CHAPTER 10

GRADING TIMBER AND GLUED STRUCTURAL MEMBERS

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1. INTRODUCTION

Because of its biological nature, which is influenced by many factors as discussed in Chapter 6, the quality of timber is enormously variable. Therefore, some sort of arrangement or classification must be undertaken prior to its use, in order to get the most out of this valuable resource. It is obvious that not all lumber can be used for the same purposes because not all of it has the same properties. It is the intension of this chapter to discuss the various classification or 'grading' techniques that are applied to timber and glued structural members.

A grading rule is a set of definitions of timber characteristics together with methods for measuring them. Grading rules determine, in an orderly manner, the way in which a given piece of timber from a certain species or group of species will be designated and located into any of a number of groups or categories. Grading of timber has evolved into two major categories: material graded for structural use and material graded for appearance. Strength and stiffness of timber are primary considerations for structural use, whereas appearance grades are dictated by the size of the largest clear cutting. Different grading rules apply to these two situations. Both categories will be discussed, but the majority of this chapter will be concerned with the grading rules appropriate for timber as a material for structural uses. Also, in this chapter a distinction is made between the properties of 'wood', that is, clear, defect-free material, and 'timber' (called lumber in the U.S.) with all its natural defects of knots, splits, cross-grain, and distortion.

The grading of timber should be viewed as part of a marketing strategy, designed to ensure that timber buyers obtain the quality of timber appropriate for their needs and timber sellers receive an optimal price for their product. Unfortunately, grading suffers from conflicting objectives and can be best described as an attempt to bring some order out of what would otherwise be a chaotic situation.

Timber, being a natural material, is very variable in strength and appearance. This is compounded by the enormous number of commercial species and by the multiplicity of grading rules that evolved in isolation to take account of the vagaries of each species. There is strong historical justification for such practice. Heart rot and brittleheart may be particular problems with certain over-mature tropical hardwoods, while corewood is encountered in softwood plantations. In theory, rationalization of grading rules ought to be simple. However, rationalization will never be easy as timber grading can be a powerful tool in non-tariff protection of local interests. Naturally local grading rules are written with local timber in mind. It would be unrealistic to disadvantage home-grown material. In recent years, more objective and rational procedures for the grading and property assignment of timber have been developed, driven by increased international trade. Unfortunately, there has been only limited success to date in adopting these procedures.

2. THEORETICAL STRENGTH OF WOOD

The theoretical limits of wood strength are impressive. The strength of a cellulose molecule dwarfs the values associated with high strength steel (Table 10.1). Individual fibres are incredibly strong in tension, but once assembled into solid wood, much of this potential is lost because of weakness across the grain.

The real advantage of timber structures over steel and concrete equivalents usually lies in their strength to weight ratio. Wood has a very high strength to weight ratio and therefore requires a less massive foundation for an equivalent load. Timber is also aesthetically pleasing and non-corrosive.

Table 10.1. Indicative values for mechanical properties of an air-dried softwood and other materials (Gordon. 1978; Mark, 1967; Marra, 1975). Densities for timber, concrete and steel are taken as 500 kg m^{-3}, 2300 kg m^{-3}, and 7800 kg m^{-3} respectively.

Strength	MPa
A cellulose molecule in tension	7000
Individual delignified fibres in tension	700
Clearwood in tension along the grain	140
Clearwood in compression along the grain	50
Clearwood in tension across the grain	3
Construction lumber in tension along the grain	30
Timber, allowable working stress in tension along the grain	10
High tensile engineering steel	1600
Concrete in compression	40
Concrete in tension	4
Stiffness	**GPa**
C-C covalent bond	1200
Clearwood	14
Timber	10
Steel	210
Concrete	25

The variability in the quality of timber is large, even within a selected grade of a particular species assessed by visual techniques. Thus one distinctive feature of timber grading is the inability to assess reliably the strength of a piece of timber: to date, the best that can be done is to estimate how weak the piece might be. Historically, the quality of wood required for construction depended on tradition and local experience for the most part. Trade guilds and craftsmen applied judgements that resulted in magnificent structures, such as cathedrals in the Middle Ages, shipbuilding from the fifteenth to nineteenth centuries, and railroads and bridges during the nineteenth century. More recently, machine-grading techniques have successfully reduced the variation in the properties of lumber and related products.

3. TIMBER GRADING FOR NON-STRUCTURAL PURPOSES

Timber sawn from logs varies widely in quality. Some pieces are clear, others have a few knots, and still others are very knotty, Some contain checks or splits, and others have bark on the edges or can have areas of decay. Because of this variety, it is necessary to separate timber into classes or grades based on the number, condition, and size of defects. In 1764 in Stockholm, Sweden, Swan Alversdon published the first set of grading rules of which there is an authentic record (Ivory *et al.*, 1923). These rules recognized four grades of lumber: (i) bests or clear lumber, (ii) good or select lumber, (iii) common or lumber containing numerous sound knots, and (iv) culls or usable lumber containing coarse defects.

These early Swedish grades were based on the appearance of each piece, and lines of demarcation between grades were drawn on the basis of the character and position of the admitted defects. The rules were applied to lumber regardless of potential use. Use of these rules spread during the nineteenth century. For example, these grading rules accompanied Swedish loggers to the United States and followed them as they progressed west.

While all lumber was originally graded on an appearance basis only, two major categories of grading developed with time: appearance grading and structural grading. Material technology developments and different requirements of wood consumers have further subdivided grading into three distinct systems of use: the two appearance use categories of Factory or Shop timber, and of Yard timber; and a Structural use category of structural timber. Factory and Shop refers to timber that will undergo a number of further manufacturing steps and reach the consumer in a significantly different form. Yard and Structural timber relate principally to timber expected to function as graded and sized after primary processing (sawing and planing). Appearance qualities are important for Yard lumber, whereas Structural lumber is material that is graded for structural use with assigned design properties.

The grading rules described and discussed relate to those applicable in various parts of the United States. They are illustrative of the principles that apply. Other countries adopt different rules and the terminology may be different, but the underlying principles are generally the same.

3.1. Hardwood grades

A principal use for hardwood lumber is for floors, siding/weatherboards, scaffold planks, stair treads, truck decks, rail-ties/retaining walls *etc.* For these end-uses the lumber sizes and grades relate directly to the final product. The major constraint is the restricted availability of high grade large dimension hardwood lumber, and this necessitates finding and retaining markets for the predominant amounts of lower grade material.

The alternative strategy recognizes that small blemishes severely downgrade whole boards. Hardwood factory and shop grades provide very profitable markets for such material by cutting out such defects and using the smaller pieces in the manufacture of furniture, cabinetwork, and pallets, or directly for flooring, panelling, moulding and millwork. The rules adopted in the U.S. by the National Hardwood Lumber Association are discussed here as an example of a standard in grading hardwood timber intended for cutting into smaller pieces to make furniture or other fabricated products (NHLA, 1991). In these rules, the grade of the timber is determined by the size of the piece and the proportion of the piece that can be cut into a certain number of smaller pieces, commonly called cuttings, which are generally clear on one side, have a sound reverse face, and are not smaller than a specified size. Figure 10.1 shows typical examples of such cuttings and their grades.

The best grade in the Factory timber category is termed First and Seconds (FAS). The second grade is FAS one face (F1F). The third grade is Selects, which is followed by No. 1 Common, No. 2A Common, No. 2B Common (sound wormy), No. 3A Common, and No. 3B Common. These admit progressively larger defects/ blemishes. This summary is only given as an example of the thought processes used to separate out Factory and Shop grade timber.

3.2. Softwood factory and shop grades

As with hardwoods, here softwood lumber is sorted at the sawmill into factory or shop grades on the basis that these boards can be recut to yield a certain proportion of smaller pieces of specific quality and size. This lumber provides the basic raw material for many secondary manufacturing operations.

The variety of species available has led to numerous grade names and grade definitions that seek to reflect as accurately as possible the grade and yield that can be obtained in the subsequent cutting operations. During secondary manufacturing processes, the quality, size, and often the entire appearance of the pieces are changed (as defects are chopped out) and these transformed cuttings become integral parts of the final end-product. The names of these factory grades can reflect end-use, e.g. industrial clears, box lumber, moulding stock, and ladder stock. Here, some of the more common classifications are outlined briefly. Such grading procedures are largely the responsibility of manufacturers' associations and, because of the wide variety of wood species, industrial practices, and customer needs. different lumber grading practices coexist. For details, reference must be made to industry sources for the certified grading rules for that country. region, and species.

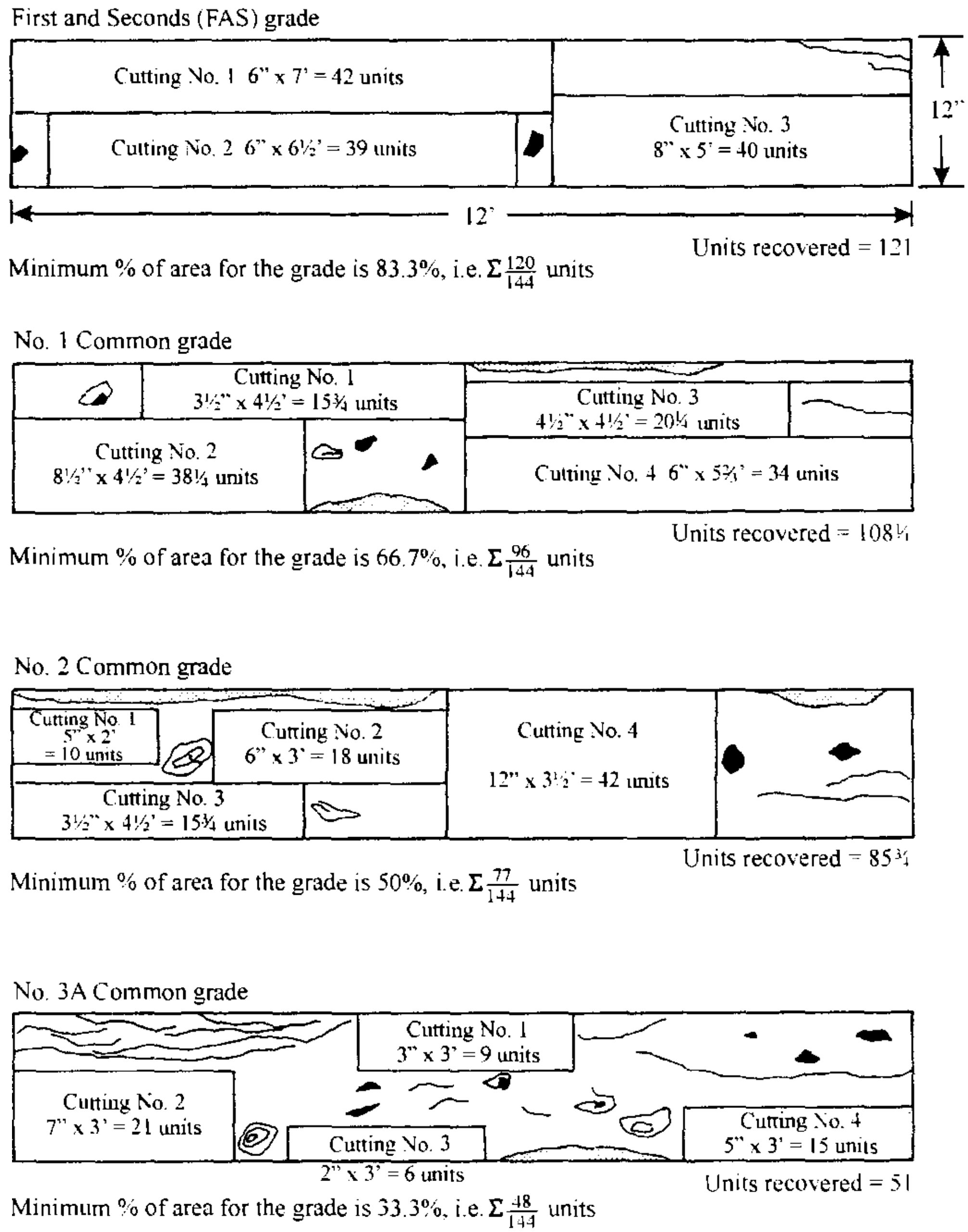


Figure 10.1 Greading of hardwoods: cutting strategies for boards that vary greatly in quality (NHLA, 1991). In this example the 12 foot x 12 inch board has a surface area of 144 units.

Traditionally, softwood timber used for cutting has been called Factory or Shop. Some grading rules refer to these softwood grades as Factory, while others refer to them as Shop. All impose a somewhat similar nomenclature in the grade structure. Shop timber is graded on the basis of characteristics that affect its use for general cut-up purposes or on the bases of the size of cutting required for sash and doors. Factory Select and Select Shop are typical high grades, followed by No.1 Shop, No. 2 Shop, and No. 3 Shop.

Grades and grade rules take account of the width, length, and thickness of the original piece and of the amount of high quality material that can be obtained by cutting. Factory Select and Select Shop lumber is required to contain 70% of cuttings of specified size, clear on both sides. No. 1 Shop is required to have 50% cuttings, and No. 2 Shop only 33-1/3%.

Industrial Clears are used for trim, cabinet stock, garage door stock, and other product components where excellent appearance, mechanical and physical properties, and finishing characteristics are important. The principal grades are B&BTR (B and better), C, and D Industrial. Grading is primarily on the best face, although the influence of edge characteristics is important and varies depending upon piece width and thickness. In redwood, the Industrial Clear All Heart grade includes an 'all heart' requirement for decay resistance: it is used in the manufacture of cooling towers, tanks, pipe, and similar products.

Moulding, ladder, pole, tank, and pencil stock requirements relate to specific consumer products. Custom and the characteristics of the wood supply have led to different grade descriptions and terminology. For example, with U.S. West Coast species, the ladder industry can choose between 'ladder and pole stock' grade plus two ladder rail grades and one ladder rail stock grade. With southern pine, ladder stock is available as Select and Industrial. Moulding, tank, pole, stave and stadium seat stock, as well as box timber, and pencil stock are other classes oriented to a specific final product. Some product classes have only one grade level; a few offer two or three levels. Special features of these grades may include a restriction on sapwood related to desired decay resistance; specific requirements for slope of grain and growth ring orientation for high-stress use such as ladders; and particular cutting requirements as in pencil stock.

3.3. Softwood yard timber

The grading requirements of yard timber relate specifically to the construction uses intended, and little or no further grading occurs once the piece leaves the mill. Yard timber falls into two categories, Select and Common, and encompass those products in which appearance is of primary importance; structural integrity, while sometimes important, is a secondary feature.

3.3.1. Select timber

Select timber is intended for natural, stain and paint finishes. This category of timber includes material that has been machined to a pattern, and further processing of these items is limited to on-site fitting, i.e. cutting to length and mitering. The Select category includes trim, siding, flooring, ceiling, panelling, casing, stepping, and finish boards.

In the United States, most Select grades are described by names (Superior. Prime) or by letters and combinations of letters (B&BTR, C&BTR, D) depending on the species and grading rules under which the timber is graded. The specifications

FG (flat grain). VG (vertical grain), and MG (mixed grain) are offered as a purchase option for some Select timber products. Select timber grades emphasize the quality of one face and in consequence the reverse side may be of lower quality.

Colour can play a role in grade descriptions. For cedar and redwood. there is a pronounced difference in colour between heartwood and sapwood. Heartwood also has high natural resistance to decay, so some grades are denoted as 'heart'.

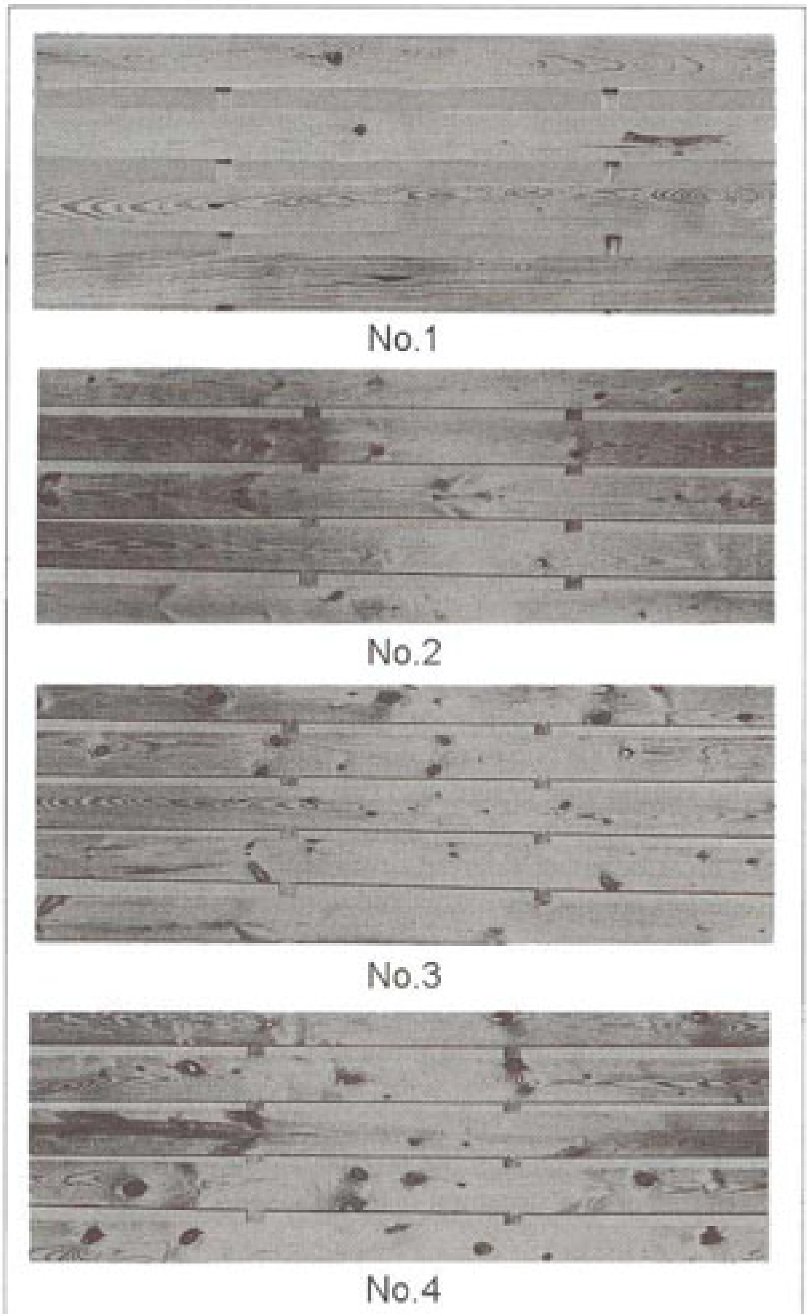


Figure 10.2. Typical examples of softwood boards in lower Common grades

3.3.2. Common timber

Common timber is generally not stress-graded. The grades reflect suitability for general construction and utility purposes. Common timber is segregated into three to five grades depending on the species and grading rules involved. These may be described by number (No. 1, No. 2; or No. 1 Common, No. 2 Common) or by descriptive terms ('Select Merchantable', Construction, Standard). Differences in the inherent properties of various species and in the names of their corresponding grades means that the grades and grade names for different species are not always interchangeable.

