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GD 3 Timber materials - Properties & associated design procedures with Eurocodes



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Cover photographs: *Clockwise from top left:* 1. Savill Gardens Visitor Centre, Windsor Great Park – Grid-shell roof using strength graded and finger jointed larch from Royal Estates, in conjunction with Kerto LVL and Finnish structural plywood; © CJM TRADA Technology. 2. Laajasalo Church, Helsinki – Orthogonal roof grillage using combination of girders with glulam chords + steel webs, crossed by glulam horizontals; © Wood Focus. 3. Lahti Symphony Hall, the assembly space - Circular-section columns, glulam roof trees, LVL mullion trusses (background, right); © CJM TRADA Technology. 4. Pohjola Stadium, Vantaa, Finland – Box-sectioned, cantilevered LVL frames; © Finnforest.

Rear photographs: *Left:* Doubly-curved, spiral lamella roof in sustainable European softwood glulam – Eden Project; The Core – Education & Exhibition Building, Cornwall; © CJM TRADA Technology. *Right:* Round-sectioned and curved ribs in glulam with kiln-dried solid softwood slats, moulded OSB dome – Swiss National Exhibition, Lausanne; © CJM TRADA Technology.

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GD 3 Timber materials - Properties & associated design procedures with Eurocodes

CONTENTS

Section	Title	Page
1	Principles of limit states design with Eurocodes	1
2	Design values for material properties – general principles	2
3	Load cases and time dependency	2
4	Basis for characteristic values	3
5	Design properties for glulam and LVL	7
6	Geometrical data	10
7	Stiffness parameters in analysis	13
8	Partial factor for materials properties in design	14
9	Load duration classifications and modifications	16
10	Effect of member size on strength	22
11	Structural wood-based panels	23
12	Structural adhesives	24
13	Metal fasteners and connectors	26
	References	27
	Bibliography	30

GD 3 Timber materials - Properties & associated design procedures with Eurocodes

1 Principles of limit states design with Eurocodes

1.1 The partial factor method

BS EN 1990 defines the principles and main requirements for the safety, serviceability and durability of all types of structure¹. It is based upon the limit state concept, used in conjunction with a particular partial factor method. Internationally, other non-identical partial factor codes exist. Eurocodes BS EN 1991 to 1999 inclusive conform to the Eurocode 0 basis. These developments have taken place within the framework of the European Committee for Standardization (CEN), and it is an important and progressive step for the BS EN 1995 set of codes for timber structures to adopt an identical basis of design to that for the other main materials.

1.2 Design situations

These are sets of physical conditions representing reality². They occur during a certain time interval, for which the designer should demonstrate that relevant limit states are not exceeded. Examples of design situations are:

- Transient design situations – those relating to temporary conditions eg during construction or repair
- Persistent design situations – those relevant during a period in the normal working life of the structure
- Accidental design situations – examples of accidental events that BS EN 1990 indicates are fire, explosion, impact and local failure.

Note the emphasis upon time intervals in all three of these examples. This is especially important for timber structures, since their performance is strongly influenced by the underlying load duration behaviour of the material.

1.3 Ultimate limit states

Limit states in general are those beyond which the structure no longer fulfils the relevant design criteria. Ultimate limit states are associated with collapse or other similar forms of structural failure³. Clearly, design procedures are aimed at ensuring that these limits are not reached or exceeded during the design working life of the structure.

1.4 Serviceability limit states

These correspond to conditions beyond which specified service conditions for the structure or structural member are no longer met⁴. Again, design procedures are aimed at ensuring that the limits are not exceeded, however designers are given permission and information to enable greater choice over where to pitch the actual limits than is the case with ultimate limit states. This is a novel feature of Eurocodes in comparison with many older national codes, including BS 5268.

¹ EC0/Foreword

² EC0/Cl.1.5.2.2

³ EC0/Cl.1.5.2.13

⁴ EC0/Cl.1.5.2.14

2 Design values for material properties – general principles

2.1 Characteristic values⁵

The use of characteristic values in identifying material properties is fundamental to the Eurocodes' design basis. Characteristic values generally correspond to a specified fractile of an assumed statistical distribution.

For timber codes, this is not a new concept (1); for example, BS CP 112, first introduced in 1952, and subsequently the BS 5268 set, introduced in 1984, gave values of strength and stiffness properties for grades of timber that were based on statistical lower exclusion values. These were derived from standardised test procedures and were deduced using well-established statistical procedures. Estimates of 1 % lower exclusion values were the basis of the grade stresses and the minimum moduli in CP 112, whereas 5 % lower exclusion values were adopted in the later code. At that stage, other factors used to develop the published grade values were adjusted accordingly, so that selected calibrated designs were not radically altered by the change. These steps were taken in preparation for the anticipated limit states design codes that have now emerged.

2.2 Design values

Through an important BS EN 1990 principle⁶, safe design values for material properties are obtained by dividing the characteristic value by a partial factor. The symbol adopted by BS EN 1995-1-1 for the partial factor for materials properties⁷ is γ_M . BS EN 1990 also provides for another type of partial factor for material, designated γ_m , and the use of the capital letter "M" as the subscript for timber is significant, since this code does not employ the alternative version implied by the lower case. The preferred definition and the associated symbol for timber indicate that the partial factor for material properties also accounts for model uncertainties and for dimensional variations. This continues the general approach of earlier timber codes, and is an important point when considering the straightforward procedure adopted by BS EN 1995 for geometrical data, as discussed in more detail below.

3 Load cases and time dependency

As indicated above, design situations take account of the temporal conditions experienced by the structure. Timber displays a significant loss of strength over a period of time (2). Also, it is prone to creep (3), which is formally acknowledged when designing in accordance with BS EN 1995-1-1. Broadly speaking, the first effect is of concern in ultimate limit states design (ULS) whilst the second affects mainly the serviceability limit states (SLS) verifications.

TRADA Technology Guidance Document GD2 (4) explains how the expressions for the design values of actions are developed, and it shows important types of design situation arranged according to categories of limit states and durations of action combination. Important preliminary steps in successful timber design entail understanding and correctly assessing the action combinations, so as to identify significant load durations and derive the appropriate timber-specific modification factors. This applies both to ultimate limit states design, and to serviceability design, but the critical action combinations for each of these two main considerations are not usually the same as one another.

