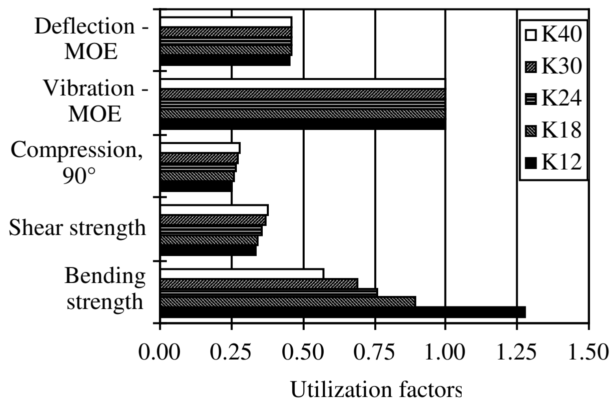

Figure 4 - Utilization factors for floor T-joist (45 x 220 mm) with particleboard of 22 mm. The span had to vary, i.e. 4 m for K12 to 4.5 m for L40, to obtain the same governing vibration criterion. Different structural classes expressed in Kxx, where xx is the characteristic strength.

In order to obtain utilization values for different structural timber classes, the 45 x 220 joists were calculated when the vibration criterion was utilized to 100%. To fulfil this criterion for different timber classes, the span had to vary for each class. As a result, the span for the T-joist with dimensions of 45 x 220, together with structural particleboard of 22 mm thickness, varied as follows for different timber classes: K12: L = 4.02 m, K18: L = 4.13 m, K24: L = 4.28 m, K30: L = 4.41 m, K40, L = 4.49 m, see Figure 4. Bending strength is the governing property only for the lowest strength class K12

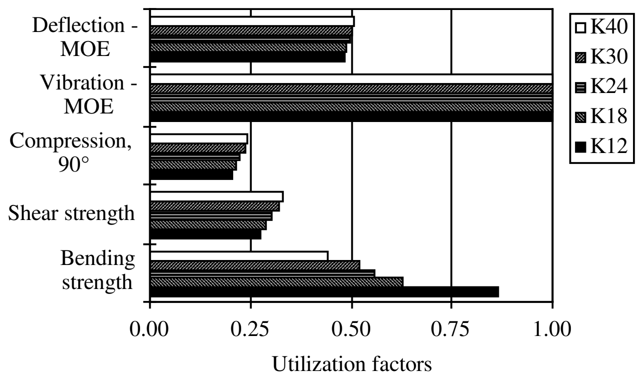

Figure 5 - Utilization factors for floor joists (45 x 220 mm). Different structural classes expressed in Kxx, where xx is the characteristic strength. There is no interaction between particleboard and timber joist.

12 RESULTS AND DISCUSSION

The mechanical requirements which are set for floor joists 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. However, 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.

The design calculations showed very clearly that the present grading system does not permit the optimization of floor beams 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 beams, assuming it is straight. 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 4.57 m, which would utilize a bending strength of about 20 MPa (based on the example with particleboard as flooring), cf. Figure 6.

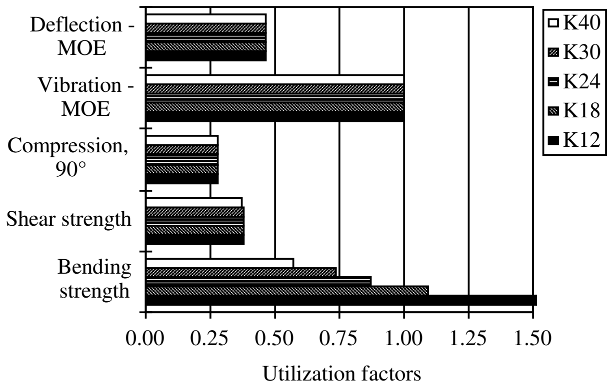

Figure 6 - Utilization factors for floor T-joists (45 x 220 mm) with particleboard of 22 mm. Timber joists are calculated with an average E of 14 GPa independent of strength class. The span is 4.57 m for timber and 4.5 m for glulam L40 (as E = 13 GPa for glulam was taken from the Code) to obtain the same governing vibration criterion. Different characteristic bending strength applied to each structural class expressed in Kxx.