Features such as knots and knotholes are permitted to be larger and more frequent as the grade level becomes lower. Figure 10.2 shows examples of four grades of softwood boards produced in the United States. The top grade boards (No. 1, No. 1 Common, 'Select Merchantable') are usually graded for serviceability, but appearance is also considered. These grades are used for things like siding, cornice, shelving, and panelling. Intermediate grade boards are often used for such purposes as subfloors, roof and wall sheathing, and concrete formwork. Lower grade boards are selected for adequate strength, not appearance. They are used for roof and wall sheathing, subfloor, and rough concrete formwork.

3.4. Softwood structural lumber

Structural timber is material. graded for use as. a structural member. What makes structural grading so challenging is that lumber sawn from a log, regardless of species and size, is very variable in mechanical properties. Pieces may differ in strength by several hundred percent. For simplicity and economy in use, pieces of lumber of similar mechanical properties are placed in categories called stress grades, which are characterized by (i) one or more visual or mechanical characteristic, (ii) a set of properties for engineering design, and (iii) a unique grade name.

As is the case for properties of any structural material, allowable engineering design properties must be either inferred or measured non-destructively. From one to six design properties are usually associated with a stress grade: bending modulus of elasticity for an edgewise loading orientation; stress in tension and in compression parallel to the grain; stress in compression perpendicular to the grain; stress in shear parallel to the grain; and extreme fibre stress in bending. With lumber, the properties may be inferred through visual grading criteria, or by non-destructive measurement such as flat-wise bending stiffness or density, or by a combination of these methods.

At this point, it is best to consider the mechanical properties of wood and timber and the potential of timber as a structural material.

3.4.1. Introductory concepts

Everyone has been exposed to wood and its use in everyday life. The terms 'strong', 'stiff' and 'tough' are familiar words. However. such familiarity should not be confused with knowledge of what is technically meant by these terms. Strength is defined in terms of the ability of a material to sustain a load. The load that can be carried by an object depends on the size, shape, and properties of the object. Stress is the magnitude of a load distributed over a unit of area. For all materials there is a critical stress at which they will fail. At less than the critical stress, the material will simply be compressed, stretched, or bent, often by an almost imperceptible amount. The load can be applied in tension, compression, shear, or some combination of these. With wood, the situation is even more complicated. Wood is orthotropic (properties differ in the radial, tangential, and longitudinal directions), so it is necessary to define thedirection of the stress with respect to the grain of the wood. Wood tested in tension or compression and loaded parallel to the grain is considerably stronger than wood loaded perpendicular to the grain, but the reverse applies in shear. To add to the complexity, strength is a function of moisture content.

The first systematic testing procedures to determine the properties of wood used small specimens, either 20 by 20 mm or 2 by 2 in. in cross-section, free of all defects (BSI, 1986; ASTM, 2005a). The mechanical properties of numerous woods available to the British timber trade are listed in Lavers (1969), and those of North America are found in the Wood Handbook (USDA, 1999). An enormous amount of work is required to fully characterize the mechanical properties of small clearwood of a single species. It is important to appreciate that these values relate to the timber sampled and the standard rate of loading applied. The data are representative of only the population from which the samples were taken.

Stress applied to clearwood specimens results in some distortion or deformation of the body. This deformation is known as strain. In a tensile test, the sample is very slightly stretched and the strain, ε, is defined as the change in length divided by the length, $\delta L/L$. Most materials fail in tension after they have experienced a strain of about 1%. Figure 10.3a illustrates the green and dry tensile behaviour of wood. Initially, the strain, ε, increases proportionally with the stress, σ, up to the limit of proportionality *(PL)*, i.e., $\sigma = E\varepsilon$, where E is known as the modulus of elasticity *(E* or MOE). The MOE is the ratio of the stress to the strain for the initial slope of the stress–strain diagram. The modulus of elasticity for wood is a quantitative measure of its resistance to deformation. A high modulus of elasticity indicates a stiff material, necessitating a greater applied stress to achieve a given amount of strain. Beyond the limit of proportionality, the tensile stress–strain curve becomes slightly non-linear and the specimen soon fails. For standard testing speeds, the limit of proportionality occurs at about 80% of the failure stress (known as the ultimate tensile stress). The behaviour of wood in compression parallel to the grain is also shown (Figure 10.3a). When dry, the maximum crushing strength of clearwood is on average no more than half the ultimate tensile strength, and the ratio is even smaller when wood is tested green. Compression failure is initiated by buckling and separation of individual fibres adjacent to ray tissue, probably in the earlywood, which throws a disproportionately large load on the adjacent fibres. These in turn become unstable over a portion of their length, and a buckled failure band eventually spreads across the specimen. The failure band is only about 0.2 mm

(0.008 in.) wide. and, typically, lies perpendicular to the grain on the radial face (Figure 10.4a).

Tensile testing of small clearwood specimens parallel to the grain has never been part of these systematic studies and, until recently, bending strength has been taken as an adequate surrogate measure of tensile strength. Indeed it is extremely difficult to get clearwood specimens to fail in tension because the tensile strength of wood parallel to the grain is so much greater than is its shear strength parallel to the grain or its crushing strength perpendicular to the grain. Thus, it is difficult to pull a specimen in tension without getting premature shear failure or crushing in the grips used to hold the specimen. The tensile specimen must be gradually necked down to a narrow waist some distance from the grips (Figure 10.3b), resulting in a much smaller necked area that has to sustain a much higher stress than occurs in the wood in the vicinity of the grips. Also, test specimen alignment is critical to avoid the introduction of unknown bending stresses.

If tension is about pulling and compression is about pushing, then shear is about sliding (Gordon, 1978). In contrast with compressive and tensile strength in which values along the grain are much higher than values across the grain, the shear strength of wood is much higher across than along the grain. Shearing wood across the grain involves severing the fibres, whereas shear parallel to the grain merely displaces the fibres relative to one another (Figure 10.4b). The low shear stress parallel to the grain presents design problems: a simple example would be the

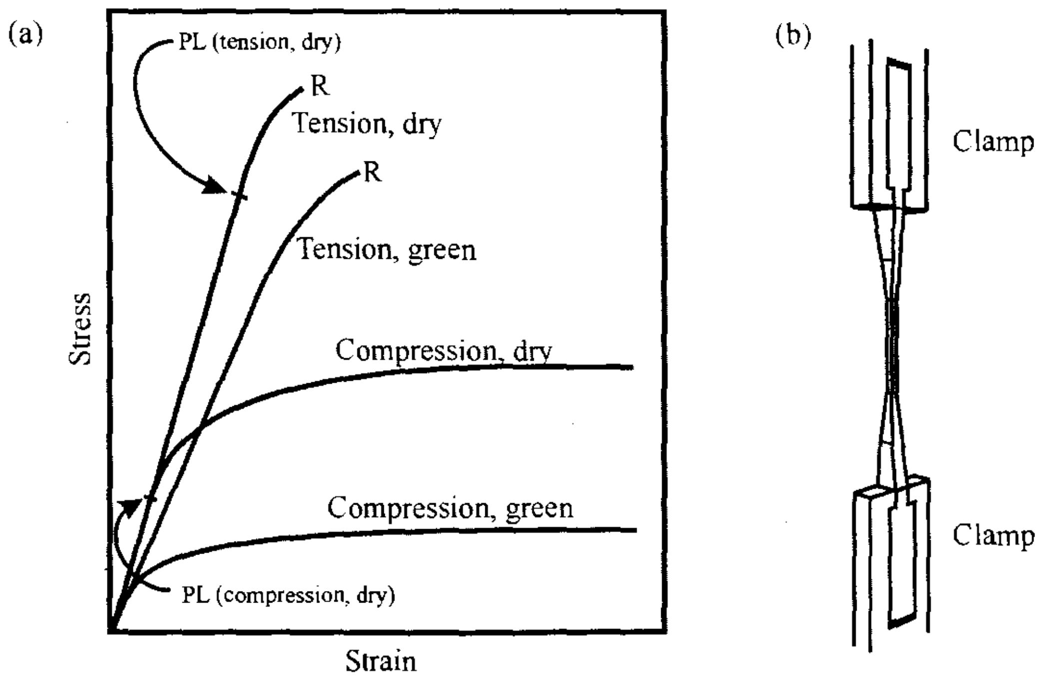


Figure 10.3. (a) Tensile and compressive behaviour of small clearwood samples in green and dry conditions: PL = proportional limit; R = rupture or failure stress. Wood in compression does not rupture suddenly under load but buckles. (b) Geometry of a necked-down tensile specimen.

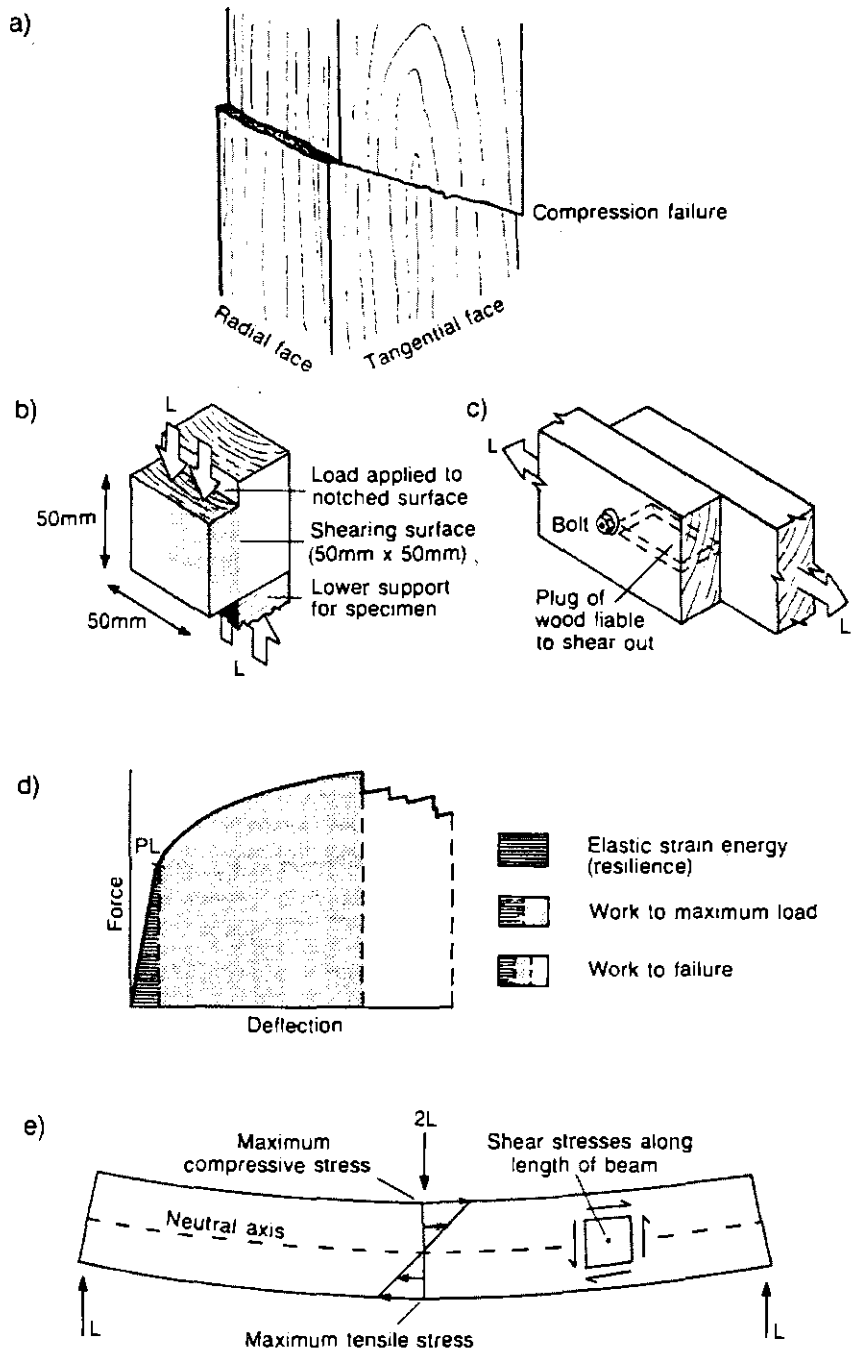


Figure 10.4. Examples of failure modes and bending tests. (a) Buckling failure of short specimens compressed parallel to grain (ASTM, 2005a). (b) Shear test of notched specimen: wood has low shear strength parallel to grain. (c) Low shear strength: timber members in tension parallel to grain cannot be readily connected with bolts, which tend to pull out under comparatively small loads. (d) Load–deflection curve during a bending test. (e) A three-point bending test, with maximum deflection at mid-span

premature pulling out of a bolt when the tensile stress is still modest (Figure 10.4c). Any benefit from using several bolts to form a more shear resistant joint is partially offset by the reduction in the effective section resulting from additional bolt holes. Furthermore, load sharing within an array of bolts is not equal, so that doubling the number of bolts does not double the load that can be sustained by the joint. Engineers devote a great deal of attention to the design of joints and other connector systems because good structural design using timber is dependent on the ability of these elements to transfer large stresses.

In a standard bending test, the beam is supported at either end and loaded at the mid-point. The span to depth ratio should be between 14:l and 21:l to increase the likelihood that the beam will rupture on the tension side. The load-deflection curve resembles the stress–strain curve of the compression or tensile tests (Figure 10.4d). However, the bending strength and stiffness of the wood must be calculated since stress and strain vary throughout the beam (Figure 10.4e). The following equation is used to estimate the modulus of elasticity in bending, E_b:

$$E_b \approx F_p l^3 / (4 \Delta b h^3) \tag{1}$$

where E_b = modulus of elasticity in bending,
F_p = load at proportional limit,
L = span between supports,
b = breadth of beam,
h = depth of beam,
and Δ = deflection at mid-point of beam under load F_p

The deflection at the proportional limit is:

$$\Delta \approx F_p l^3 / (4 E_b b h^3). \tag{2}$$

The bending strength, also known as the modulus of rupture or MOR, is calculated using:

$$\mathrm{MOR} \approx 3 F_R l / (2 b h^2), \tag{3}$$

where F_R = load at failure.
The maximum load that the beam can carry is:

$$F_R \approx (2\ \mathrm{MOR}\ b h^2)/3l \tag{4}$$

The horizontal shear stress is a maximum at the mid-depth of the beam (known as the neutral plane because here the bending stress is zero) and the shear stress falls to zero at the upper and lower surfaces. The shear stress in the neutral plane is:

$$S \approx 3\ F_R / 2bh \tag{5}$$

The modulus of rupture is an estimate of the stress at the upper and lower surfaces of the beam. It is calculated on the assumption that wood behaves elastically up to the point of failure, and it assumes that the maximum crushing strength and ultimate tensile strength have the same value. As Figure 10.6b illustrates, this is not true, but the analysis is an acceptable approximation for many purposes. The modulus of rupture (MOR) overestimates the crushing strength parallel to the grain at the upper surface and underestimates the tensile strength parallel to the gain at the lower surface of the beam. The equations given here assume a rectangular beam: the numerical constants and the form of the equation change somewhat if a member of a different cross-section carries the load, e.g. an I-beam or pole.

3.4.2. Simple beam theory

A beam is really two cantilever beams joined back to back (Figure 10.5a) and then turned upside down (Figure 10.5b). Thus, the largest compressive stress occurs on the concave surface of the beam at the mid-span, while the largest tensile stress occurs on the convex surface at the mid-point. Although it is obvious that tensile and compressive forces are generated within a beam when it is bent, it may not be self-evident that shear forces also exist. In a loaded beam, shear stresses act in both the horizontal and vertical directions.

The diagonal compressive and tensile stresses in a girder are equivalent to the two shear forces in a solid beam (Gordon, 1973). The shear forces act at right angles to each other and are oriented at 45° to the equivalent compressive and tensile forces. Both stress systems will deform a square piece of material into a diamond (Figure 10.5c). In a beam, the shear forces lie horizontally and vertically. The imposed weight, 2L, seeks to shear the beam in the vertical direction. The shear force acting at a point within the beam is defined as the algebraic sum of all the perpendicular forces acting on that portion of the beam that are either to the right or to the left of the point considered. Thus, the vertical shear stress acting at any point within the beam between A and B is always L (Figure 10.5b). In addition, an equally strong shear stress must act in the horizontal plane; otherwise the beam would rotate.