⁵ EC0/Cl. 1.5.4.1

⁶ EC0/Cl. 1.5.4.2

⁷ EC5/Cl. 2.4.1

4 Basis for characteristic values

BS EN 1995-1-1 relies upon the generic Eurocode 0 definition for a *characteristic value*, without any modification⁸. A characteristic value of any material property is the value that has a prescribed probability of not being attained in a hypothetical unlimited test series. This value generally corresponds to a specified fractile of the assumed statistical distribution of the particular property.

For solid structural timber and glulam, procedures for the determination (*ie desk-based derivation*) of the characteristic values are provided in BS EN 384 (5). A complementary standard, BS EN 14358 (6) *Timber structures – Calculation of characteristic 5-percentile values and acceptance criteria for a sample* covers timber fasteners, connectors, and wood-based panels. Hence, although it has taken time, uniform methods for determining properties of all of the timber and wood-based material families, and associated items, are now established.

4.1 Conformity

For solid timber (softwood or hardwood), the essential harmonised standard⁹ for full compliance with BS EN 1995-1-1 is as follows:

- *Timber structures – Strength graded structural timber with rectangular cross-section – Part 1, general requirements* – BS EN 14081-1 (7).

The code adds by note¹⁰ that strength classes for timber are given in the following, which is the document actually containing all of the physical and mechanical properties necessary for day-to-day structural design:

- *Structural timber – Strength classes* - BS EN 338 (8).

Table 1 of this Guide gives a selection of the properties extracted from BS EN 338 for three commonly available strength classes. For a more comprehensive selection, reference should be made to the standard itself. Further discussion of the technical aspects of strength classes for solid timber follows in Sections 4.3 to 4.7 of this Guide.

A further standard (currently under preparation) is referenced by the code,¹¹ namely prEN 14544 (9). This will be for round cross-section solid timber for use in structures. This is a less commonly available material than rectangular section timber, so when contemplating its use, potential suppliers should be consulted.

4.2 Means and fifth percentiles of moduli of elasticity

Particular attention is given to the definitions of characteristic values with respect to the moduli of elasticity. As indicated in Table 1 below, there are two categories, since in addition to the expected lower 5-percentile property, the mean value is also regarded as a “characteristic” value. Although absolutely essential for appropriate timber design, this is rather unusual in terms of Eurocode 0. In general, the lower fifth percentile modulus is used for ultimate limit states verifications. For example, it is involved in checking the buckling of columns, where there is a calculation of relative slenderness values¹², and also in determining the critical bending stress associated with the lateral-torsional buckling of beam-columns¹³. For serviceability conditions, the mean modulus of elasticity is employed¹⁴, even for what BS 5268 terms “principal members”, hence this is a significant difference between the two codes.

⁸ EC5/C1. 1.5.2.1

⁹ EC5/C1. 3.2(1)P

¹⁰ EC5/NOTE to C1. 3.2(1)P

¹¹ EC5/C1. 3.2(1)P

¹² EC5/C1. 6.3.2(1)

¹³ EC5/C1. 6.3.3 (2)

¹⁴ EC5/C1. 2.2.3(2)

Table 1 Selected strength classes for solid softwood – characteristic values

Property		Units	Strength classes		
			C16	C18	C24
Bending strength	$f_{m,k}$	N/mm ²	16	18	24
Tension strength	$f_{t,0,k}$	„	10	11	14
Tension strength perp. to grain	$f_{t,90,k}$	„	0.5	0.5	0.5
Compression strength	$f_{c,0,k}$	„	17	18	21
Compression strength perp. to grain	$f_{c,90,k}$	„	2.2	2.2	2.5
Shear strength	$f_{v,k}$	„	1.8	2.0	2.5
Mean modulus of elasticity	$E_{0,mean}$	„	8000	9000	11000
Lower 5-percentile modulus of elasticity	$E_{0,05}$	„	5400	6000	7400
Mean modulus of elasticity perp. to grain	$E_{90,mean}$	„	270	300	370
Shear modulus	G_{mean}	„	500	560	690
Characteristic density ^a	ρ_k	kg/m ³	310	330	350
Mean density ^b	ρ_{mean}	„	370	390	420
^a Used for verifying mechanically fastened connections					
^b Used for calculating self-weight of members					

4.3 Strength properties of solid timber

The worldwide sources of supply of timber are based upon numerous botanical species (10). Furthermore, there are artificial “species groups” that are included in specifications to support the needs of commerce and sustainability. For all such combinations, simple but effective methods of strength grading are required, alongside provisions for advances in mechanical and automated non-destructive selection. Procedures are also necessary for physically determining properties by test, as well as for deriving characteristic values afterwards. The details of these steps are quite extensive, and a full explanation would also involve further topics such as differences between visual and mechanical strength grading; also for instance defect-free specimen testing versus structural-sized testing. The References and Bibliography at the end of this Guide will assist readers wishing to investigate such matters in greater depth.

In essence, the standards treat timber as a naturally variable material, which it is necessary to strength grade according to formal quality-assured procedures. Hence test samples of solid structural timber (softwood or hardwood) are selected from a population that is to be graded visually or by machine to the requirements given in BS EN 14081-1. For the physical tests relating to both visual and machine strength grading, the population that is to be sampled is expected to be capable of being identified at all stages of production and supply, including the time when it reaches the factory or construction site.

The actual basis for visual strength grading is stated in BS EN 14081-1, since it is a requirement that it must be carried out, but the precise procedures and defect measurement methods are still provided by national standards. For instance, the UK and many of its suppliers in the Nordic Region operate visual strength grading for softwoods against BS 4978 (11). BS 14081 Parts 2 – 4 (12), (13), (14), cover machine strength grading in great detail, and these aspects now apply uniformly throughout the CEN zone without subsidiary reference to any national alternatives.