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, Eq 1, 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.2 and Figure 7. 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.

$$L/H = (0.006 \times E/1000 \times B/k)^{1/3} \qquad (2)$$

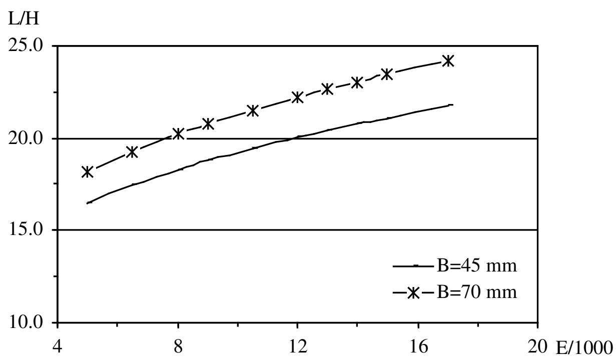

Figure 7 - Relationship between L/H (span/height) and MOE for two different breadths (in mm) in a joist in a floor structure which fulfils the criterion of a limited deflection of 1.5 mm due to a concentrated load of 1 kN in the middle of a single span.

13 PRODUCT SPECIFICATION

The main structural requirement for floor joists is related to the short-term modulus of elasticity (MOE). It would be advantageous to produce timber joists with an average MOE of 14 GPa or higher. The corresponding bending strength (5-%) of 18 MPa is enough to fulfil the strength criterion. The requirements for shear, compression and tension strength in both directions can be reduced when compared with the code values for different structural classes. The values for strength and stiffness requirements given in Table 2 provide an indication of the most probable level for each governing property.

14 THE FUTURE

Perhaps there is a tendency towards product production, at least in Sweden. During the last five year period the stress graded volumes have increased with 70%, extra drying (less than 18% MC) has increased with 156%. On the other hand the cutting to exact length has only increased with 11%. There has also been made an attempt to produce and sell wall studs with a certain specification. These studs were used in two test buildings, together with ordinary studs. The special studs showed not to be cost effectiv, the material cost was too high.

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Structural requirements The strength and stiffness requirements specified in the code should be fulfilled when required by the designer. As high a modulus of elasticity (MOE) as possible. Timber graded in terms of MOE class where E0 ≥ 12 GPa for a corresponding bending strength of 18 MPa. Dimension - geometry Length: lengths up to 9 m desirable — Thickness: 45-95 mm, tolerance: ± 1 mm Precision-cut: tolerance ± 1.5 mm — Width: 170-300 mm, tolerance: ± 1 mm 50 mm at the ends free from knots Shape Cup: max 2% of the width, max 5 mm — Spring: 5 mm measured on 2 m, max 8 mm on the entire length of the piece of timber. Bow: Max 10 mm on the entire length of the piece of timber. — Twist: 2% of the width measured on 2 m, max twist of 10 mm on the entire length. Moisture content (depends on the application) a) joists above the foundation or in the loft ceiling structure - timber should be delivered kiln-dried to a moisture content of 15% ± 2%, unless otherwise specified. b) joists in the intermediate structure - timber should be delivered kiln-dried to a moisture content of 12% ± 2%, unless otherwise specified. If timber is delivered with a higher moisture content than 17%, the producer of studs must comply with the shape requirements (as above) when studs dry from their delivery moisture content to the equilibrium moisture content for use in a building. Miscellaneous Microbial attack: Mould and rot are not acceptable. All discoloration is acceptable. Knots: No limitations with respect to appearance, but the ends of the timber (last 50 mm) should be free from knots. Wane or rounded corners: Not accepted for timber where the thickness is less than 40 mm.

Table 2 - Summary of requirements set for floor joist timber.

16 ACKNOWLEDGEMENT

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