In a solid beam, the compressive and tensile stresses are not confined to the surfaces. The compressive stress in a section is highest at the upper surface and gradually diminishes to zero at the neutral plane. Similarly, the tensile stress is highest on the lower surface and diminishes to zero at the neutral plane (Figure 10.6a). While the beam deforms elastically, the compressive and tensile stresses increase proportionately with distance from the neutral plane. The compressive stress at a distance, *d*, above the neutral plane will be the same as the tensile stress at a distance, *d*, below the neutral plane. Further, as the modulus of elasticity is the same in compression and tension, the strain at both positions will be similar. Simple beam theory assumes that the beam behaves elastically until failure. However, the limit of proportionality in compression is quite low and once exceeded the fibres near the upper surface will start to buckle, crush, and strain at a greater rate: while

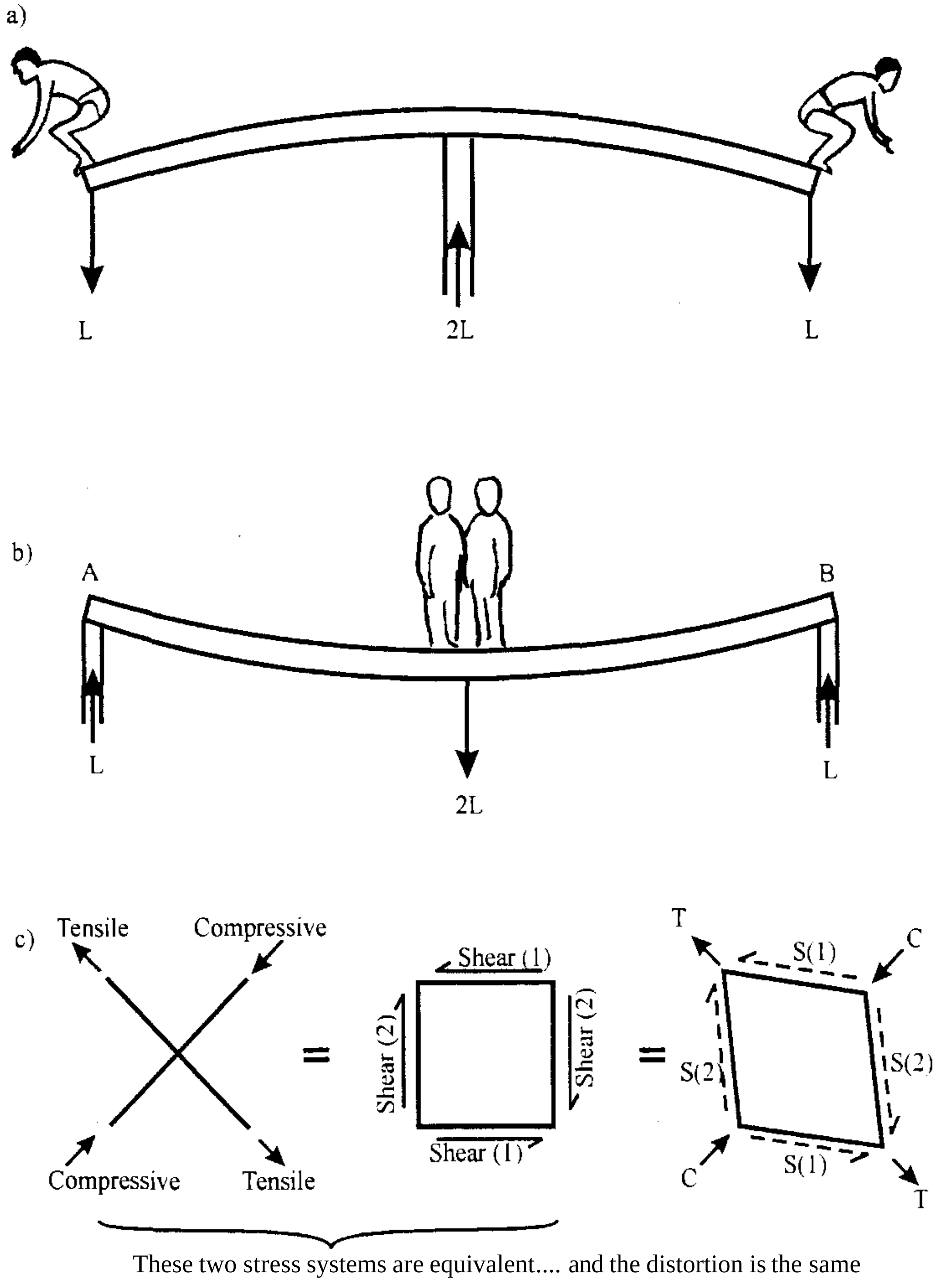


Figure 10.5. A beam under load is equivalent to two cantilevers placed back-to-back and rotated through 180°. Diagonal tensile and compressive stresses in a cantilevered girder are identical to two shear forces acting horizontally and vertically within a solid cantilever or beam. The effect of both stress systems is the same, deforming a square of material into a diamond (Gordon, 1973).

fibres in tension near the lower surface will still be deforming elastically (Figure 10.3a). An increased compressive load can be carried by moving the region of compression towards the lower face. In other words, the location of the neutral plane shifts. There is a little non-elastic deformation when the stress on the lower surface reaches the ultimate tensile strength value (Figure 10.6b). The ultimate tensile strength, calculated from simple elastic beam theory, underestimates the true tensile strength of 'wood', but not, as we shall see later, that of 'timber'.

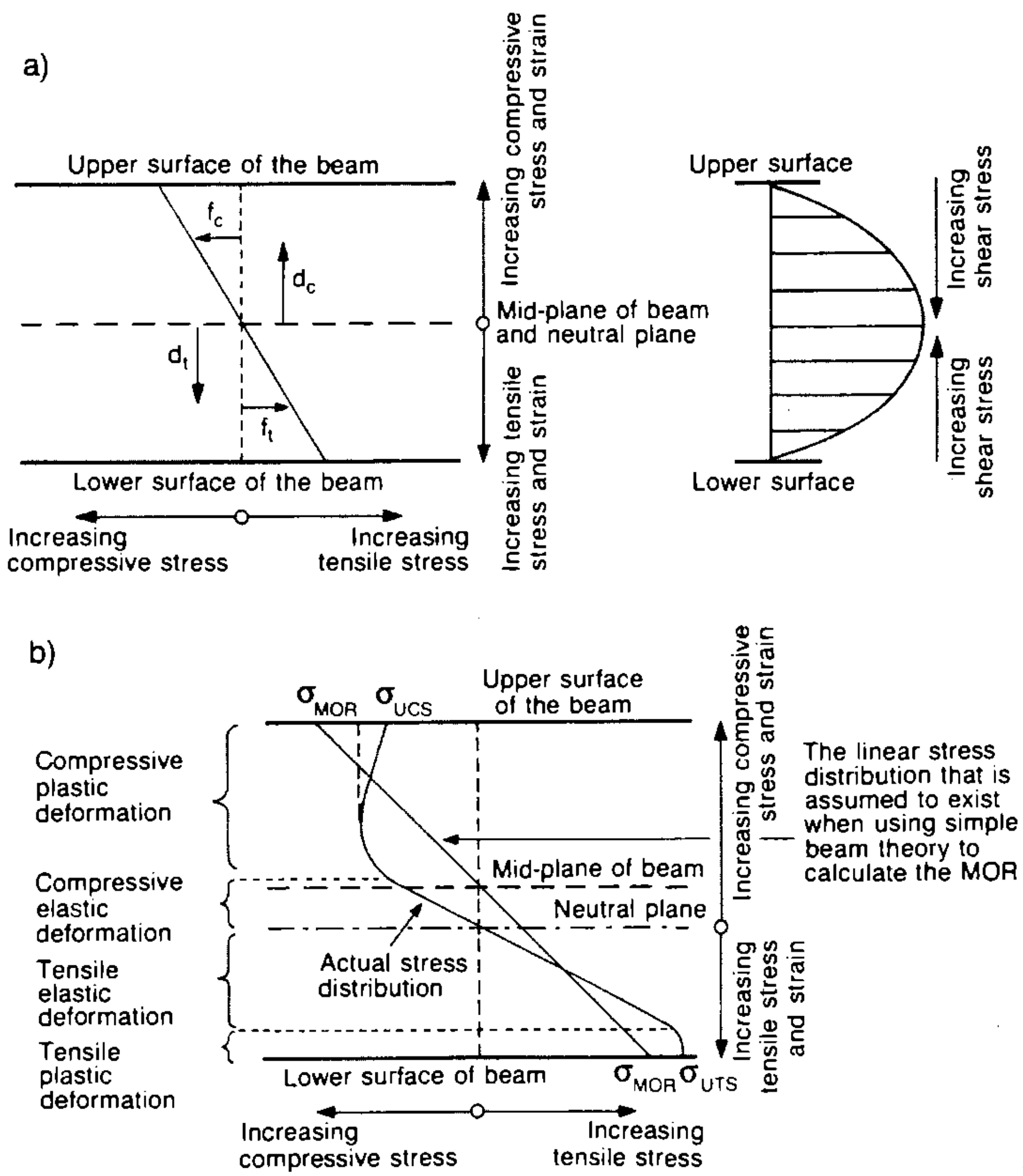
3.4.3. Some implications of beam theory

With large spans, excessive deflection under load can be a problem. Referring to the simple beam equations (equations l-5), it can be seen that doubling the length of the beam will result in an eight-fold increase in the deflection at the mid-point of the beam (Eq. 2), while reducing the load capacity of the beam by half (Eq. 4). Doubling the width of the beam only halves the deflection (Eq. 2) and doubles the load that can be sustained without the risk of rupture or shear failure (Eqs. 4 and 5). However, doubling the depth of the beam reduces the deflection by a factor of eight (Eq. 2), while the load that the beam can sustain before failure is quadrupled (Eq. 4). This means that it is more economic to increase the stiffness and strength of a beam by increasing the depth of the beam than to increase its width, because less material is needed in the cross-section. However, the shear stress within a beam decreases as the cross-section increases but it is not affected by the geometry of the cross-section or the length of the beam (Eq. 5). Shear failure can be a problem in short or deep beams that otherwise would sustain very heavy loads without excessive bending or failure. Shear failure is usually initiated by end splitting. Increasing the depth of the beam only results in a linear increase in the horizontal shear load that the beam can sustain, whereas the bending strength increases proportionate to the $(\text{depth})^3$.

Frequently. shear stresses do not govern in the design of beams; either the stiffness or the bending strength limit the carrying capacity of the beam. This means that material in the centre of the beam depth is not highly stressed. Engineers can design more efficiently by using an I-beam, which has wide flanges to carry the high stresses on the upper and lower surfaces and a thin diaphragm in the middle to bear the shear stresses and to keep the flanges apart.

High strength and stiffness are not the only criteria to judge structural efficiency. A third criterion is toughness, the ability of the material to absorb energy. Lignin, both in the middle lamella between fibres and as part of the matrix material between microfibrils, is able to absorb large amounts of energy without irreversible damage. Toughness is important in pit props, which have to sustain enormous loads without risk of sudden failure, and in highway fencing or power poles, which can be subject to impact in a traffic accident. For toughness the optimal MFA is about 25-30°.

Toughness can be defined and measured in a number of ways. A simple impact test can be used to measure the energy absorbed in the high strain rate fracture of a standard notched specimen. Another approach is to measure the strain energy



σ_{MOR} = modulus of rupture

σ_{UCS} = ultimate crushing strength

σ_{UTS} = ultimate tensile strength

Figure 10.6. Bending of timber beams. (a) Schematic stress distribution at the mid-span of the beam, assuming that the beam deforms elastically. (b) In practice, clearwood starts buckling due to compression failures at the upper surface, whereas knotty timber is more likely to fail in a brittle manner in the vicinity of a knot lying in the tension zone. The behaviour of knotty timber is more akin to a beam deforming elastically up to brittle failure (rupture).

absorbed as timber under flexural loading is bent (Figure 10.4d). The elastic strain energy, also termed resilience, corresponds to the energy absorbed when timber is loaded to the elastic limit: it is equal to the area beneath the load–deflection curve up to the proportional limit (PL). The other two strain energy terms are work to maximum load and work to failure, which correspond to the area beneath the load–deflection curve from zero to the maximum load and to the failure point, respectively. Energy absorption is slightly better in green timber relative to the usual dry service moisture conditions, but it may increase with extreme drying. Round wood is tougher than sawn timber, as the sweep of grain around knots may be severed in sawn timber whereas it is preserved around branches in round wood.

Simple beam theory is a good starting point to understand the major implications of changes in dimensions in wood members, but lumber has further complexities that simple beam theory cannot interpret. Lumber is anisotropic and has many natural defects. Grading is a formal attempt to allow for the impact of these natural defects. The weakening effect of knots is very critical to determining the performance of particular timber products. However, before discussing grading further, it is critical to develop an understanding of the variability present in wood.

3.4.4. Effect of specimen variability on wood properties

Wood as a material inherently has a great deal of variability since it is naturally formed. Even with small clearwood specimens there is considerable variability in the strength (Table 10.2). This is to be expected. It reflects differences in density and microfibril angle within a tree, between trees in a particular stand, and between trees from contrasting locations and growing under difference management systems. For example, the bending strength of European redwood, *Pinus sylvestris,* based on a representative sample collected from material imported into Britain, is approximately Gaussian (Figure 10.7a). The distribution of strength values about the mean is very important. From this information, an estimate can be made about the probability of a piece withstanding a particular load. In this example of European redwood, there is a 1 in 100 chance of the piece failing under a bending stress of 26.1 MPa (378.6 lb/in^2) during the test; this value is significantly less than the mean value of 44.4 MPa (644 lb/in^2). The coefficient of variation (CV), the ratio of the standard deviation to the sample mean, provides a measure of the range of this distribution. A small coefficient of variation is highly desirable as it means less variation in the measured values of the property.

Unlike the strength of clearwood specimens, the strength distribution of material with defects is typically not symmetric. The distribution of material with many defects can be positively skewed, resulting in a lower mean value and a high strength tail (Figure 10.7b).

Typical coefficients of variation for clearwood, for graded kiln-dried Douglas fir, Hem-fir and Southern Pine, and for alternative materials is given in Table 10.2. The variability in properties increases on going from small clearwood specimens to commercially graded material. The poorer grades of timber display more variable

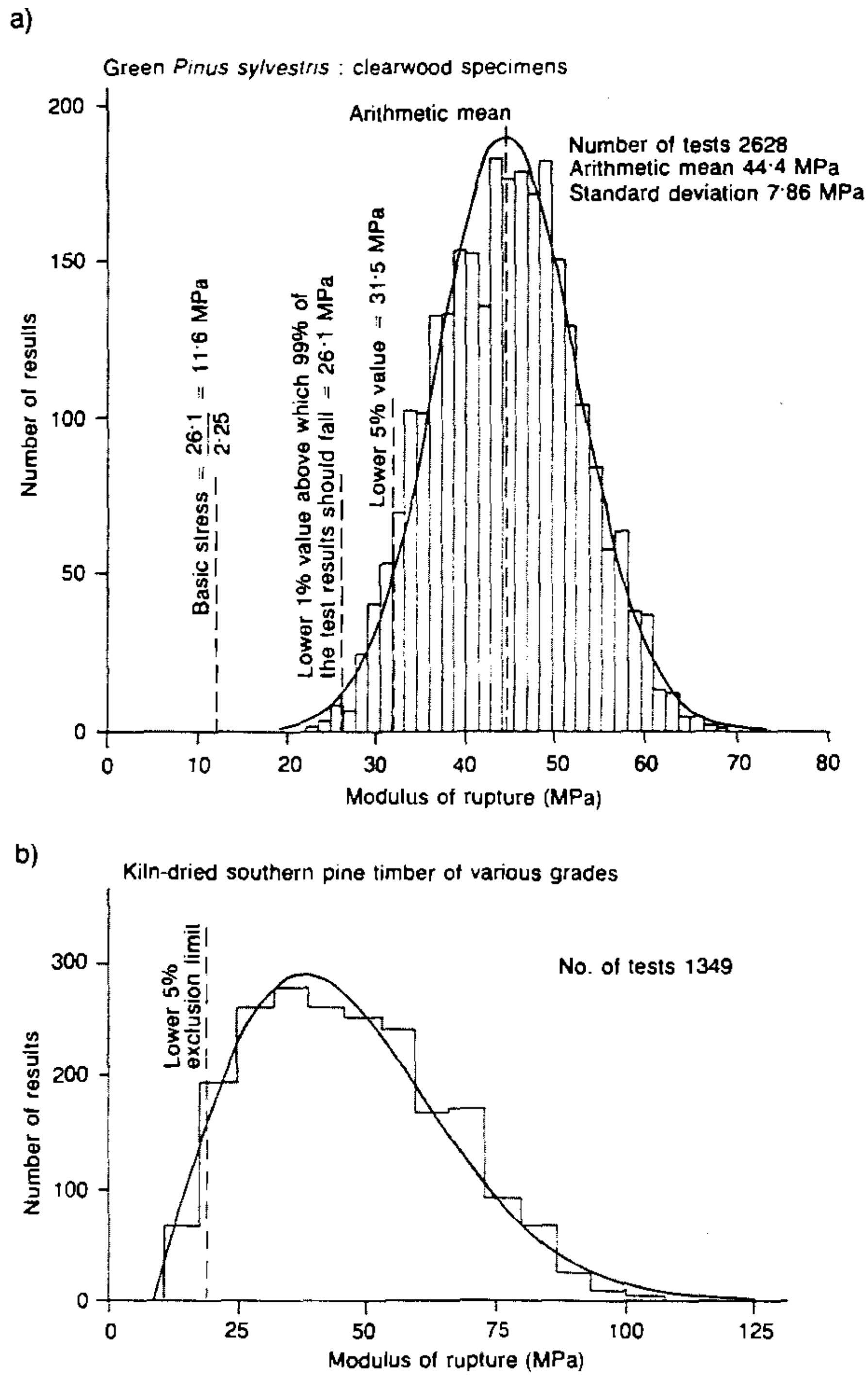


Figure 10.7. Bending strength of clearwood and timber. (a) Small clear green specimens of *Pinus sylvestris* (Sunley, 1968). Data approximates to a normal distribution with a coefficient of variation of 17.7%. Thus 1% of population fails before the stress reaches 26.1 MPa (44.4 - 2.33 x 7.86) and 5% fails below 31.5 MPa (44.4 - 1.645 x 7.86). (b) Variability in bending strength of kiln-dried southern pine of various grades (Doyle and Markwardt, 1966).

Table 10.2. Coefficients of variation for mechanical properties of clearwood and kiln-dried visually graded lumber compared to those of competitive structural materials. Clearwood values are based on tests of approximately 50 species (USDA, 1999) and lumber properties are from Green and Evans (1989). MOR is modulus of rupture, MOE is modulus of elasticity.