4.4 Derivation procedures

Once structural-sized testing has taken place physically, in accordance with a standard method (see 4.5 below), sample lower 5-percentiles for strength properties are determined by ranking methods that are detailed in BS EN 384. For densities however, a normal population distribution is simply assumed, and this is used to derive mean and corresponding lower 5-percentile characteristic values - the latter being important for the design of timber connections. BS EN 384 addresses all of the essential aspects of the population definition and property derivations, including the following:

- Sampling procedures - taking account of the methods chosen for strength grading – whether to visual procedures or by following machine strength grading processes, in either instance complying with BS EN 14081.
- Reference conditions for the physical testing ie moisture content, standard cross-sectional sizes to which others are adjusted, and span: depth ratios.
- The analysis of the data – methods are given to permit characteristic values to be determined even when a less than ideal amount of data can be provided. In this case, reduction factors are included to reflect the lower degree of confidence that ensues.

4.5 Physical test methods

The physical and mechanical properties of both structural solid timber (rectangular or round cross-section) and glued laminated timber (glulam) are now established through test procedures that are elaborated in BS EN 408 (15). Prior to this, most of the well-established solid timbers of major importance in the UK were tested against BS 373 (16). Booth and Reece (1), already cited, described the subsequent derivation procedure for basic and grade stresses, used with older national codes such as BS CP112 and BS 5268. As recognised by BS EN 384 *Clause 7*, limited reliance on small clear data to evaluate minor species is still necessary, especially for hardwoods, which belong to a very wide botanical and geographic group.

BS EN 408 specifies test methods for the following properties:-

1. Modulus of elasticity in bending.
2. Shear modulus.
3. Bending strength.
4. Modulus of elasticity in tension parallel to the grain.
5. Tension strength parallel to the grain.
6. Modulus of elasticity in compression parallel to the grain.
7. Compression strength parallel to the grain.
8. Modulus of elasticity in tension perpendicular to the grain.
9. Tension strength perpendicular to the grain.
10. Modulus of elasticity in compression perpendicular to the grain.
11. Compression strength perpendicular to the grain.

In any determination of the mechanical or physical properties of a material, the precise values obtained depend upon the exact test methods used. Structural timber, as opposed to wood in a small clear specimen, is inhomogeneous. Dependent upon the species, grade, and other factors, it contains a varying number of features that significantly affect its strength and stiffness. Examples of these gross features include knots, sloping grain and fissures. At the same time, even “small clear” or perfect specimens display natural variability on a finer scale. These variations reflect the botany of the tree and the growing conditions. Using structural-sized specimens, the BS EN 408 procedures evaluate both types of variability together, by means of controlled sampling and testing methods.

Furthermore, certain types of test yield results that are particularly strongly configuration-dependent. Examples are the two test procedures included in BS EN 408 for modulus of elasticity in bending – “local modulus of elasticity in bending” and “global modulus of elasticity in bending.” The former is a procedure yielding data required in the calibrating procedures for non-destructive strength grading machines, whereas the latter leads to results more closely reflected in the data actually provided to code-users through standards such as BS EN 338 for strength classes.

Broadly, the test types listed in 1 to 8 above have been conducted for decades, albeit in various configurations. The great majority of significant structural timbers and all of the common glulam species have been covered. On the other hand, experience is still being gained in developing design properties that might previously have been regarded as “minor” – including types 8 to 11. For instance, debate is still taking place over the significance and interpretation of the perpendicular to grain properties of structural-sized timbers (17). Hence it is possible that future editions of Eurocode 5 may step back from what some feel has become an over-complex presentation of such properties for day-to-day design purposes.

4.6 Strength classifications for solid timber

The strength class system associated with BS EN 1995-1-1¹⁵ combines specified grades and species having similar strength and stiffness properties to one another. This makes the correct combinations interchangeable with respect to engineering calculations. Already introduced, the principal standard for solid timber is BS EN 338. Timber code users will have become familiar with this standard, even if not yet fully versed in BS EN 1995-1-1, since the classification system has been in use for some time with BS 5268, albeit with properties expressed in “working stress” safety format. Now, with Eurocode 5, the indicative numerical labels to the Strength classes, eg C24, C27 etc. do actually express the characteristic strength in bending of the class concerned, and this is used directly in design.

A simple introduction to the contents of this standard is to be found in a Wood Information Sheet (18), including extracts from the main classification tables, giving properties. This Information Sheet also provides examples of the combinations of species and visual grades of softwood placed into strength classes. Unlike the case with machine strength grading, where this is a procedure that occurs automatically through the calibrations and settings of the equipment, for visual grading, it has to be dealt with by documented species assignments. Consequently, numerous visual strength grades, species and geographical sources of timber are listed in BS EN 1912 (19), where they are actually assigned to the requisite BS EN 338 classes.

Specifying a strength class, and using the design properties for that class, ensures greater flexibility of supply. However for other reasons, individual species or groups of species might still be preferred. For example, the durability of wood and wood-based products varies according to the species – see BS EN 350-2 (20) and its associated standards. Also, particularly where the timber structure is architecturally expressed, a selected species may be designated for appearance purposes. Nevertheless, in view of the numerous potential combinations of species and mechanical properties, and the many variations in the type and quality of timber, a grouping and strength classification system goes a long way towards presenting the material in a more organised and straightforward manner.

When grades and species are assigned to the strength classes, only three characteristic values, namely the bending strength, the mean modulus of elasticity parallel to grain, and the density, are considered for qualification. Other properties for a particular species combination and grade are assigned on the basis of values whose derivation algorithms are listed in Annex A (Informative) at the rear of BS EN 338. These expressions have been determined from the relationships amongst the mechanical properties that have been observed with experience, over a wide range of groups and grades.

Within the strength classes, visually graded timber is selected to a standard that meets the requirements of BS EN 14081-1. In the UK, the choice is between BS 4978 for softwoods, and BS 5756 (21) for hardwoods. As indicated above, for machine graded timber BS EN 14081-1 is also the harmonised standard that is mandatory for full compliance with Eurocode 5. In detail however, this material is specified through further references to BS EN 14081-2 and BS EN 14081-3, although recourse to these additional standards may not be necessary for day-to-day design work. If details are required of the geographical sources of the timbers assigned to machine graded classes, then BS EN 14081-4 is also necessary. Note that provided the setting data are available to the operator, and the size is within certain limits, timber can be machine graded directly to fulfil a strength class. This is an efficient method of selection, and suppliers are aware of the appropriate machine grade choices to fulfil particular end-uses, being able to advise on the commonly available specifications.