	Coefficient of variation (%)					
Material	Properties of other materials	MOR	MOE	Tension parallel to grain	Compression parallel to grain	Shear parallel to grain
Clearwood		16	22	–	18	14
Select Structural						
Douglas Fir		22	24	34	17	–
Hem–Fir		22	21	31	17	–
Southern Pine		23	18	32	18	–
No. 1 & Better						
Douglas Fir		30	25	41	20	–
Hem–Fir		38	23	36	20	–
Sonthern Pine		25	19	38	20	–
No. 1						
Douglas Fir		28	22	34	14	–
Hem–Fir		28	21	30	16	–
Southern Pine		28	23	36	20	–
No. 2						
Douglas Fir		34	27	47	22	–
Hem–Fir		35	26	40	20	–
Southem Pine		37	24	48	23	–
Concrete	10–20					
Structural steel	5–15					
Metal connectors	10–15					

mechanical properties. The gradual exhaustion of the prime virgin forests of the world and the utilization of second-growth and plantation forests have forced manufacturers to use lower grade and more variable material. This in turn has necessitated the development of different grading methods that take account of this greater variability in timber properties.

There are three main methods to stress-grade timber for structural use: visual stress grading, mechanical stress grading, and proof grading.

4. VISUAL GRADING OF STRUCTURAL LUMBER

Visual grading of structural lumber imposes limits on the maximum size of knots and slope of grain and the minimum density permitted for a given grade. It involves turning the timber to examine all four faces. Yet the relatively low value of the product does not allow for a slow, deliberate examination. A piece of timber is typically graded in two or three seconds. Visual grading has to be able to tolerate errors; a packet of graded timber is deemed to meet the grade if, on re-examination, at least 95% of the pieces are of that grade. Destructive testing of visually graded timber shows that very few pieces fail below the grade stress value, but many pieces are far stronger than the grade stress would indicate. The characteristics of visually grading are that:

- It does not require great technical skill,
- It is safe but inefficient,
- It is labour-intensive but fast,
- It is ideal for small mills and local markets,
- It permits a quick primary sort (to remove visually unacceptable material that might have inadequate strength) prior to other structural grading techniques, and
- It retains market acceptability

4.1. Visual sorting criteria

Visual grading is the original method for stress grading. Originally it was based on the premise that mechanical properties of lumber differ from mechanical properties of clearwood only because of the many growth characteristics that affect properties. and these characteristics can be seen and judged by eye. Growth characteristics are used to sort lumber into stress grades. The typical visual sorting criteria for softwoods are knots, slope of grain, shake, checks and splits, density, decay, pitch pockets, wane, growth rate and pith. Other features may be characteristic of a great number of tropical species and a few temperate ones, such as interlocked grain, brittleheart, and severe growth stresses.

4.1.1. Knots

Knots cause localized cross-grain with steep slopes. A damaging aspect of knots is that the continuity of the grain around the knot is interrupted by the sawing process. The weakening effect of knots depends on: knot size; mode of testing; and position of the knot within the piece of timber (Figure 10.8).

There is a modest correlation between the strength of timber and knot size. The adverse effect of a knot is primarily attributed to the presence of cross-grain in the immediate vicinity of the knot, rather than to the size of the knot itself. Knots have a greater effect on strength in tension than in compression; in bending the effect depends on whether a knot is on the tension or compression side of a beam (knots along the centre line only affect shear). Intergrown (or live) knots resist compression and transmit some tension, but neither bark-encased knots (unless very tight) nor knotholes can carry a tensile stress. On the other hand, distortion of grain is greater around an intergrown knot than around an encased (or dead) knot of equivalent size. As a result, overall strength effects are roughly equalized, and often no distinction is made in stress grading between intergrown knots, dead knots, and knotholes.

The distorted cross-grain around a knot is not ‘parallel to piece’ so its stiffness is less than that of straight-grained wood; thus, knots are associated with local areas of low stiffness. However, such zones generally constitute only a minor part of the total volume of a piece of lumber and, because overall stiffness of a board reflects the sum of all its parts, 'whole piece' stiffness is not greatly influenced by knots.

The effect on strength depends roughly on the proportion of the cross-section occupied by the knot, the knot's location, and the distribution of stress in the piece. Limits on knot sizes are therefore made in relation to the width of the face and the location of the knot within the face. Compression members are stressed about equally throughout, and no limitation related to the location of knots is imposed. In tension, knots along the edge cause an eccentricity that induces bending stresses, and they should therefore be more restricted than knots away from the edge. In simply supported structural members subject to bending, stresses are greater in the middle of the length and at the top and bottom edges than at mid-height. These facts are recognized in some grades by differing limits to the sizes of knots in different locations. Thus some grading rules distinguish between knots lying at the edge/margin and in the central part of the wide face (Figure 10.8). Other rules apply the 'knot area ratio' concept to determine the impact of knots on overall properties

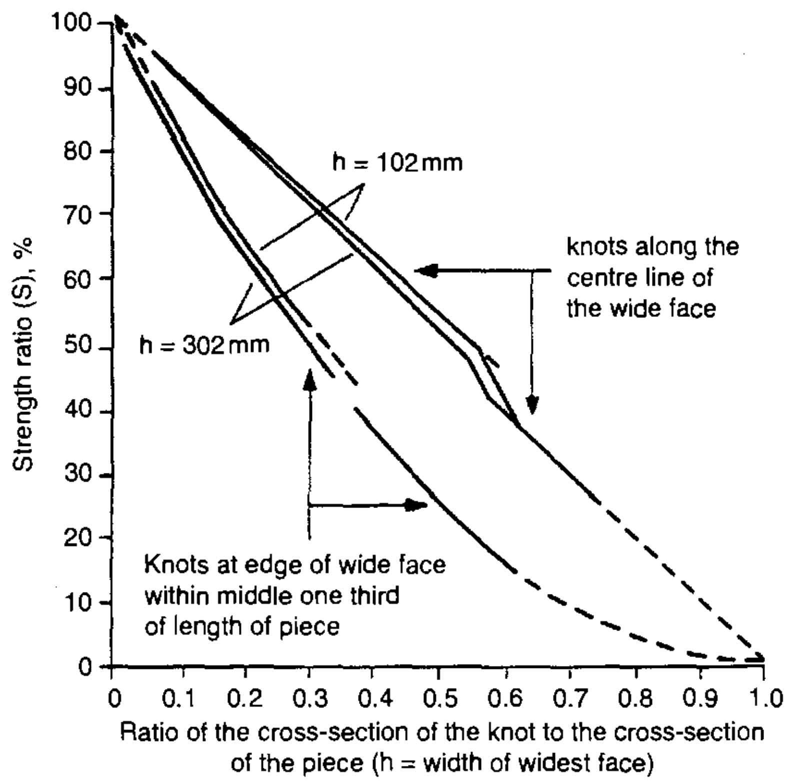


Figure 10.8. The loss in strength due to knots is a function of their size and location. The equations here are from an appendix in ASTM D245 (ASTM, 2005b). In essence, the strength ratio for a timber with a knot on the edge/margin of the wide face is deemed to be equivalent to the square of the strength ratio of a timber with an identical knot that lies at the centre of that face.

(Figure 10.9). Bending strength is more sensitive to margin hots than to centre-face knots, while the effect of hots confined to the narrow edge of the member is less than but similar to that due to a knot in the edge/margin of the wider face. The results are expressed in terms of a strength ratio that relates the strength of the timber with hots occupying a proportion of the cross-section to the strength of an equivalent knot-free member.

4.1.2. Slope of grain

An empirical, elliptical relationship, originally developed by Hankinson (USDA, 1999), is often used to describe the effect of grain orientation on strength properties:

$$\sigma_\theta = \frac{\sigma_{\|}\,\sigma_{\perp}}{\sigma_{\|}\sin^n\theta + \sigma_{\perp}\cos^n\theta} \tag{6}$$

where σ_θ is the strength property at an angle θ to the fibre direction, and (σ//) and $\sigma\perp$ are the strength parallel and perpendicular to the grain respectively, while *n* is an experimentally determined constant. Slope of grain reduces the mechanical properties of lumber because the fibres are not parallel to the edges. Representative values for *n* and $\sigma\perp/\sigma//$, are given in Table 10.3. Note that the lowest $\sigma\perp/\sigma//$ value of 0.03 for compressive strength applies to very low density wood: a ratio of 0.1 or more is more typical.

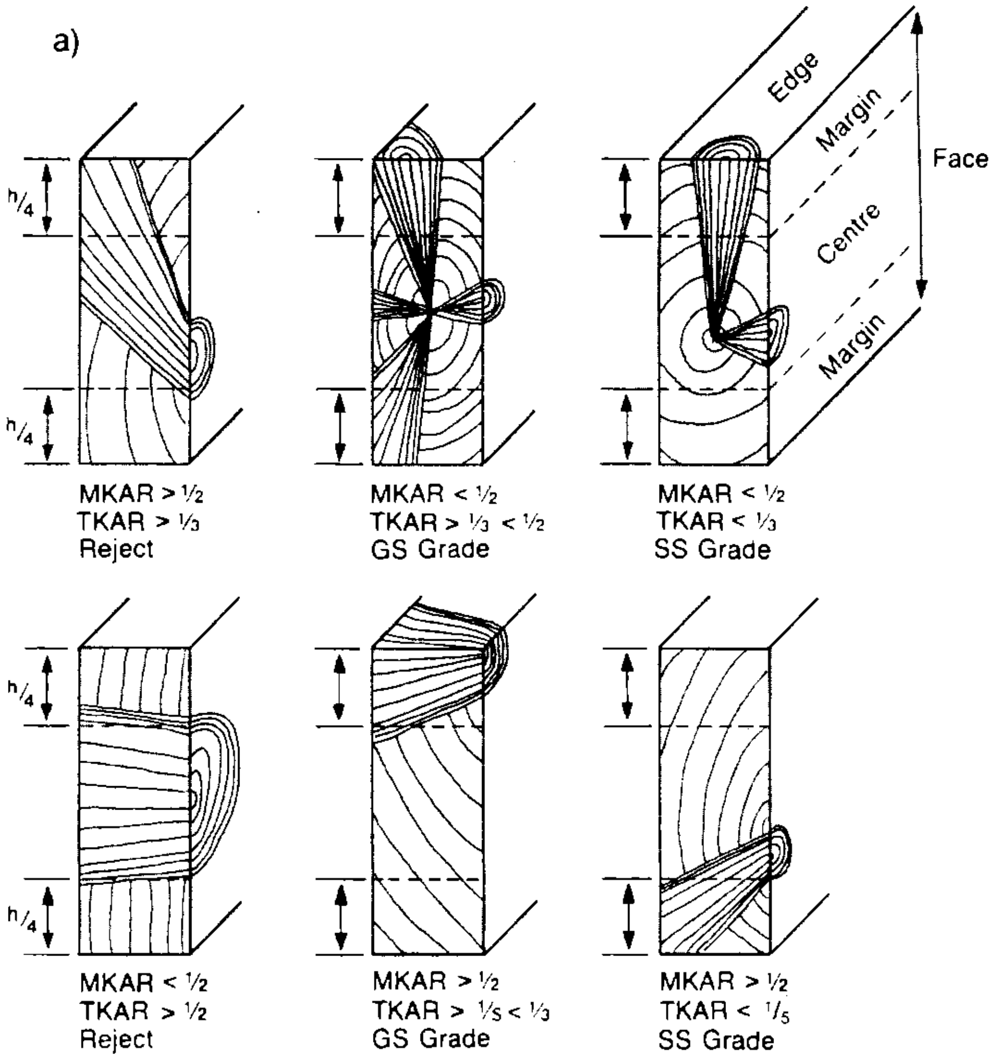
Table 10.3. Constants for Hankinson's formula for the effect of grain orientation on strength properties (USDA, 1999).

Property	n	$\sigma\perp/\sigma_{11}$
Tensile strength	1.5–2.0	0.040.07
Compressive strength	2.0–2.5	0.03–0.40
Bending strength	1.5–2.0	0.04–0.10
Modulus of elasticity	2.0	0.04–0.12
Toughness	1.5–2.0	0.06-0.10

Lumber with highly localized cross-grained (arising from hots) are especially undesirable as they tend to warp with changes in moisture content. Stresses caused by shrinkage during drying are greater in structural lumber than in small, clear, straight-grained specimens and are exaggerated in zones of distorted grain. To provide a margin of safety, the reduction in design properties resulting from cross-grain in visually graded structural lumber is considerably greater than that observed in small, clear specimens that contain similar cross-grain.

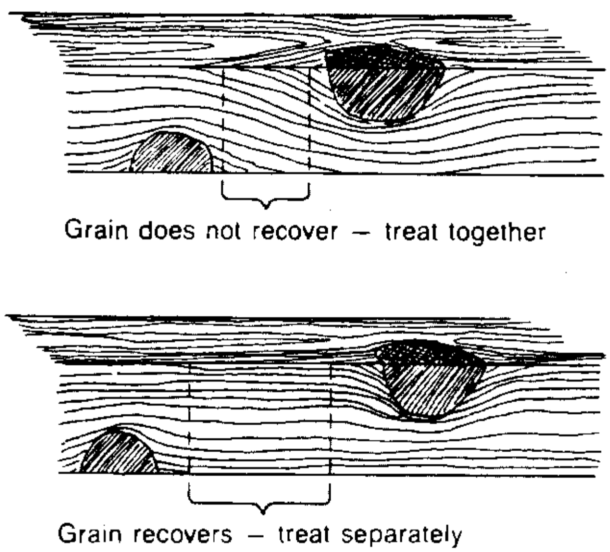
Figure 10.9. Grading rules must take knots into account. (a) Typical knot area ratios (KAR) and resulting grades (BSI, 1986); (b) Knots are considered to act together and occupy the same cross-section if the grain disturbance around the knot has not recovered before the grain starts to deviate around the next knot (TRADA, 1974).

a)



Edge
Margin
Centre
Margin
Face
h/4
h/4
MKAR > 1/2
TKAR > 1/3
Reject
MKAR < 1/2
TKAR > 1/3 < 1/2
GS Grade
MKAR < 1/2
TKAR < 1/3
SS Grade
MKAR < 1/2
TKAR > 1/2
Reject
MKAR > 1/2
TKAR > 1/5 < 1/3
GS Grade
MKAR > 1/2
TKAR < 1/5
SS Grade

b)



Grain does not recover — treat together
Grain recovers — treat separately

4.1.3. Checks, splits, shake and pitch pockets

Checks and end-splits develop during drying and their influence is confined to their immediate vicinity. Shake is a separation that occurs between or through growth rings, that is presumed to extend lengthwise without limit. They occur in the tree due to some environmental stress or on felling. Grading rules restrict end-splits and shake most severely in those parts of a bending member where shear stresses are highest. Also they may be limited because of appearance and because it permits entrance of moisture that may result in decay.

Pitch pockets ordinarily have so little effect on structural lumber. However, the presence of a large number of pitch pockets may indicate shake or weakness of bond between annual rings.

4.1.4. Density

Density is a pragmatic index for predicting intrinsic properties, because it is a measure of the amount of cell wall material in a given volume. A general equation (USDA, 1999) relating strength to density is:

$$\text{Strength property} = k\,(\text{density})^n \tag{7}$$

where k and n are constants. For modulus of rupture, n has a value of about 1.05.

The lowest strength pieces can be eliminated from grades in some codes by excluding those that are of exceptionally low air-dry density (<400 kg/m^3). Effectively this excludes the worst corewood, as with softwoods the average density of corewood can be as little as 60-65% of that of outerwood. A related approach adjusts property values assigned to lumber by taking account of the rate of growth and percentage of latewood, using these as surrogate and indirect measures of density - just as density itself is taken to be a surrogate for more fundamental characteristics of the cell wall. Typically, growth rate (rings per inch/cm) and the percentage of latewood should be within a specified range.

Some visual stress grading rules limit the growth rate and exclude all pith. There are two separate issues. The exclusion of with-pith material is understandable as corewood in its vicinity has a number of undesirable characteristics, including low density, low stiffness, and dimensional instability. However, a restriction on growth rate is less satisfactory unless it is coupled with a criterion that addresses ring curvature to ensure that such sorting only excludes material in proximity to the pith.

4.1.5. Miscellaneous: wane and decay

Aesthetics and the need for an adequate edge/face for fabrication or to provide ample bearing or nailing surfaces generally impose stricter limitations on wane than does strength. Wane relates to the rounded cambial surface (with or without bark) that may be found in lumber cut from outerwood.

Decay in most forms is prohibited or severely restricted in stress grades because the extent of decay is difficult to determine and its effect on strength may be greater than visual observation would indicate. Further without preservative treatment arrested decay in dry wood will resume if the material were to be rewetted. There are circumscribed exceptions. Limited decay of the pocket type, e.g. *Fomes pini,* can be permitted in stress grades, as it occurs in knots but not in the surrounding wood.

4.2. Responsibilities and standards for visual stress grading

An orderly, voluntary, but circuitous system of responsibilities has evolved in most countries to handle visual stress grading. Most visually stress graded lumber is dimension lumber produced in sizes from 35 to 90 mm (1-1/2 to 3-1/2 in.) thick and 35 to 200 mm (1-1/2 to 8 in.) wide. Each country has its own series of grades that are applied to their products. Table 10.4 provides a partial list.

In North America, stress grading is handled under the auspices of the American Lumber Standard Committee (USDC, 1999). In Europe, individual countries have their own grade classifications but a visual grading standard EN 518 (ECS, 1995) is used as the overarching guideline for property development. Elsewhere the following apply: South Africa SANS 1783 (SANS, 1997); Australia AS 2858 (SAA, 1986a); New Zealand NZS3631 (SANZ, 1988); Japan JAS 143 (JAS, 1997).

Attempts are currently under way to develop a more standardized international approach through the International Organization for Standardization (ISO).

Table 10.4. Partial list of various grades for visually graded timber throughout the world.

European visual grades										
Belgium	France	Germany	Greece	Holland	Ireland	Italy	Nordic	Portugal	Spain	UK
S10	B	S13	S10	A	SS	S10	T3	S10	Eng	SS
S8	S	S10	S8	B	GS	S8	T2	S8	P2	GS
S6		S7	S6	C		S6	T1	S6	P1	
			S4	D			T0			

Elsewhere							
Australia		China	Japan	New Zealand	South Africa	US. & Canada	
F14	F7	Grade1	No. 1	Eng	S14	SS	Const
F11	F5	Grade2	No. 2	No. 1	210	No. 1	Std
F8	F4	Grade3	No. 3	No. 2	S7	No. 2	Util

4.3. Classification into strength groups

In grouping species into strength classes, MOE and MOR are assigned conservative values. Species are usually grouped together where they have roughly the same mechanical properties and so can be treated as equivalent, or where two or more species are very similar in appearance, or for marketing convenience.

The advantages of strength groupings were first recognized in Australia where an enormous number of indigenous species have been evaluated for structural purposes (Leicester, 1988). In tropical regions, there are literally thousands of individual timbers, which are often difficult or impossible to identify once sawn. Similar looking species can have very different strength characteristics. In Malaysia only 400 of 2500 species are deemed to be of commercial value. To achieve orderly marketing, these 400 species are grouped so that, in effect, 70% of the commercial timbers of Malaysia are actually species mixtures.

The Australian standard AS 2878 (SAA, 1986b) offers two approaches to categorize a timber into strength groups. Where adequate but limited data of mean strength Characteristics are available, a positive strength grouping is possible. Where these data are not available, the mean air-dry density of the timber is used instead to give a more conservative, provisional strength grouping (Table 10.5). Application of visual grading rules (SAA, 1986a) leads to four or more stress grades for each of the 600 species listed (SAA, 1986b), giving a total of 2500 individual stress grades.

Table 10.5. Lower limits for strength groups for seasoned timber (SAA, 1986b)

Strength group	Testing of small clearwood specimens			Density at 12%MC
	Bending (MPa)	Compression (MPa)	Stiffness (GPa)	(kg m^{-3})
SD1	150	80	21.5	1200
SD2	130	70	18.5	1080
SD3	110	61	16.0	960
SD4	94	54	14.0	840
SD5	78	47	12.1	730
SD6	65	41	10.5	620
SD7	55	35	9.1	520
SD8	45	30	1.9	420

These stress grades have been reconciled and rationalized into only 12 interlocking stress grades in a geometric preferred number series (Table 10.6). For structural purpose, it is sufficient for the engineer to specify the desired stress grade, i.e. F14. Selection may be tempered by considerations such as cost, natural durability, or amenability to preservation, seasoning, or gluing characteristics.

Strength groups avoid any confusion that can arise where it is presumed all material of a given grade has equivalent properties. No. 1 dark red meranti does not have the equivalent strength of No. 1 balau: dark red meranti falls into SD6 group and its No. 1 lumber is F14, whereas balau is in SD3 and its No. 1 lumber is F27. Balau and dark red meranti both contain species groupings of the genus *Shorea.*

A number of grading systems are employed in Europe. To remove barriers to trade, the European Union (EU) instituted a strength class approach to species groupings as part of the development of a EU lumber building code, Eurocode 5 (EC5, 1995), to provide member countries with a unified framework of harmonized

Table 10.6. Basic working stresses and stiffness for structural timber (SAA, 1988b). Each grade stress is 25% greater than that below. MOE includes an allowance for shear.

	Basic working stresses (MPa)				MOE
Stress grade	Bending	Tension	Shear	Compression	(GPa)
F34	34.5	20.7	2.45	26.0	21.5
F27	27.5	16.5	2.05	20.5	18.5
F22	22.0	13.2	1.70	16.5	16.0
F17	17.0	10.2	1.45	13.0	14.0
F14	14.0	8.4	1.25	10.2	12.0
F11	11.0	6.6	1.05	8.4	10.5
F8	8.6	5.2	0.85	6.6	9.1
F7	6.9	4.1	0.70	5.2	7.9
F5	5.5	3.3	0.60	4.1	6.9
F4	4.3	2.6	0.50	3.3	6.1
F3	3.4	2.0	0.45	2.6	5.2
F2	2.7	1.6	0.35	2.1	4.5

standards and regulations (Cooke, 1988; Sunley, 1979). Table 10.7 shows the strength classes that have been established in the Eurocode.

The ISO Technical Committee 165 is developing a global strength class system that will be compatible with the existing European and other systems.

A strength class system does not exist for visual stress grades in the United States and Canada. However, ASTM D2555 (ASTM, 2005e) has procedures for calculating clearwood properties for groups of species to be used with D245 (ASTM, 2005c). Also, D1990 (ASTM, 2005d) contains procedures for calculating design properties for groups of species tested as full-size members. The properties assigned to a group by such procedures will often be different from those of any species in that group. The group will have a unique identity, with nomenclature approved by a given country's regulatory agency.

Table 10.7. Minimum strength requirements for European strength classes (ECS, 2003).

Mechanical	European (EN 338) strength classes (C-Grades)								
property	C14	C16	C18	C22	C24	C27	C30	C35	C40
F_b, MPa	14	16	18	22	24	27	30	35	40
F_t, MPa	8	10	11	13	14	16	18	21	24
F_c, MPa	4.3	4.6	4.8	5.1	5.3	5.6	5.7	6.0	6.3
E, MPa	7000	8000	9000	10 000	11 000	12 000	12 000	13 000	14 000

F_b is bending stress; F_t, tension parallel to grain; F_c, compression parallel to grain; E, modulus of elasticity.

4.4. Revision of the visual stress grading philosophy

In the mid-l960s, some allowable properties for lumber began to be questioned as more data on full-size lumber specimens became available (Bohannan, 1966; Doyle and Markwardt, 1966, 1967, 1968). This was especially true for tension parallel to grain. In 1968, a new provision was adopted in ASTM D245 that set tension values at 55% of bending values for visually graded timber. By the 1970s, additional work on full-size lumber (Johnson and Kunesh, 1975; Kunesh and Johnson, 1972, 1974; Littleford, 1978; Littleford and Abbott, 1978) provided enough evidence to show that the visual stress grading procedures used at that time were no longer appropriate or particularly efficient. Also, during this period there was a major liability suit centred on the failure of a large cooling tower constructed of wood, which heightened the concerns of the North American lumber industry. The final straw came from a series of studies on full-size lumber by Borg Madsen at the University of British Columbia (Madsen, 1975, 1976, 1978). Madsen described these studies as ‘in-grade’ tests because they were tests of material representative of typical commercial lumber that was within grade. These tests implied that published bending stress values could be overstated by as much as 25% to 35%. Also, Madsen called into question the current moisture adjustment procedures for commercial structural timber. Another study at Colorado State University seemed to confirm that bending stress values were overstated (Bodig, 1977).

The basis for the grading of small clear timber had been developed when it was relatively easy to obtain large timber members with few, if any, serious defects. These members could be cut from enormous trees in the virgin forests of most continents. Today, such timber is much more difficult to obtain. This is significant since the failure mode of clearwood in bending is quite different from the failure mode of pieces in graded structural timber (Figure 10.10). Tensile failure perpendicular to the grain. caused by localized grain disturbances around knots, weakens structural timber considerably. Madsen argued that because of different failure mechanisms, strength characteristics of structural timbers should be obtained by evaluating graded material directly rather than using clearwood strength to estimate the allowable grade stresses. A large testing program known as the North American In-Grade Testing Program evaluated material in the grades as produced in the United States and Canada (Green *et al.* 1989).

It should be emphasized that all visual grading procedures are quite crude systems for categorizing the strength properties of timber. Thus, there will be a significant proportion of low grade material, e.g. No. 3, which would sustain a stress equivalent to that for a higher grade, e.g., Select Structural. Equally, a much smaller proportion of SS only has the strength equivalent to that expected of No. 1, No. 2, or even No. 3 lumber.

Grading rules for home construction timber have generally abandoned the clearwood approach outlined in Figure 10.7. In the old system clearwood tests established the lower percentile values for the population (either the lower 1% or 5%) which were reduced further to obtain a basic stress for clearwood, by applying

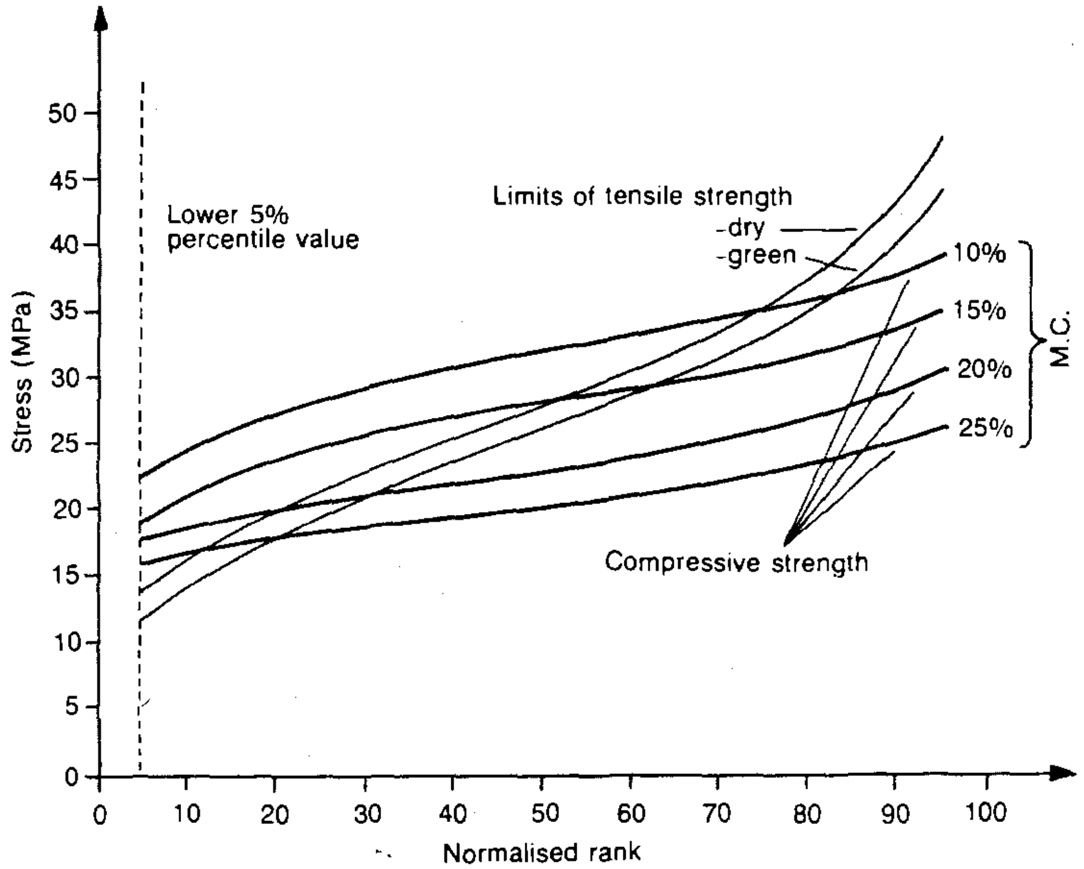


Figure 10.10. Ranked data of compressive and tensile tests with 38 x 140 mm (2" x 6") spruce-pine-fir (S-P-F) of No. 2 grade and better (Madsen, 1984b). The tensile strength is less sensitive to changes in moisture content than is the compressive strength. Consequently at the low strength end of the distribution pieces experience brittle failure in tension, in the immediate vicinity of cross-grain or knots. This contrasts with clearwood tests (equivalent to the strongest lumber, ranked to the right in this figure) where the tensile strength always exceeds the compressive strength.

corrective terms for long term loading and a factor of safety/ignorance - remember samples are broken in standard tests in a matter of minutes, yet a timber beam is expected to carry a load for many years. Finally grade stresses were obtained by considering the extent to which permitted defects in a particular grade reduced the properties of that grade relative to that expected of clearwood. The original British grades (Sunley, 1968), had strength ratios of 0.75, 0.65, 0.50 and 0.40 relative to the basic stress of clearwood

The updated BS 4978 (BSI, 1986) specification for softwood grades for structural uses replaced the four grades by just two visual stress grades, general structural (GS) and select structural (SS), which have strength ratios of the order of 0.3-0.35 and 0.5-0.6, respectively. However the strength ratio is no longer derived.

Instead the grade stress is determined directly by in-grade testing, and the link with clearwood values through the strength ratio has been broken.

Unlike clear wood specimens, the strength distribution for in-grade material is asymmetric: the population is positively skewed. This results in a lower mean value and a high strength tail (Figure 10.7b). Therefore, a Gaussian distribution function cannot be used to estimate the lower fifth percentile exclusion limit. Instead, it is preferable to characterize the distribution function and determine the fifth percentile value non-parametrically. A three-parameter Weibull distribution has been found to accurately characterize these skewed distributions.

4.5. Procedures for deriving design properties

The mechanical properties of visually graded lumber may be established by (i) tests of a representative sample of full-sized members, or (ii) appropriate modification of test results conducted on small clear specimens. Design properties for the major commercial species in a country may be a mixture of these two methods. For example, values for softwood dimension lumber species listed in current design specifications and codes in the United States have been derived from full-size member test results using D1990 (ASTM, 2005d). In contrast, design properties for most hardwood dimension and structural timbers are still derived using results of tests on small clear samples under standard D245 (ASTM, 2005c).

4.5.1. Application of strength ratios

The influence of knots still needs to be assessed; in the United States with the strength ratio method (Figures 10.11 and 10.12); in the UK by looking at the proportion of the cross-section that they occupy, their interaction with one another, the total knot area ratio (TKAR), and their location within a member (Figure 10.9). Smaller knots are permitted in the margins than elsewhere in the member. The permissible knots are presumed not to lower the strength of the material below the stress assigned to that grade. The weakening effect of adjacent knots, even if not lying in the same cross-section, is recognized: in such cases: both knots are deemed to be in the same cross-section (Figure 10.9b). This takes account of any serious

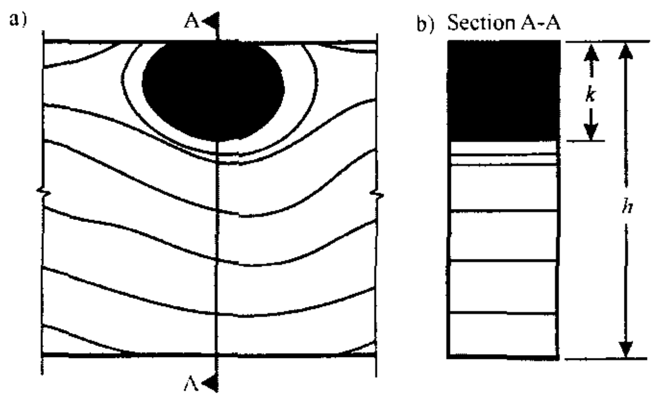


Figure 10.11 (a) Edge knot in timber (b) Assumed loss of cross-section (shaded area).

cross-grain in the vicinity of one knot interacting with the grain around an adjacent knot. Other defects are prescribed, e.g. the slope of grain must not exceed 1:6 for general structural and 1:10 for select structural.

In the United States, sorting criteria that influence mechanical properties of hardwoods are handled with 'strength ratios' for the strength properties and with 'quality factors' for the modulus of elasticity. Conceptually each strength property of a member is derived from the product of the clearwood strength for a population representing the species and a measured limiting strength ratio for that member, i.e. the strength ratio is the hypothetical ratio of the strength of the piece with visible strength-reducing growth characteristics to its strength if those characteristics had been absent. The true strength ratio is never known and can only be estimated.

Estimated strength ratios for cross-grain and density have been obtained empirically; strength ratios for other growth characteristics have been derived theoretically. For example, to account for the weakening effect of knots, the assumption is made that the knot is effectively a hole through the piece, reducing the cross-section, as shown in Figure 10.11. For a hardwood beam containing an edge knot, the bending strength ratio can be idealized as the ratio of the bending moment that can be resisted by a beam with a reduced cross-section to that of a beam with a full cross-section:

$$SR = 1 - (k/h)^2 \tag{8}$$

where SR is the strength ratio, *k* the knot size, and *h* the width of face containing the knot: effectively comparing two beams of depth *h* and *(h-k)* using Eq. (2) assuming that depth of the beam is reduced by the size of the knot. Figure 10.12 shows how the strength ratio changes with knot size according to this formula. Strength ratio formulae are given in D245 (ASTM, 2005c). The worst defect in an individual piece having several defects is used to derive the strength ratio.

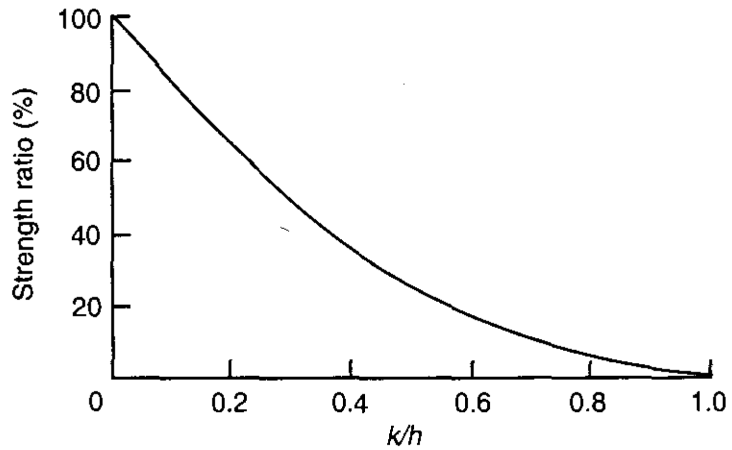


Figure 10.12. Relationship between bending strength ratio and the size of an edge knot expressed as fraction of the face width: *k* is knot size; *h*, the width of face containing the hot.

The range of strength ratios in a grade and the natural variation in clearwood strength values give rise to variation in strength between pieces in the grade. To account for this variation and to ensure safety in design, it is intended that the actual strength of at least 95% of the pieces in a grade exceed the design properties assigned to that grade (before a reduction for duration of load and safety). In visual grading, according to D245, this is handled by using a near-minimum clearwood strength as a base value and multiplying it by the minimum strength ratio permitted in the grade to obtain the grade strength property. The near-minimum value is the 5% exclusion limit (Figure 10.7a). D2555 (ASTM, 2005e) provides clearwood strength data and a method for estimating the 5% exclusion limit.