¹⁵ EC5/Annex D (Informative)

4.7 Finger-jointed structural timber

Currently approved for publication is a harmonised standard that is expected to be referenced in future by Eurocode 5. The anticipated title is prEN 15497 *Timber structures – Finger jointed structural timber – Performance requirements and minimum production requirements* (22). The term “finger-jointed structural timber” in this context refers to individual elements whose length has been extended and/or whose defects have been culled by this process. Once the specified and approved end jointing has taken place, the elements are used in the same manner as individual solid timber members, in accordance with BS EN 14081 and the related strength classes.

Finger jointed timber produced to another standard that is already published, namely BS EN 385 (23), is used to manufacture glued laminated timber. This occurs during the stage at which individual laminations are being prepared. When prEN 15497 is published, it is expected that a revised edition of BS EN 385 will be retained for glulam manufacturers. Other types of bonded end joint, named “large finger joints,” are also used in glulam and LVL; however these serve another purpose and are specified and approved through a different standard, BS EN 387, which is discussed in Section 5.3, in conjunction with glulam and LVL structures.

A clause of BS EN 1995-1-1 requires as a principle that finger-jointed timber should conform to BS EN 385¹⁶. This comes under the main clause heading “Solid timber,” for the reasons just explained. Structural finger joints are machine-cut to designated profiles, so that interlocking fingers can be bonded to one another and pressed together using approved equipment and structural adhesives. Other types of finger joint also exist, for applications such as joinery and furniture, so the structural designer should take care to call up the correct performance requirements and minimum production requirements through reference to these standards. The physical testing of finger-jointed structural timber other than the “large finger joint” type is addressed by BS EN 408, which was discussed above. Desk-based derivations of characteristic values follow BS 384, and these have also been covered above.

5 Design properties for glulam and LVL

5.1 Glued laminated timber

For glued laminated timber (glulam)¹⁷, the essential harmonised standard for use with BS EN 1995-1-1 is:

- *Timber structures – Glued laminated timber – Requirements* - EN 14080 (24).

Referenced through a “note” in the code¹⁸, there follows the standard which gives the values of strength and stiffness properties for glued laminated timber, also allocated to strength classes. For convenience of the readers of this Guide, two further glulam standards required in design are also mentioned at this point:

- *Glued laminated timber - strength classes and determination of characteristic values* – BS EN 1194 (25).
- *Glued laminated timber – performance requirements and minimum production requirements* – BS EN 386 (26). *Glued laminated timber – sizes – permissible deviations* – BS EN 390 (27).

5.2 Glulam strength classes

A selection of characteristic properties for glulam strength classes extracted from BS EN 1194 is shown in Table 2 of this Guide. Clearly, for the complete range, reference should be to the standard itself. The significance of the symbols “h” or “c” in the designations, e.g. GL32h, is to show whether the glulam is fabricated from stock of a single strength grade ~ h ≡ “homogeneous”, or whether two grades are used, with a higher specification selected for the outer laminates ~ symbol c ≡ “composite”.

¹⁶ EC5/C1. 3.2(5)P

¹⁷ EC5/C1.3.3(1)P

¹⁸ EC5/NOTE to C1. 3.3(1)P

Table 2 Selected strength classes for softwood glulam – characteristic strength & stiffness values (N/mm²); densities (kg/m³)

Property		Strength classes			
		GL28h	GL32h	GL28c	GL32c
Bending strength	$f_{m,k}$	28	32	28	32
Tension strength	$f_{t,0,k}$	19.5	22.5	16.5	19.5
Tension strength perp. to grain	$f_{t,90,k}$	0.45	0.50	0.40	0.45
Compression strength	$f_{c,0,k}$	26.5	29	24	26.5
Compression strength perp. to grain	$f_{c,90,k}$	3.0	3.3	2.7	3.0
Shear strength	$f_{v,k}$	3.2	3.8	2.7	3.2
Mean modulus of elasticity	$E_{0,mean}$	12600	13700	12600	13700
Lower 5-percentile modulus of elasticity	$E_{0,05}$	10200	11100	10200	11100
Mean modulus of elasticity perp. to grain	$E_{90,mean}$	420	460	390	420
Shear modulus	G_{mean}	780	850	720	780
Characteristic density ^a	ρ_k	410	430	380	410
Mean density ^b	ρ_{mean}	460	500	440	480
^a Used for verifying mechanically fastened connections					
^b Used for calculating self-weight of members					

The actual allocation of a manufacturer's output to a particular strength class is based on the strength of the species or species combination used as the laminating source. The strength of the individual finger joints in each of the laminations is also considered, and for some types of glulam (the "c" designations), the position of the lamination grades within the overall beam lay-up is significant. Softwood glulam manufactured in the Nordic countries is often of strength class GL32. This approximates to an earlier common Scandinavian class L40, which is sometimes still mentioned.

Glulam manufactured by other methods, eg with alternative lay-ups of the cross-section, may be used structurally in accordance with BS EN 1995-1-1, provided it is an approved product. Also, species other than the commonly available European whitewood may be considered. Several suppliers offer structurally laminated Siberian larch, for instance, and since this is a more durable species, it is sometimes preferred for external structures or those that may suffer from occasional wetting. Such applications have also been met with durable structurally laminated tropical hardwoods such as iroko, whilst laminated temperate oak, both from Europe and from North America, is occasionally chosen for projects of high architectural merit, where the finished structure is revealed. Several of these combinations of lay-up and species may lead to alternative strength classes, for which there is provision within BS EN 1194.