The assigned modulus of elasticity, *E,* is an estimate of the average modulus of clearwood when tested in static bending, adjusted for shear. The average modulus of elasticity for clearwood of North American species is recorded in D2555. The clearwood average is multiplied by empirically derived ‘quality factors’ to represent the reduction in modulus of elasticity that occurs by timber grade for pieces tested in an edgewise orientation. This procedure is outlined in D245 (ASTM, 2005e).

4.5.2. In-grade procedure

First, the natural population of lumber is visually segregated into sub-populations (grades). The properties of these grades have broad distributions that overlap one another, but the properties of each grade are more discrete and less imprecise than run of mill lumber.

The mechanical properties for specified grades are established from tests of full-size specimens of those grades, testing representative samples of the population following procedures outlined by a given country’s standard. In the United States, those standards are D2915 and D1990 (ASTM, 2005f,d). The specimens are tested using appropriate test procedures for the United States, D198 or D4761 (ASTM, 2005b,h). The 5% exclusion limit for the strength of the grade being tested is established directly and further modified for design use by consideration of service moisture content, duration of load, and safety. Adjustment of the data for strength ratios is not needed. In Europe, the development of characteristic properties is covered in EN 384 (ECS, 2004).

4.5.3. Visual stress grade stamps

Visually graded timber should be marked with a grade stamp (Figure 10.13). With few exceptions, the grade stamp should include five features: (i) trademark, indicating identity of agency with quality supervision; (ii) mill identification, giving product manufacturer’s name brand or mill number; (iii) grade designation number or abbreviation; (iv) species or species group identification; and (v) condition of seasoning, indicating moisture content at time of surfacing.

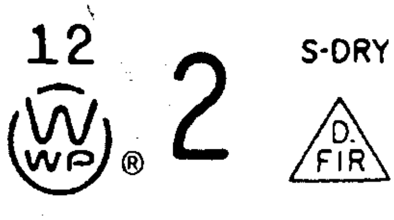


Figure 10.13. An example of a grade stamp for visually graded No. 2 Douglas fir, surfaced dry and produced by mill #12 of the Western Wood Products Association. Reproduced with permission.

5. MACHINE-GRADED STRUCTURAL TIMBER

Machine-graded timber is graded by machine using a non-destructive test followed by visual grading to screen out certain characteristics that the machine cannot or may not properly evaluate. In New Zealand and Australia, machine-graded structural timber is described as machine stress-graded (MSG). Terms common in the United States and Canada to describe machine-graded structural timber are machine-stress-rated (MSR), machine-evaluated lumber (MEL), and E-rated timber. No matter the terminology, machine-graded timber allows for better sorting of material, with reduced variability, for specific applications in engineered structures.

The attraction of machine grading lies in the fact that individual pieces are tested so that the deflection in bending (the usual method for allocating a piece to a grade) reflects both the natural defects (knots *etc.)* and the intrinsic features (density, MFA *etc.)* of that piece.

The basic components of machine-grading systems are sorting and prediction of strength through machine-measured non-destructive determination of properties coupled with visual over-ride; the assignment of design properties based on strength prediction; and quality control to ensure that assigned properties are being obtained.

The quality control procedures ensure:

- proper operation of the machine used to make non-destructive measurements,
- appropriateness of predictive parameter–bending strength relationship, and
- appropriateness of properties assigned for tension and compression.

5.1. Machine sorting criteria

Generally timber is machine-graded using the modulus of elasticity, *E,* as the sorting criterion for mechanical properties. The modulus of elasticity can be measured in a variety of ways. Usually, the apparent *E,* derived from three-point bending, is measured (Figure 10.14). Because timber is heterogeneous, the apparent E depends on span, orientation (edge or flatwise in bending), load speed of test (static or dynamic), and method of loading (tension, bending, concentrated, or uniform). As long as the grading machine is properly calibrated, any of the apparent *E* values can be used to assign the graded piece to a 'not to exceed' grade category. Most grading machines are designed to detect the lowest local stiffness in flatwise bending, E_{min}, that occurs in any 1.2-m (4-ft) length as well as the average flatwise bending, E_{av}, for the entire length of the piece. Here the timber is fed continuously through the stress grader. The machine flexes each piece as a plank between two supports applying a fixed deflection (Figure 10.14) and measuring a load, or measuring the deflection under a particular load. Thus the piece is tested as a plank (to obtain a significant measurable deflection) but is used as a joist. The visual over-ride considers edge knots that have a far greater influence on strength when in service as a joist than they have when the piece is tested in bending as a plank.

In the United States and Canada, MSR and MEL timber are subject to a visual override because the size of edge knots in combination with E is a better predictor of strength than is E alone. Maximum edge knots are limited to a specified proportion of the cross-section, depending on grade level. Other visual restrictions, which are primarily for appearance, are placed on checks, shake, skip (parts of the board 'skipped' by the planer), splits, wane, and warp.

Another method of sorting machine-graded timber is to use density to estimate knot size and frequency. X-ray sources in conjunction with a series of detectors gather density profiles in the timber, which are sensitive to knots. This information is then used to assign the graded piece to a 'not to exceed' grade category.

For over 40 years, it has been known that strength correlates with stiffness, and appropriate regression equations have been established for commercially important timbers. In Britain, for example, regression equations were derived by taking a representative sample of the timber, lightly loading each piece in bending as a plank to determine its stiffness, E_{plank}, and then turning the piece on edge and loading to

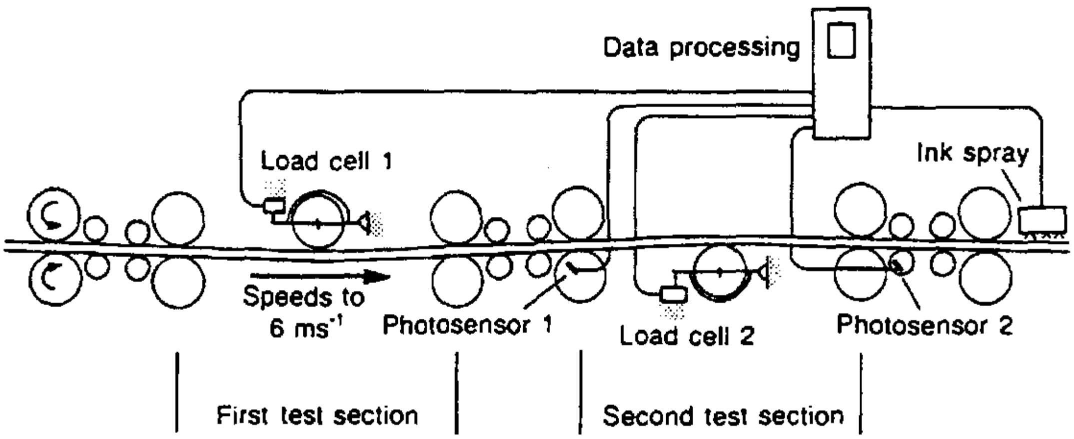


Figure 10.14. The continuous lumber tester (CLT) measures the load required to achieve a fixed deflection, continuously along the length of the piece. Measurements from both bending directions are combined to compensate for distortions in the timber (Metriguard Inc., Pullman, Washington). Deflections are set so that pieces experience a stress level roughly equivalent to the 10-year design bending strength for the grade. A few pieces break during their passage through the machine (normally not more than three pieces per shift), which helps to rid the machine-grades of 'rogues' that have relatively high stiffness but low strength.

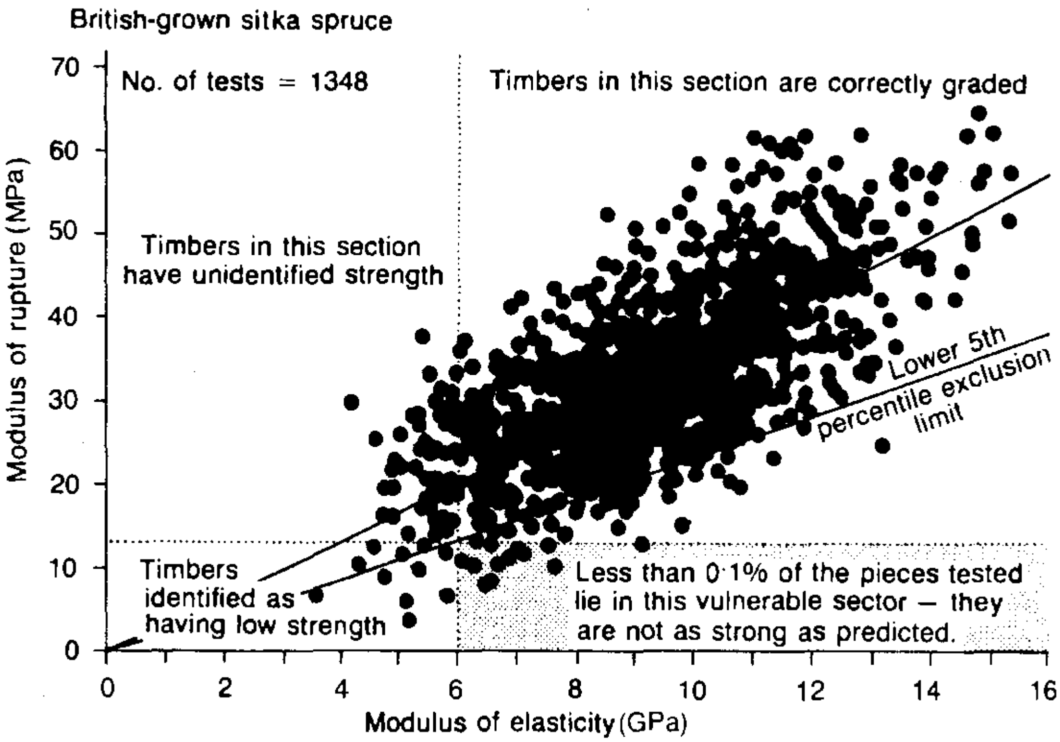


Figure 10.15. Relationship between MORjoist, and E_{plank} for British-grown Sitka spruce, *Picea sitchensis.* MOR = 0.002065 $(MOE)^{1.0573}$ with correlation coefficient of 0.702.

determine the bending strength, MOR_{joist}. The MOR_{joist} is then plotted against E_{plank} and the regression calculated and superimposed over the data points (Figure 10.15).

The scatter about the regression line is attributed both to the inherent variability of the timber due to its density and MFA and to the presence of defects. The regression coefficient (r), which describes how tightly the data cluster about the regression line, is generally found to fall between 0.5 and 0.85. The square of the regression coefficient, known as the coefficient of determination, indicates the percentage of variability of one variable, MOR_{joist}, that is accounted for by the other variable, E_{plank}. Thus, a correlation coefficient of 0.707 means that 50% of the variability in bending strength can be accounted for by E_{plank}.

Like the designations for visually graded material, a number of different grade designations are used in various countries. A partial list of grade names for machine-graded timber available from different countries is shown in Table 10.8.

Machine stress grading is more objective and efficient than visual stress grading. A typical regression of MOR_{joist} on E_{plank} has a regression Coefficient of 0.6 to 0.7, which compares favourably with a regression coefficient of around 0.3 to 0.4 for MOR_{joist} based on visual grading, using knot area ratio. Even so, the correlation between stiffness and strength is still not that good as 60-70% of the material in a grade can sustain a stress twice that allocated to timber of that grade. In essence grading is focussed on the weakest pieces in the grade - how weak the poorest pieces might be - and says nothing about the strength of better pieces in the grade.

Table10.8. Examples of machine-graded timber designations from different countries

Country		Machine-graded timber designation							
UK		M10	M14	M18	M22	M26	M30	M35	M40
Canada	MSR }		1200f	1450f	1650f	1950f	2400f	2700f	2850f
& U.S.	MSR }		−1.2E	−1.3E	−1.5E	−1.7E,	−1.7E,	−2.2E,	−2.3E
	MEL }			M-10		M-19	M-23	M-24	
Australia & NZ		MGP6	MGPS	MGP10		MGP12		MGP15	
Europe			C14	CI8	C22	C26	C30	C35	C40

Fast-grown plantation species have been viewed with suspicion by sawmillers, merchants and specifiers. Machine stress grading provides the forest owner with an objective way of comparing the strength characteristics of their timber with traditionally acceptable timbers, e.g. it offers Chile a way of enhancing the status of its plantation-grown radiata pine in overseas markets. Machine stress grading is the current ultimate 'truth machine' - revealed timber properties can differ dramatically between populations, and these have a dramatic impact on profits.

The results shown in Figure 6.5 for radiata pine illustrate this point. Changes in silvicultural management, especially the age of clearfelling, can have a dramatic impact on timber quality. Figure 6.5 compares the strength–stiffness characteristics of timber coming from more mature plantations with those of material harvested at a younger age. The loss of the low MFA, high density outerwood is the major reason for the lack of high strength material in the younger population. Unimproved pine has an abundance of low quality wood, and the failure to meet certain grading thresholds devastates profits. Tree breeding offers a realistic opportunity to transform profitability if superior stock is selected.

Independent statutory agencies formalize these grading rules and oversee quality control procedures. Depending on the country, visually and mechanically graded timber may be branded or grade stamped. The stamp usually includes details such as grade agency, grade, species, mill identification, or company number.

An advantage of machine stress grading is that fewer grades are required. All species can be graded to a limited number of stress settings. There are more than 80 different design values for 2 by 4 lumber of visually graded softwood in the Unites States, compared with some 20 machine-grades. Benefits are reduced complexity for the designer and far fewer inventory items for the fabricator.

5.2. Procedures to derive design propertiesfor machine-graded structural timber

Because modulus of elasticity, *E,* is a less than perfect predictor of strength, lumber sorted solely by average *E* falls into one of four 'accept-reject' categories (Figure 10.16a):

• Category 1–Material that has been accepted correctly, i.e. pieces have sufficient strength and stiffness as defined

• Category 2–Material that has been accepted incorrectly, i.e. pieces do not have sufficient strength

• Category 3–Material that has been rejected correctly because it does not have sufficient strength; nor sufficient stiffness

• Category 4–Material that has been rejected correctly because it does not have sufficient stiffness

Only Category 2 presents a real problem. These pieces are accepted as having sufficient strength but in reality they do not.

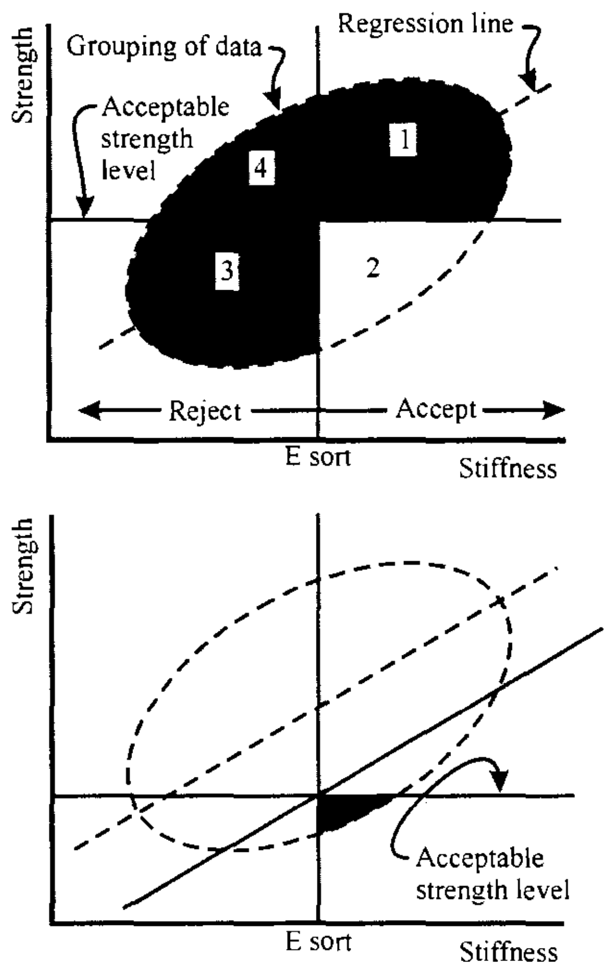


Figure 10.16. Schematic E sort. (a) A regression line used as the predictor for four categories: (1) accepted correctly; (2) accepted incorrectly; (3) rejected correctly; and (4) rejected correctly. (b) With the lower confidence line used as the predictor, then a relatively low proportion of material lies in the 'accepted incorrectly' category (lower right).

Engineers deal with this problem by minimizing the amount of material that falls into category 2. A lower confidence line, usually the lower 5th percentile exclusion limit, is used as the prediction model (Figure 10.16b). The number of pieces that fall into category 2 is now much lower compared with the mean regression line model. Furthermore, the probability of a piece (and thus the proportion of pieces) falling into category 2 is controlled by the confidence line selected.

Additional grading criteria (edge-knot limitations, for example) are also added to improve the efficiency of the sorting system.

5.3. Standards for machine-rated lumber

A number of standards outline the product requirements for machine-rated lumber. In Australia and New Zealand, the standard is AS/NZS 1748 (AS/NZS, 1997). In the United States, the standard is D6570 (ASTM, 2005k). In Europe, EN 519 (ECS, 1995) contains the requirements for machine-rated lumber.

In most MSR systems, the timber is sorted (graded) into E classes. In the United States and Canada, the number of grades has increased as specific market needs have developed for MSR timber. The grades are designated by the recommended extreme fibre stress in bending, F_b, and edgewise modulus of elasticity, E. Thus '2100F–1.8E' designates a MSR grade with a design stress F_b of 2,100 lb/in^2 (14 MPa) and E of 1.8 x 10^6 lb/in^2 (12.4 GPa).

In theory, any F–E combination can be marketed that can be supported by test data. In practice, a mill will produce only a few F–E classifications depending on the qualities of the timber being harvested, mill production capabilities, and product or market demand. Once the desired grades have been chosen, grade boundary machine settings are used to separate the timber into the F–E classifications. A qualification sample of timber is tested by a grading agency for strength and stiffness to verify that the proper machine settings are being used. After initial qualification, additional quality control tests are performed during production.