5.3 Large finger joints

A typical large finger joint, forming the haunch of a glulam portal frame, is shown in Figure 1. With BS EN 1995-1-1, mandatory compliance for this type¹⁹ relates to the following:

- *Glued laminated timber – Production requirements for large finger joints. Performance requirements and minimum production requirements – BS EN 387 (28).*

¹⁹ EC5/C1. 3.3(4)P

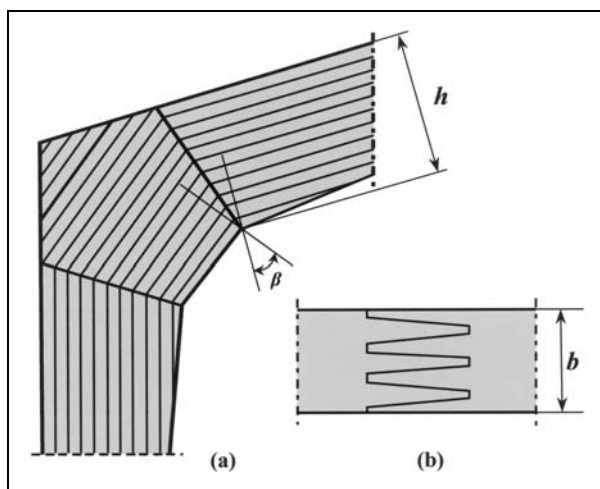


Figure 1 Typical "large finger joint" forming the haunch of a glulam portal frame; (a) elevation, showing critical angle β , (b) part plan *n.t.s.*

Large finger joints are not permitted for structures that are to be installed in Service class 3, because the direction of the grain often changes significantly at the joint, as is the case in Figure 1. Introducing the kite-shaped corner piece reduces the angles denoted β , thus using a pair of large finger joints rather than a single one. Nevertheless, for high moisture situations, the total grain direction change between the stanchion and the rafter remains significant since differential swelling or shrinkage would be likely to over-stress some of the bond lines over a period of time, leading to a gradual deterioration of their strength.

5.4 Tension perpendicular to grain

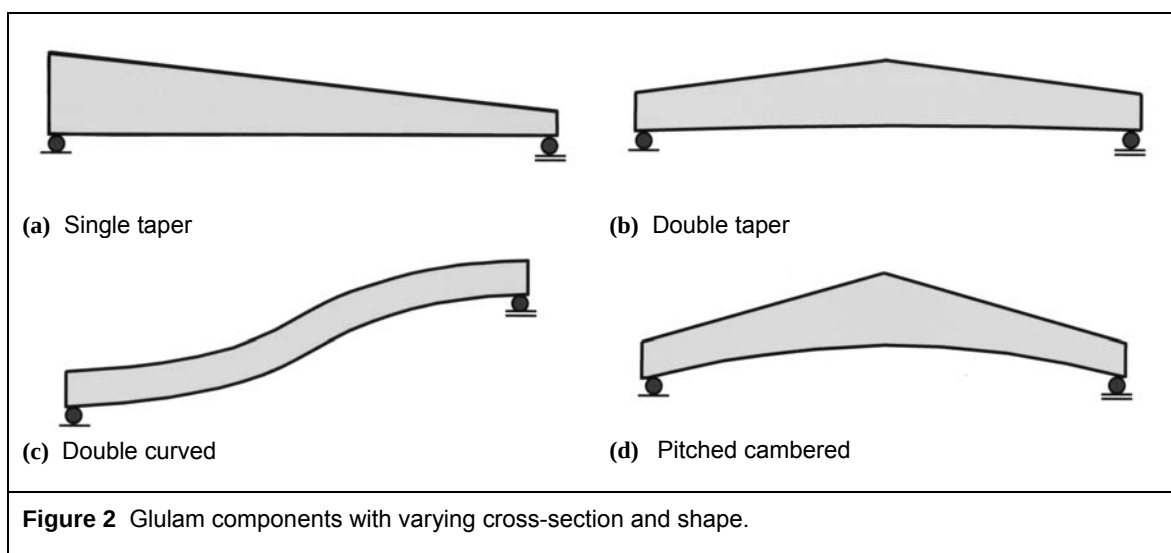


Figure 2 Glulam components with varying cross-section and shape.

The clause²⁰ calling for account to be taken of the effect of member size on the tensile strength of glulam perpendicular to the grain has no obvious adjacent accompanying application rule. However, for components with varying cross-section and shape, Figure 2, Section 6 of the code²¹ has rules controlling this condition.

²⁰ EC5/Cl. 3.3(5)P

²¹ EC5/Cl. 6.4.2 and 6.4.3

For single and double tapered, curved and pitched cambered glulam beams, the code expressions give volume-related design factors for tension stresses perpendicular to the grain. Other special factors relating to these shapes are also included in Section 6, covering the break-out of the end-grain fibres on the upper tapered profiles and the stresses induced in the laminations during the manufacture of the curves.

5.5 Laminated Veneer Lumber (LVL)

For this hot-pressed veneer material, the essential harmonised standard that is referenced²² for compliance with BS EN 1995-1-1 is:

- *Timber structures – Structural laminated veneer lumber – Requirements* – BS EN 14374 (29).

The majority of the LVL that is used in Europe is produced in Finland, under the brand type known as “Kerto.” The standard Kerto LVL has the grain of all of its veneers running essentially in one direction (Kerto-S). Also manufactured by a very similar process is a product in which some of the veneers are cross-grained with respect to the longitudinal axis of the sheet. This material is known as Kerto-Q. This may also be used structurally. It is especially useful for instance for shear-resistant diaphragms and decks. Because of its different lay-up, Kerto-Q is assigned separate characteristic mechanical properties, and the relevant standard, cited normatively²³ by Eurocode 5, is:

- *Laminated veneer lumber (LVL) – Specifications, definitions, classification and requirements* – BS EN 14279 (30).

The current technical advice (31) from Finnforest, the main manufacturer of European LVL, provides characteristic values of mechanical properties for Kerto-S and Kerto-Q; also information on physical properties, standard sizes, and fire resistance; the latter evaluated independently by the Technical Research Centre of Finland.