In Canada and the United States, the relationships between the 5th percentile 10-year bending stress and those in tension and compression are based on limited timber testing of the three properties but supported by years of successful experience in construction with visual stress grades of timber (ASTM, 2005j). For tension: it is assumed that the ratio of design tensile stress F_t to design bending stress F_b is 0.45 unless other test data are available; for compression the ratio is assumed to be

$$F_c = [0.338\ (2.1F_b) + 2060.7]/1.9 \tag{9}$$

Strength in shear parallel to the grain and in compression perpendicular to the grain is poorly related to modulus of elasticity. Therefore, in machine stress grading these properties are assumed to be grade-independent and are assigned the same values as those for visual timber grades, except where otherwise predicted from specific gravity (basic density) on a mill-by-mill basis.

5.4. *Quality control*

Quality control procedures are necessary to ensure that stresses assigned by a machine-grading system reflect the actual properties of the timber graded. These procedures must check for correct machine operation. Two basic quality control systems are used; machine-controlled or output-controlled. In a machine-controlled system, which was mainly developed in Europe, each individual machine must be strictly assessed and controlled by a regulatory agency. The machine settings that control the operation of these machines are set by and are under the control of the third-party inspection agency. This system allows for the handling of a large number of sizes and species. In output control, the machine settings are controlled by feedback from daily testing of specimens. Statistical procedures are used to monitor and adjust the settings of the machines doing the grading. QC procedures are highly technical and local regulatory agencies are deeply involved.

5.5. *Proof grading*

Proof grading is practiced in Australia for situations where production is small. The multiplicity of timbers available encourages such a development. The procedure involves a quick visual segregation into two or more grades followed by passing each grade through a continuous proof testing machine that sorts out the exceptionally weak pieces at the tail of the grade distribution (Leicester, 1988). The proof load is set for each grade such that 1% to 3% of the pieces in that grade break. The unbroken pieces are deemed capable of sustaining over time a grade load that is equal to the short-term proof load divided by 2.1. Alternatively, sorting for grade could be based on stiffness, which would be preferable for high-strength tropical hardwoods where stiffness tends to control design. In theory any grading method can be used provided the presumed strength class is verified by proof testing.

Proof grading is also used in glued-laminated production plants to determine the quality of fingerjoints.

5.6. *Non-destructive testing*

It would be better if some wood quality assessment could be performed on sawlogs before they go into the sawmill. Significant savings can be made if poor quality structural material can be eliminated before the expense of sawing and drying occurs. Research in the area of non-destructive testing has been a most active area of wood research in the last two decades. Non-destructive testing techniques such as acoustic wave propagation, x-rays, lasers, microwaves, and near-infrared spectroscopy have been developed to the point where tools for early assessment of wood quality are available (Pellerin and Ross, 2002; Knowles *et al.*, 2004; So *et al.*, 2004). These techniques can determine or estimate the stiffness, density, or local slope of grain in logs and lumber prior to further processing. As mill operations become increasingly automated, non-destructive testing will become an integral part of the grading process.

6. ADJUSTING STRUCTURAL TIMBER PROPERTIES FOR DESIGN USE

The assigned values for grades of particular species may need further adjustments to take account of factors such as the effects of drying after grading, member size, duration of load, creep, chemical treatments, temperature and, in allowable stress design, an additional factor of safety. The principles underlying some of these adjustment factors are outlined briefly. Adjustment factors are primarily of interest to engineers. Specific adjustments are given in national standards and codes such as ASTM (2005c,d) designations D245 and D1990.

The strength of small clearwood specimens is noticeably improved on drying below fibre saturation point. For example, in D2555 (ASTM, 2005e) values for bending strength of Douglas fir at 12% MC are increased by 72%, stiffness by 22% and shear strength by 50%. However, when drying lumber its properties do not improve nearly as dramatically: presumable uneven, differential shrinkage around knots, for example, induces checking and distortion that weakens the drying wood. Thus for lumber, less than 102 mm ($\leq$4 in.) only a small adjustment is permitted, whereas for thick lumber, greater than 102 mm ($\geq$4 in.), green property values also apply to the dry condition - no improvement on drying is recognized. Green and Evans (1989, 2003b) and Kretschmann and Green (1996) have studied these effects.

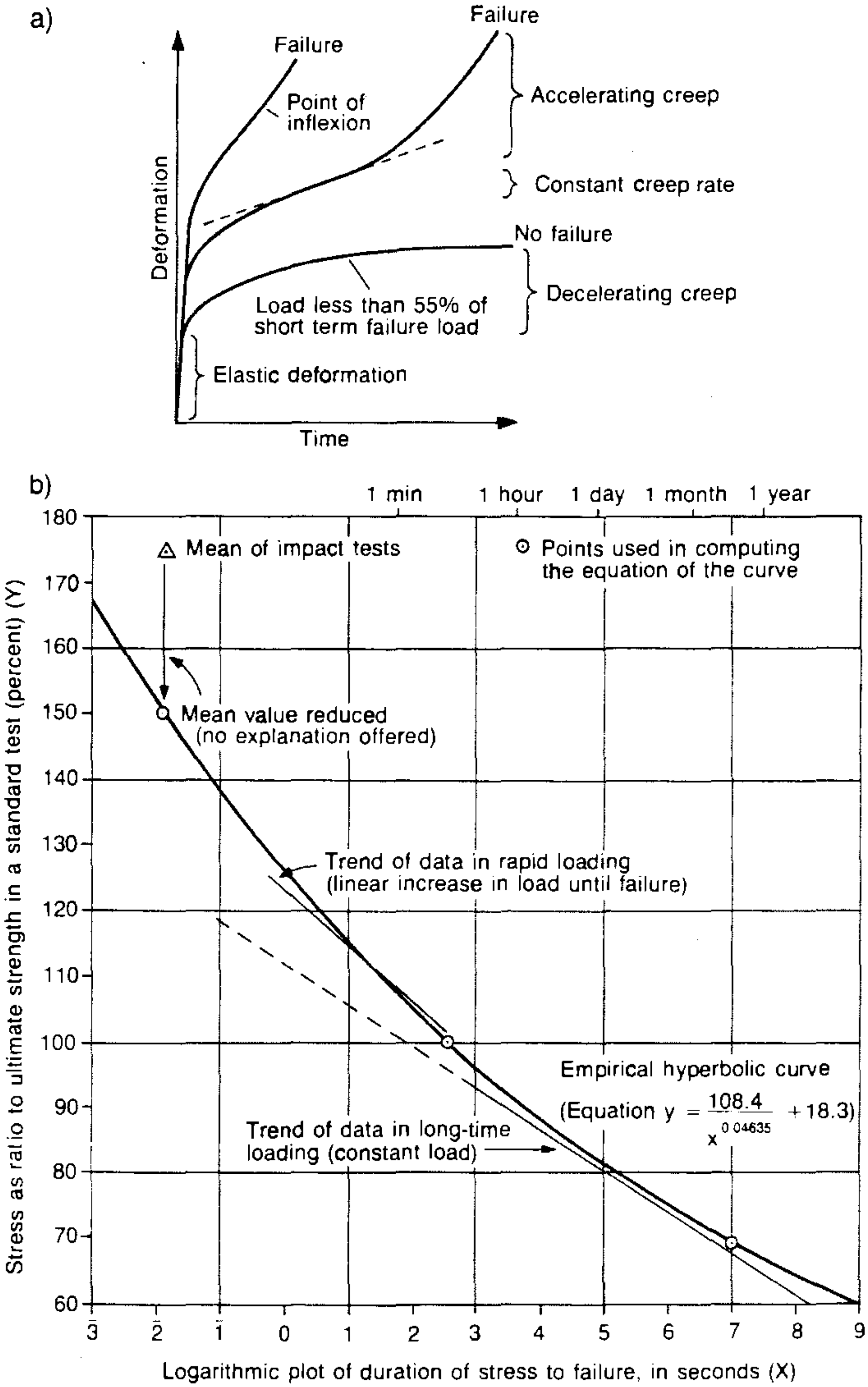
An interesting feature of in-grade timber is that tensile strength is not changed significantly on drying, whereas compressive strength is (Figures 10.3 and 10.10).

In general, a size effect causes small members to have greater unit strength than that of large members. Brittle fracture theory (Bohannan, 1966; Madsen and Buchanan, 1986; Green and Evans, 2003a,b) interprets this in terms of the weakest link principle, which assumes that the member is as weak as its weakest part. It follows that the probability of finding a large strength-reducing defect within the member is greater the greater the volume of the member. As a result 100 x 50 mm members of a given grade are in general stronger than 200 x 50 mm members, which in turn are stronger than 300 x 50 mm members.

Strength properties are time dependent. The load that timber can sustain without failure decreases with time. If the short-term ultimate load in the 5-minute static bending test is taken as the reference point, then wood will fail, on average, at about 66% of that load after 1 year, at 62% after 10 years and at 56% after about 27 to 200 years depending on the curve used to fit the data: there is a dearth of long term experimental evidence (>10 yr).

Creep behaviour is particularly interesting. Under low stresses and for short loading periods deformation may be considered to be elastic. However, where a beam is held under constant load, over time, the deflection increases gradually although at a rate that diminishes (Figure 10.17a). When the load is removed there is →

Figure 10.17. Time-dependent creep of timber. (a) The creep decelerates where the stress is less than 50% of the short-term failure stress but there is an inflection and accelerating creep where the stress is about 90% of short-term failure stress. (b) Estimated strength ratios for small clearwood specimens expressed as a ratio of the short-term strength, in the 5-minute bending test (Wood, 1951).


a)
Failure
Failure
Point of inflexion
Accelerating creep
Constant creep rate
No failure
Deformation
Decelerating creep
Load less than 55% of short term failure load
Elastic deformation
Time
b)
1 min
1 hour
1 day
1 month
1 year
Mean of impact tests
Points used in computing the equation of the curve
Mean value reduced (no explanation offered)
Trend of data in rapid loading (linear increase in load until failure)
Empirical hyperbolic curve
(Equation y = 108.4 / x^0.04635 + 18.3)
Trend of data in long-time loading (constant load)
Stress as ratio to ultimate strength in a standard test (percent) (Y)
180
170
160
150
140
130
120
110
100
90
80
70
60
3̄
2̄
1̄
0
1
2
3
4
5
6
7
8
9
Logarithmic plot of duration of stress to failure, in seconds (X)

an immediate elastic recovery, a smaller delayed elastic recovery and an irrecoverable component. This time-dependent phenomenon is known as creep. Creep under a long-term constant load results in a long-term deflection that is roughly twice the initially observed elastic deflection. With higher stress levels, above about 55% of the short-term ultimate stress, the creep rate declines gradually before passing through a point of inflection and accelerating again (Figure 10.17a).

Evidence of creep is seen in the sag between supports along an old roofline. Musicians and archers only string their instruments tightly before use and release the tension immediately afterwards to prevent creep. Where green timber is used as the lintel, of a double garage door for example, it is advisable to provide some means of support, e.g. a strut, until the beam has partially dried: without initial support the deflection can easily increase to more than three times the initial short-term deflection. Even when dried, fluctuations in moisture content greatly accelerate creep: the long-term deflection can be as high as six times the short-term deflection. At the molecular level creep is the result of a rearrangement of molecules and bonds relative to one another. Such rearrangements occur more readily in the presence of water, so it is not unexpected that creep is much greater in green timber.

Certain treating processes have been shown to affect the final strength of wood (Winandy, 1995a,b,c). Incised and treated lumber has been shown to have a 5-10% reduction in E and a 15% reduction in strength. Reductions in energy-related properties are about 1.5 to 2 times those reported for static strength properties. There is no difference in long-term duration of load behaviour between treated and untreated material; however, current design standards in the U.S. prohibit increases in design stresses for short-term duration of load when considering impact-type loading for material treated with waterborne preservative.

Finally, as wood is cooled below normal temperatures, its properties increase. When heated, its properties decrease. The magnitude of the change depends upon moisture content. At temperatures up to 65°C (150°F) in the United States, the effect of temperature is assumed by design codes to be reversible. Prolonged exposure to elevated heat can lead to a significant permanent loss in strength (Green and Evans. 2003a, USDA, 1999).

In many design circumstances there are several loads on the structure, some acting simultaneously and each with a different duration. Intermittent loading causes cumulative effects on strength and is treated as a continuous load of equivalent duration. This 'cumulative' load may be more significant that a less severe constant load - and should be calculated. The most severe condition governs the design. Either the design stress or the total design load (but not both) can be adjusted.

7. GLUED STRUCTURAL MEMBERS

There are many types of glued structural members, with more products actively being developed. These use woody material that is reassembled with adhesives to make a wide range of structural products. The grading of glued structural members is either handled by a proprietary process internally by the various manufacturers or. with glulam, it is handled more like dimension lumber with third-party regulations.

Glued structural members are manufactured in a variety of configurations:

- Structural composite lumber (SCL) products consist of small pieces of wood glued together into sizes common for solid-sawn timber (Figure 10.18).
- Glued-laminated timber (glulam) is an engineered stress-rated product that consists of two or more layers of timber in which the grain of all layers is oriented parallel to the length of the timber.
- Glued structural members incorporate timber that is glued to panel products, to form box beams and I-beams, and structural sandwich construction.

7.1. Structural composite lumber (SCL)

Structural composite lumber was developed in response to increasing demand for high quality timber at a time when it was becoming difficult to obtain this from the forest resource. Structural composite lumber products are made from smaller pieces of wood glued together into sizes common for solid-sawn timber.

An example of SCL product is laminated veneer lumber (LVL), which is manufactured by laminating specially graded veneer with all plies parallel to the length. Another type of SCL product consists of strands of wood or strips of veneer glued together under high pressure and temperature. Depending upon the component material, this product is called laminated strand lumber (LSL), parallel strand lumber (PSL), or oriented strand lumber (OSL) (Figure 10.18). These types of structural composite lumber products can be manufactured from raw materials, such as aspen or any other under-utilized species. Different product widths can be ripped from SCL for various uses.

Figure 10.18. Three examples of structural composite lumber (top to bottom): laminated veneer lumber (LVL), parallel strand lumber (PSL), and oriented strand lumber (OSL).

Structural composite lumber is a growing segment of the engineered wood products industry. It is replacing timber in various applications and in the manufacture of other engineered wood products, such as prefabricated I-joists, that take advantage of engineering design values that are superior to those commonly assigned to sawn timber.

7.1.1. Laminated veneer lumber (LVL)

In early operations LVL was made in multidaylight presses using 3.2 to 2.5 mm (1/8 to 1/10 in.) veneer, which were hot pressed with phenol-formaldehyde adhesive into lengths from 2.4 to 18.3 m (8 to 60 ft) or more.

Commonly, LVL is produced in 0.6 to 1.2 m (2-4 ft) widths in a thickness of 38 mm (1.5 in.). New plants with continuous presses form a potentially endless sheet that is cut to the desired length. Various widths of product can be manufactured or recut in the retail facility.

Veneers are carefully selected to achieve the desired engineered properties. The visual plywood grading criteria of PS 1-95 (NIST, 1995) are inadequate of themselves and additional ultrasonic selection and sorting of veneer are needed to ensure that the finished product has the desired engineered properties. End joints between individual veneers may be staggered along the product to minimize their effect on strength. The end joints may be butt joints, or the veneer ends may overlap for some distance to provide load transfer. Some producers provide structural end-joints in the veneers using either scarf or fingerjoints. Laminated veneer lumber may also be made in 2.4-m (8-ft) lengths, having no end joints in the veneer; longer pieces are then formed by end jointing those pieces to create the desired length.

7.1.2. Parallel strand lumber (PSL)

Parallel strand lumber (PSL) is defined as a composite of wood strand elements with the wood elements primarily oriented along the length of the member: the average length of the strands must be a minimum of 150 times that of the least dimension.

Parallel strand lumber is manufactured from veneer about 3 mm (1/8 in.) thick, that is clipped into strands about 19 mm (3/4 in.) wide and 0.6 m (24 in.) long. The product was designed to use waste material from the roundup lathe as well as other less than full-width veneer arising from plywood manufacture (Chapter 11). Species commonly used for PSL include Douglas fir, southern pines, western hemlock and yellow poplar, but there is no restriction on the use of other species.

Strands are coated with a waterproof structural adhesive, e.g. phenol-resorcinol formaldehyde, and laid-up using special equipment to ensure proper orientation and distribution. The microwave continuous press both densifies the material and cures the adhesive. LVL is commonly produced in 0.28 by 0.48 m (11 by 19 in.) section - much thicker than that of LVL. Final product can be sawn into smaller dimension. if desired, while the length is limited only by freight and handling restrictions.

7.1.3. Laminated strand lumber and oriented strand lumber

Laminated strand lumber (LSL) and oriented strand lumber (OSL) products are an extension of the technology used to produce oriented strandboard (OSB) structural panels (Chapter 12). This product needs a greater degree of alignment of the strands than does OSB as well as higher pressure, which results in increased densification. Here the manufacturers control the grading process to produce products of certain load or span capacity. One type of LSL uses strands that are about 0.3 m (12 in.) long, which is somewhat longer than the strands commonly used for OSB. Waterproof adhesives are used in the manufacture of LSL. One type of product uses an isocyanate type of adhesive that is sprayed on the strands and cured by steam injection.

7.1.4. Advantages and uses

In contrast to sawn timber, strength-reducing characteristics of structural composite lumber are well dispersed within the veneer or strands and have much less effect on strength properties. Compared to solid the wood, these products have far smaller variations in property values, i.e. far smaller coefficients of variation (Figure 10.7 and Table 10.2). Thus high design values are assigned to the strength properties of LVL and PSL. Somewhat lower design values are assigned to LSL and OSL but they have the advantage of being produced from a cheaper raw material that need not be in a log size large enough to peel into veneer. All SCL products are made with structural adhesives and are dependent on a minimum level of bond strength. The final moisture content of SCL products is slightly lower than that of lumber for most service conditions and little change in moisture content will occur in many protected service conditions. When used indoors, the product is less likely to warp or shrink in service. However, the porous nature of both LVL and PSL means that these products need protection otherwise they can quickly absorb water.