6 Geometrical data

BS EN 1995-1-1 indicates that design values for cross-sections involving geometrical data are taken as “nominal values.”²⁴ These are said to be obtained from the product standards, the harmonised European Standards, and their support documents (ie other ENs). Drawings for the execution of the project should also reflect these values. However, for solid structural timber, those responsible for the relevant standards have deemed it necessary to be more precise about the “target size,” whilst the term “nominal size” is deprecated and avoided. This is discussed below in relation to BS EN 336.

BS EN 1990 contains a Note within a geometrical property clause²⁵ considering situations where the limit state being verified is especially sensitive to variations in geometrical properties. However the use of geometrical values having a statistical basis is unnecessary for timber structures, even in potentially critical situations such as checks on buckling, since there is strict control of all types of materials dimensions within the supply chain.

6.1 Target sizes and tolerances

The National Annex (NA) 2003, to BS EN 336 *Structural timber – Sizes, permitted deviations* (32), explains the details of “customary” and “target” sizes. Economy of supply has established ranges of customary sizes that are produced by nearly all sawmills. Sawn sizes, initially to Tolerance Class 1, are frequently further machined on two opposing faces or on all four surfaces. Such processes create more accurate dimensions to meet the requirements of Tolerance Class 2. The choice of tolerance is considered, according to the specific demands of the project. The NA to BS EN 336 gives further advice, indicating that tolerances should be designated as “T1” or “T2” as appropriate in all specifications and drawings.

²² EC5/C1. 3.4(1)P

²³ EC5/C1. 3.5(1)P

²⁴ EC5/C1.2.4.2(1)

²⁵ EC0/C1.1.5.5.2

The “target size” is the size actually specified in the design, and this is the basis given by the standard BS EN 336. It is defined as:

- *The size specified (at the reference moisture content), and to which the deviations, which should ideally be zero, are to be related.*

The reference moisture content for the target size is 20%, although once the timber has been installed and has settled down in a structure, it generally reaches an equilibrium moisture content a few percent lower, even in Service class 2. There is also the option of selecting Service class 1 for a design, equating to approximately 12% equilibrium moisture content, and some suppliers of dry strength graded and fully surfaced softwoods are now aiming to meet such levels. Service classes for design are further discussed below.

The NA to BS EN 336 provides five tables of sizes for softwood structural timber that is commonly available in the UK. In order to enjoy the efficiency of supply and the accuracy of design discussed above, reference should always be made to these tabulated sizes. The tables indicate customary lengths; target cross-sectional sizes for sawn material; material that is machined on the width only; and material machined on all four sides. The final table covers softwood surfaced on all four sides to Canadian Lumber Standards and American Lumber Standards. Note that CLS/ALS are identical to one another in this respect, and only involve a selection of seven cross-sections in total.

6.2 Geometrical imperfections

Several of the clauses and expressions in BS EN 1995-1-1 make allowance for geometrical imperfections. Generally, these take into account effects such as:

- Geometrical imperfections of elements, eg bow, spring or twist along the length of a member
- Structural imperfections arising from fabrication and erection
- Innate inhomogeneity, eg due to asymmetrically-occurring knots in solid timber.

Geometrical imperfections are mentioned for instance in the section of the code dealing with the stability of members,²⁶ where there is a principle that the bending stresses induced by initial curvature need to be taken into account. Further in this same section, expressions (6.21) to (6.29) provide for checks on the strength of columns, and these also take imperfections into account. Elsewhere, in the section on bracing,²⁷ the principle is included that the stresses caused by geometrical and structural imperfections should be taken into account. These items often give rise to enquiry, since it is unclear how imperfections are to be estimated. However it can be explained that to implement such clauses, the designer does not normally require specific data on the extent of inadvertent geometrical imperfections. This is because the code makes standard allowances for the eccentricities and curvatures that are permitted within the grades and classes of the material concerned. Of course, in certain design situations, recognisable eccentricities are deliberately included within the details. This is a different case, which often arises at connection zones for instance. Here the secondary moments and other effects certainly do need to be calculated by the designer, just as they would for a steel frame, for example.

6.3 Hardwood sizes

The dimensional standard BS EN 336 applies mainly to normal cross-sections of solid sawn softwoods, and the tables of commonly available sizes for the UK, given in its National Annex, consider only these. Solid sawn hardwoods offer the possibility of larger cross-sectional dimensions and in some instances greater lengths are also available – up to around 12.0 m in cases of material such as greenheart and karri, for example. Both tropical and temperate hardwoods include species and species types (i.e. commercially recognised combinations) that are regularly used for structures. In addition to the potential advantage in terms of dimensions, material belonging to higher durability categories – ranging from “Moderately durable” to “Very durable” – BS EN 350-2 (20), is also available.

²⁶ EC5/Cl.6.3.1(1)P

²⁷ EC5/Cl.9.2.5.1(2)P

Further information on the choices amongst construction hardwoods in general is to be found in the Wood Information Sheet series (10), (33), whilst a dedicated Technical Bulletin has also been published (34). Recently, design recommendations and best practice guidance has been published for those wishing to use green oak in particular (35). Successful green oak design requires a good understanding of aspects such as quality selection, as well as strength grading, and there are specific provisions for coping with drying shrinkage and movement in use. All of these aspects are discussed in the publication.

6.4 Glulam and LVL dimensions

Stock glulam sizes: Straight glulam elements of rectangular cross-section are normally manufactured from 45 mm or 33.3 mm thick laminations, whose widths correspond to the standard ranges of solid timber cut by the sawmills (36). After completion of most of the manufacturing work, the side faces of the glulam are planed. Hence the finished width of the horizontally laminated glulam member (normally dimension “b” ie structural breadth) is a few millimetres less than the width of the original board laminates. The exact finished size depends upon whether the side faces of the glulam are planed and sanded, or only planed - in which case occasional patches of un-planed lamination are accepted. Producers’ tables of sizes are available, generally indicating a full range of sections from typically approximately 42 x 180 mm to 215 x 1620 mm. Smaller section softwood laminated products also exist, but these may not fully qualify for all of the design assumptions made for standard glulam, although they do provide advantages of great precision and uniform low moisture content, appropriate for Service class 1 situations.

Maximum glulam dimensions: The maximum lateral dimension b, measured parallel with the plane of the bond-line in the finished beam, is restricted by the fact that it is difficult to obtain softwood boards suitable for laminating which are wider than 225 mm. After planing, this corresponds to a width of 215 mm. Consequently, elements of up to 500 mm width (breadth of completed beam) are produced as “specials” by edge-bonding the laminations. However this is a highly controlled operation, requiring special equipment, hence only the original glulam manufacturer should be requested to perform it. Alternatively, designs often include paired elements, especially in flexure but also as spaced columns, for instance. This is another efficient way of achieving wider stable sections, whilst eliminating the need for special manufacturing facilities.

Another limitation is the maximum depth, ie the beam cross-sectional dimension h, measured at right angles to the plane of the bond-line. This is normally restricted to about 2000 mm, the constraint being the availability of planing equipment for the beams that, after bonding, have to be cleaned up and regularised by machining on the wider faces. Larger depths are achieved by various expedients, such as bonding a ridge piece onto a pitched cambered beam, Figure 2, at a later stage. Up to 3000 mm deep glulam components are made in this way, but again, only the original manufacturer should be asked to do this type of work, and he should be consulted before specification. Under no circumstances should re-bonding to increase the size of glulam be contemplated in the workshops of general manufacturers, since this is likely to lead to failure in service.

As far as factory capabilities are concerned, maximum lengths of glulam are up to 60 m. However, the practical element length is likely to be restricted by project transport considerations. For this reason, a limit is suggested of 24 m if delivery is to be by a tractor vehicle with a telescopic semi-trailer. Where the site permits, greater lengths may be delivered, for example by water transport. More guidance on transport and erection considerations for large timber engineering components including glulam is given in (37). In general terms, planning and restrictions on delivery are little different to those for factory-assembled steelwork, although because of the lightweight nature of timberwork, lifting loads are generally lower.

For external structures such as bridges, foot-way stairs, walk-ways and jetties, an additional restriction is placed by BS EN 386 on the maximum thickness of individual laminations. The 35 mm maximum permitted for Service class 3, compared with the normal 45 mm for Service classes 1 and 2, is believed to ensure better durability. For such external applications, the lay-up of the outer boards is also more precisely controlled. Other details given in the standard refer to matters such as controls on bonding pressures, which also become more critical for exterior glulam.

Curved glulam: Readily-made glulam “specials” are available with round cross-sections and curved shapes, offering many interesting design possibilities. Such products are very versatile, but communication between designers and manufacturers at an early stage is essential. For curved glulam, it is necessary to diminish the thickness of the individual laminations. An expression in BS EN 386, *Clause 6.2.3*, relates lamination thickness to the desired radius of curvature and the characteristic bending strength of the finger joints in the individual laminations.

If there is significant replication of a particular shape within a design, then curved and/or round-sections can be included at less of a cost premium, since this enables the time and labour of setting up the jigs to be amortised over a greater number of components. Lightly-cambered beams are a regular product - a 600 m radius being typical, and this does not involve reducing the lamination thickness, hence such curves may not be expensive. On the other hand, very tight radii e.g. under about 9.0 m, involve significantly thinner laminations - down to 19 mm being quite common. Nevertheless, when components such as glulam portals are compared with alternatives in other materials, the increase in cost may still lead to economical solutions.

LVL Lay-ups and sizes: As mentioned above, the manufacturing lay-ups of LVL mean that it may be used in elements where it is subjected to edge-wise bending or it may be subjected to flat-wise bending, ie acting as a strip, or as a plate or diaphragm. Both structural arrangements can be met with the Finnish “Kerto” brands, available as Types S and Q – all parallel veneers, or some cross veneers respectively. Both Kerto S and Kerto Q are available in standard production sections of 27 x 200 mm to 69 x 600 mm. Kerto S is also produced in 75 mm thicknesses up to 600 mm, with Kerto Q being sawn to order in widths of up to 2500 mm. The practice of doubling-up members such as rafters and columns, described above for glulam, is also quite common in LVL design. The Kerto LVL types may be supplied to specific orders in shapes such as tapers and pre-prepared portal columns and rafters. For forms such as lamellae and domes (38), second-stage manufacturers of timber engineering work will cut large stock LVL sheets to special shapes such as curved ribs, however consultation over such possibilities should begin at an early design stage.

7 Stiffness parameters in analysis

As well as being required for estimating deformations in serviceability limit states design, stiffness parameters, particularly moduli of elasticity and sometimes shear moduli, are essential for structural analysis. This occurs of course at an early stage of design, when the action effects within a proposed structural model are first being evaluated.

Eurocode 5 introduces design member stiffness properties in a rather obscure sequence. Numerically, the first relevant clause²⁸, under the sub-heading *Ultimate limit states*, introduces as a matter of principle the values for stiffness properties that should be used in analysis. However this clause is not self-contained, but includes several forward references.

As an aid to understanding, Table 3 of this Guide summarises the BS EN 1995-1-1 choices for stiffness properties that are usual in ultimate limit states design analysis. The type of first order linear analysis in which all members are regarded as having identical time-dependent properties suffices for many common design situations. Even for more complex structures, assumptions based on a single set of mean stiffness properties (row one of Table 3) are likely to be made for preliminary sizing.

In the design of glued thin webbed beams, even though it is possible to use a simple first order linear elastic analysis, it becomes necessary to make adjustments for the alterations in internal forces with time²⁹, through the varying stiffness and time-dependency of the elements. This is discussed by Solli (39), who explains and exemplifies the usual method for determining effective values of the cross-section in timber structures. Likewise, Raadschelders and Blass (40) deal with stressed skin panels, where a similar type of calculation is required. In both types of component, the k_{def} values (see Section 9.5) are liable to differ between the various constituent elements³⁰.