All SCL products can substitute for sawn timber products in many applications. LVL is used extensively for scaffold planks and in the flanges of prefabricated I-joists, which takes advantage of its relatively high design properties. Both LVL and PSL beams are used as headers and major load-carrying elements in construction. LSL and OSL products are used for band/header joists in floor construction and as substitutes for studs and rafters in wall and roof construction. SCL products are used in non-structural applications, e.g. the manufacture of windows and doors.

7.1.5. Standards and specifications

While grading procedures by manufactures are proprietary, standards serve as guidelines for the minimum quality control of products produced. An example of such a standard is D5456 (ASTM, 2005j), which provides procedures to develop design properties for structural composite lumber products as well as requirements for quality assurance during production. Each manufacturer is responsible for gathering the required information on properties and ensuring that the minimum levels of quality are maintained during production. An independent inspection agency is required to monitor the quality assurance program. Unlike timber, no standard grades or design stresses have been established. The designer must consult the manufacturer regarding unique design properties and assembly procedures.

7.2. Prefabricated wood I-joisis

Improved adhesives and manufacturing techniques have allowed prefabricated I-joists to replace larger timber sizes in floor and roof applications for both residential and commercial buildings (Figure 10.19).

Significant savings in materials are possible with prefabricated I-joists that use either plywood or OSB for the web material and small dimension timber or structural composite lumber for the flanges. High quality timber for the flanges is difficult to obtain from visual grading methods and, instead, several manufacturers use machine-graded timber or structural composite lumber. The details of fastening the flanges to the webs vary, but all flanges must be glued with a waterproof adhesive.

The ASTM standard D5055 (ASTM, 2005i) sets out procedures for establishing. monitoring, and re-evaluating structural capacities of prefabricated I-joists. However, each manufacturer is responsible for ensuring that the minimum levels of quality are maintained during production, while an independent inspection agency is required to monitor the quality assurance program.

These prefabricated I-joists are popular with builders because of their lightweight, dimensional stability, and ease of construction. Their accurate and consistent dimensions, as well as uniform depth, allow the rapid creation of a level floor. Utility lines pass easily through openings in the webs.

The prefabricated wood I-joists industry was one of the fastest growing segments of the wood products industry during the 1980s and 1990s. Today some 15 companies prefabricate I-joists in the United States and Canada. Often product is distributed through building material suppliers. Each manufacturer has its own catalogues with span tables, construction code and design information.

Recently, the APA–EWA (2004a) has issued a performance standard for prefabricated I-joists covering products used in residential floor construction.

7.3. Glued-laminated timber (glulam)

Structural glued-laminated timber (glulam) is a long-established stress-rated product. Typically, individual laminations are made from 38mm (nominal 2 in.) thick timber where used for straight or slightly cambered members, and thinner 19 mm (nominal 1 in.) thick timber where used for curved members. Individual laminations may be joined end-to-end to produce pieces that are much longer than the laminating stock itself. Pieces may also be placed or glued edge-to-edge to make a member that is wider than the input stock. Straight members up to 41 m (140 ft) long and more than 2.1 m (7 ft) deep have been manufactured: the only limitations are handling and transport. Curved members have been used in domed structures spanning more than 152 m (500 ft).

Timber of different grades can be arranged within a laminated cross-section depending on the anticipated loading, whether loaded parallel or perpendicular to the wide faces of the laminations. For loads applied perpendicular to the wide faces of the laminations, referred to as 'horizontally laminated', cross-sections are typically designed with higher-grade laminations in the outer top and bottom layers to carry the highest stresses and lower-gade laminations in the core layers where stresses are minimal. For loads applied parallel to the wide faces of the laminations. 'vertically laminated', all laminations are subjected to the same load, whether in compression, tension, or bending so placement of grades is less critical. Frequently glulam cross-sections have the same timber grade throughout the cross-section.

7.3.1. Manufacture of glulam

In the United States glulam is manufactured according to the national standard. ANSI/AITC A190.1 (ANSI/AITC, 2002). This standard contains requirements for production, testing, and certification. Plants meeting these requirements can place their product quality mark on the glulam, which contains key information regarding the type, species, and design values.

There are four steps in the manufacturing process: (i) drying and grading the timber, (ii) end jointing, (iii) face bonding, and (iv) finishing and fabrication.

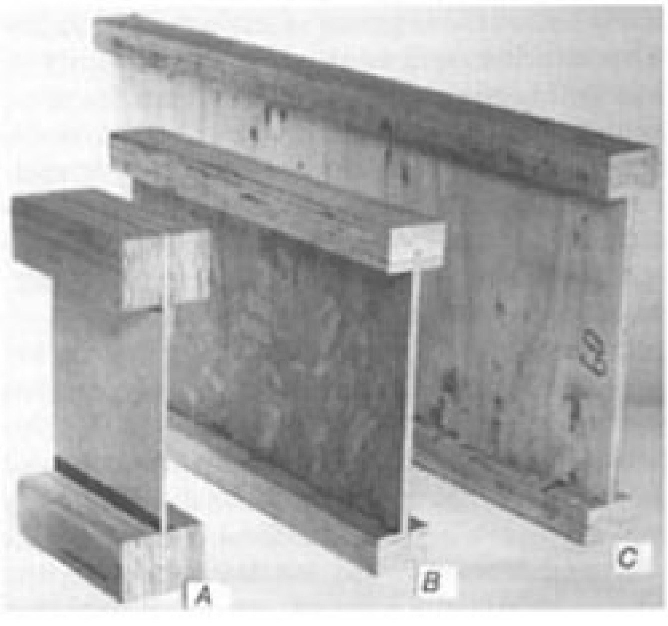


Figure 10.10. Prefabricated I-joists with laminated veneer lumber flanges and structural panel webs. (a) With an experimental hardboard web. (b) With commercially produced oriented strandboard web. (c) With a plywood web.

Glulam is generally manufactured at moisture contents below 16%, with a maximum range amongst laminations of 5% MC. This minimizes dimensional changes following manufacture. End sealers, surface sealers, primer coats, and wrapping may be applied during manufacture to minimize changes in moisture content. Required protection will depend upon the final use and finish.

Grading standards of the regional timber grading associations describe those characteristics that are permitted in the various grades of timber, while manufacturing standards such as AITC 117 (AITC, 2004) describe the combination of timber grades necessary for specific design values. Both visual graded and *E*-rated lumber is permitted. For example for visually graded lumber there are three lamination grades, L_1, L_2 and L_3, which respectively limit knot size to 1/4, 1/3 and 1/2 of the section width. For E-rated timber various E-levels are permitted with a visual override, e.g. limiting the size of edge knots when grading as a plank. Where high design stresses are sought for some laminations, such as may be required for the outer 5% on the tension side of the beam, the grading criteria for these 'tension laminations' are given in AITC 117 (AITC, 2004).

7.3.2. End jointing

End jointing is necessary to manufacture long-length glulam. The most common end joint, a structural fingerjoint, is about 28 mm (1.11 in.) long (Figure 10.20). A key advantage of this process is that fingerjointing blanks can be cut from knotty stock provided the blanks have clearwood with straight grain in the immediate vicinity of the finger: in this way certain lower grades of lumber can be upgraded to lamination stock. Continuous production equipment with radio-frequency curing under end-pressure is standard for fingerjointing. Careful control of the process - determining timber quality, cutting the fingers, applying the adhesive, mating, applying end-pressure, and curing - is needed to produce consistent high strength joints.

Fingerjointed pieces can achieve 75% of the strength of clearwood. These joints are more than adequate for most applications as most timber grades used in the manufacture of glulam permit natural characteristics that result in reductions in strength of at least 25% compared to that of clearwood.

A continuing challenge in glulam production is to eliminate the occurrence of an occasional low-strength end-joint. Procedures regarding fingerjointing and glulam manufacture are covered in ANSI/AITC A190.1 (ANSI/AITC, 2002).

It should be noted as an aside, that there is a significant market for non-structural fingerjoints, only 3-8 mm long. Here the ideal joint has fingers that match perfectly with no visible gaps and so can be painted without visible blemishes. Their strength may be only 30-40% of that of clearwood, but they are not for structural use. Under certain circumstances the lowest, knottiest grades of timber can be cross-cut profitably to give some short-length blanks, as little as 150-200 mm long, and with a recovery of only 30-50%.

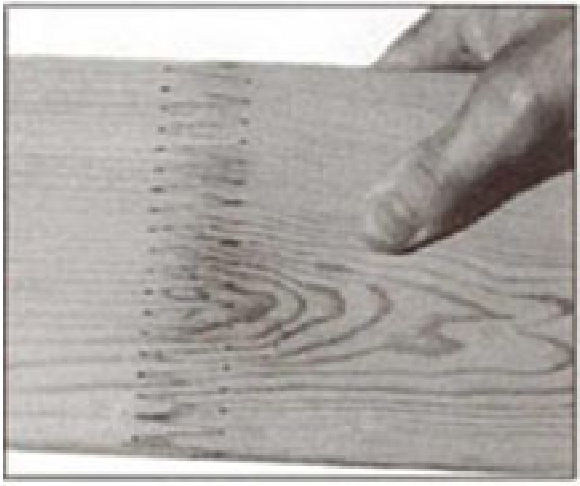


Figure 10.20. Typical fingerjoint used in glulam manufacture. The pin-holes at the tips of the fingers are typical of a structural fingerjoint.

7.3.3. Assembly, finishing and fabrication

Best practice is to dress the two wide faces of the laminations just prior to laying-up on the flat bed. This means that the beam will be rectangular and when glued and assembled the pressure will be applied evenly. Phenol resorcinol is most commonly used as adhesive. After the recommended open assembly time, the side clamping pressure is applied either hydraulically or mechanically and the adhesive is left to cure for some 6-24 hours, depending on the resin formulation and room temperature (Figure 10.21). Quality control includes shear tests on end mm samples. refer ANSI/ AITC A190.1 (ANSI/AITC, 2002). Test values should equal about 90% of the clearwood shear strength for the species. A very modest increase in glue bond shear strength (10%) occurs in the following few days.

The wide faces are planed to remove the adhesive that has squeezed out between adjacent laminations and to smooth out any small irregularities between the edges of adjacent laminations. Some additional finishing may be required following the industry standard, refer AITC 110 (AITC, 2001). Industrial appearance is applicable where appearance is not a primary concern, as in industrial plants and warehouses. Architectural appearance applies in most cases where appearance is important. Premium appearance is the highest classification.

Fabrication involves final cutting: holes are drilled, connectors added, and a finish or sealer is applied, if specified. Different degrees of prefabrication are undertaken at this point. Trusses may be partially or fully assembled. Moment splices can be fully fabricated, then disconnected for transportation and erection. Special precautions are necessary during handling, storage, and erection to prevent structural damage to glulam members, refer AITC 111 (AITC, 2005) or EWS R540 (APA–EWA,2002).

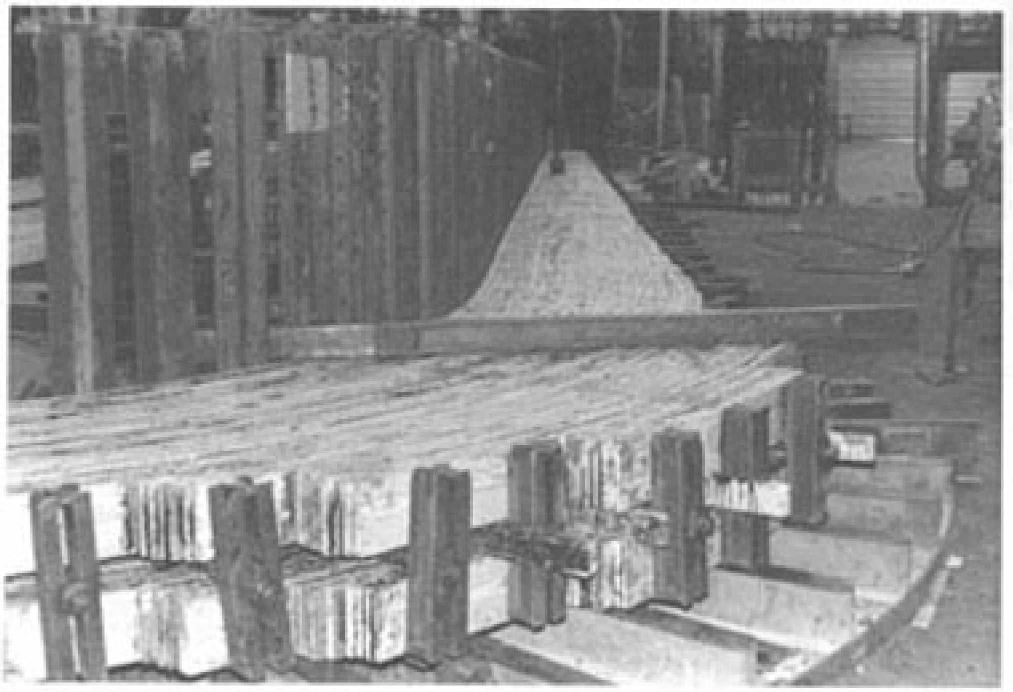


Figure 10.21. After being assembled in the clamping bed, the laminations of this Tudor arch are forced together and into shape with a manual air-driven screw clamp.

Various countries have standard practices established to determine allowable properties for glued-laminated timber. In the United States, ASTM D3737 (ASTM, 2005g) guides the allowable stress development.

7.3.5. Advantages of glulam

Compared to sawn timber as well as other structural materials. glulam has several benefits to offer:

l Size. By laminating small-dimension timber in glulam, the production of very large structural elements is possible. Straight members up to 30 m (100 ft) long are common, with some spans up to 43 m (140 ft). Sections deeper than 2 m (7 ft) have been used. Thus, glulam produces large members from small trees.

•Architecture. By curving the timber during manufacture, a variety of architectural effects can be obtained from glulam that are impossible or difficult with other materials. The degree of curvature is determined by the thickness of the laminations. Beams with curvature are generally made with 19 mm (nominal 1 in.) timber, while 13 mm (1/2-in.) or thinner material may be required for very sharp curves.

• Large dry dimensions. Timber used in glulam must be seasoned or dried prior to use. so the effects of checking and other drying defects are minimized. Design on the basis of seasoned wood permits greater design values than can be assigned to unseasoned large-dimension lumber.

• Varying cross-sections. Structural elements can be designed with varying cross-sections along their length as determined by strength and stiffness requirements. For example, the central section of beams can be made deeper to account for increased structural requirements in regions carrying higher moments. Similarly, arches often have varying cross-sections as determined by design requirements. Such beams offer great aesthetics.

• Mixing grades. A major advantage of glulam is that a large quantity of lower grade timber can be used within the less highly stressed laminations of the beams, placing the highest grades in the highly stressed laminations near the top and bottom and a lower grade around the neutral axis. Species can also be mixed to match the structural requirements of the laminations.

• Environmental consciousness. It is a modern material that emphasizes sustainability, its low energy demand during manufacture and its carbon storage capacity; and eventually it can be recycled. While aesthetic and economic considerations are major factors influencing material selection, these environmental advantages increasingly influence material selection.

8. FIRE

In a fire, the main hazard to life comes from the room contents. Wood smoke itself is relatively innocuous. Death arises most often from the choking toxic smoke and asphyxiation arising from burning plastics and synthetic fabrics. Regulatory authorities seek to eliminate such hazardous materials and to restrict the speed with which a flame spreads along a surface. Structural design aims to isolate areas and to ensure that fire is not able to spread from room to room. Thus, doors and other openings should seal properly, allowing no gaps through which fire might penetrate. Good design is an integral part of fire safety. An intumescent coating can seal small gaps and retard the spread of flame. Such coating acts by foaming when heated and insulates the substrate.

The fire rating of buildings relates to the nature of the building - home, school, hospital, or chemical warehouse. The greater the hazard to human life, the greater the required fire rating for doors, floors, walls, and ceilings. The fire rating refers to the time that the element must resist the fire without letting the flames spread further. Fire ratings range from 20 min to 3 h.

Fire damage is not directly related to the combustibility of the building materials but rather to the details of construction. Wood structures contribute very little to the fuel load in a building because large dimension material is consumed slowly and small dimension material is generally protected from fire by non-combustible cladding such as gypsum plasterboard. In an intense fire, structural failure is more likely where steel trusses or beams are exposed to the heat. With timber, the member can only char at a totally predicable rate of about 40 mm/h (1.5 in./h), so by modifiying section dimensions of the timber a structure can be reliably designed to withstand a fire for as long as required. However, the metal connectors for timber require insulative coverings. This predictability of performance for large timber or glulam beams is a highly desirable characteristic in a major fire, allowing a fire crew to enter the building confident that sudden failure is unlikely. Further, because the centre of the section is well insulated from the heat it will not lose strength or shrink along the grain, whereas a steel beam will expand along its length on heating and can push the walls of a building outwards, resulting in collapse even though the heat is not intense enough for the beam to buckle.

9. TIMBER STRUCTURES

The discussion of this chapter has centred on the properties of individual pieces of timber. In many situations, the load in a structure is shared between a number of pieces, and the inability of a weak or less stiff member to carry its share of the load is offset by the carrying capacity of other members. Thus, some variation in mechanical properties can be tolerated. In only a few situations is load sharing not possible, e.g. in door lintels, trusses, and beams. It is in these situations that the benefits of machine stress grading and proof testing are greatest. Furthermore, in timber design the emphasis is on the efficiency and the effectiveness of structures rather than the individual parts. More profit and potential lie in the sale of prefabricated components and structures, and continued development in these areas is vital if timber is to remain competitive. Considerable attention is devoted to achieving efficient connections between individual pieces to build safe, stiff, and efficient structures. Timber connections determine the safety of structures in earthquakes, fires, hurricanes, and other natural disasters. The timber is only a part of the structure. Timber design and engineering are subjects in which few foresters have even a partial familiarity and little expertise. They are important subjects in maintaining a market place for timber and in keeping timber at the cutting edge of technological development.

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