²⁸ EC5/C1.2.2.2(1)P

²⁹ EC5/C1.2.3.2.2(2)

³⁰ EC5/C1.2.3.2.2(4)

Table 3 Choices of stiffness properties for the design analysis

Type of ULS analysis	Stiffness basis	Clause references
First order linear elastic; distribution of internal forces unaffected by the stiffness distribution – all members are assigned the same time-dependency.	E_{mean} Obtained for the appropriate strength class, directly from BS EN 338 (Solid timber); BS EN 1194 (Glulam) or Type Assessment Certificate (LVL)	2.2.2(1) P – first subclause. See Table footnote 1.
First order linear elastic; but distribution of internal forces is affected by the stiffness distribution – not all members can be assigned the same time-dependency. See Table footnotes 2 and 3.	$E_{\text{mean,fin}} = \frac{E_{\text{mean}}}{(1 + \psi_2 k_{\text{def}})}$ Where: ψ_2 = quasi-permanent action combination factor; k_{def} = deformation modification factor – see below and EC5 Cl. 3.1.4	2.2.2(1) P – second subclause. 2.3.2.2(2) – for final mean values adjusted for the load component causing the most severe stress: strength ratio.
Second order linear elastic analysis – design values unadjusted for duration of load, but modified by partial factor for materials.	$E_d = \frac{E_{\text{mean}}}{\gamma_M}$ where: γ_M = partial factor for materials – see below, and EC5 Cl. 2.4	2.2.2(1) P – third subclause and its NOTE 2. 2.4.1(2) P – for design member stiffness properties.

NOTE 1: Indications are given only for modulus of elasticity. For shear and slip moduli, the principles are the same.

NOTE 2: Thin webbed beams and thin flanged beams are examples of components for which first order linear elastic analysis involves adjusting for changes due to the varying stiffnesses and time-dependency of the elements. For such components, especially careful analysis for potentially limiting ULS conditions in shear is necessary. Reference should be made to EC5 Clauses 9.1.1 & 9.1.2 and STEP Vol. 1 Chapter B9.

NOTE 3: Action combination factors are given in BS EN 1990 and explained in TRADA GD2. The ψ_2 = quasi-permanent action combination factor, is assigned = 1.0 for permanent actions, and to values ≤ 1.0 for other action combinations.

8 Partial factor for materials properties in design

As indicated above, BS EN 1995-1-1 uses the symbol γ_M for the partial factor for a materials property, indicating that the factor also accounts for model uncertainties and dimensional variations. This factor is introduced where the design value of a material property is first developed³¹.

³¹ EC5/Cl.2.4.1(1)P

8.1 Design value of a strength property

The code requires as a principle that the design value X_d of a strength property is calculated as:

$$X_d = k_{\text{mod}} \frac{X_k}{\gamma_M}$$

where:

X_k is the characteristic value of a strength property;

γ_M is the partial factor for a material property;

k_{mod} is a modification factor taking into account the effect of the duration of load and moisture content.

This expression adopts the general provision³² of BS EN 1990: 2002 for adjusting characteristic values to design values, but the important dependence of timber and wood-based materials on duration and moisture is taken into account by introducing the timber-specific k_{mod} factor, rather than retaining the generalised EC0 function denoted by symbol η . However, because of the arrangement of the timber code's content, it is at this point obliged to cross-refer³³ to its Section 3 for the application of the strength modification factor for load-duration and service classes, symbolised as k_{mod} . In this Guide, further discussion of this vital modification factor is included below, in Section 9.4.

One of the cases for determining a "design member stiffness property"³⁴, E_d or G_d , is also covered at this point in the code. This deals with the second order linear elastic analysis alternative, see Table 3 above, where it has already been introduced.

To complete this discussion of the partial factors for materials properties, a selection from the relevant code Table 2.3 is given in Table 4 below. Reference has also been made to the National Annex to BS EN 1995-1-1: 2006, Table NA.3, to ensure full conformity with the latter.

Table 4 Partial factor γ_M for material properties and associated resistances.

Factors for use with the following materials, in fundamental combinations	Value of Factor γ_M
Solid timber	1.3
Glued laminated timber	1.25
LVL, plywood, OSB,	1.2
Connections (except for metal plate fasteners)	1.3
Punched metal plate fasteners - anchorage strength	1.3
Punched metal plate fasteners - plate (steel) strength	1.15
Factor for accidental combinations, applicable to all of the above materials.	1.0

³² EC0/C1.6.3.3(1)

³³ EC5/C1.3.1.3

³⁴ EC5/C1.2.4.1(2)P

The partial materials factor values are at present Nationally Determined Parameters, and so may be varied in each country that observes the Eurocodes. However, the values of the UK National Annex only differ from the code's recommended values in one case, where an alternative is elected for design involving punched metal plate fasteners – see the two rows concerned in Table 4. Note also the important alleviating parameter for Accidental Design Situations. This is a uniform value across all Eurocode operating countries, and it is an important aspect of fire safety engineering design – see BS EN 1995-1-2 and an I Struct E introductory guidance document (41).

8.2 Calculating design resistances

It is vital that the engineer understands that for safety in accordance with the general principles of the Eurocodes, *design resistances* need to be calculated³⁵. This includes the whole of Section 8 *Connections with metal fasteners*. A “health warning” near the start of this Section might be expected, placing greater emphasis on the vital link between *Clause 2.4.3 Design resistances*, and the entire Section 8. Note that the extensive sets of expressions for the varieties of mechanical fastener and connection configuration given in Section 8 of the code only lead to *characteristic* load carrying capacities. These are not ready to be introduced into code-based calculation checks for adequate connection strength until they have been reduced by means of the appropriate materials safety factor γ_M , also the design-situation specific k_{mod} factor for load duration and moisture Service class, see below.

The design value R_d of a resistance (which in places the code also terms “load-carrying capacity”), is calculated as follows:

$$R_d = k_{mod} \frac{R_k}{\gamma_M}$$

where:

R_k is the characteristic value of load-carrying capacity;

γ_M is the partial factor for the material property,

k_{mod} is a modification factor taking into account the effect of the duration of load and moisture content.

The basis of load-duration classes and values for k_{mod} are discussed in Section 9, whilst the partial factors for material have already been covered, and as should now be clear, both are essential to calculate design resistance.

8.3 Serviceability limit states design

In accordance with the general principle³⁶ given in BS EN 1990, the timber code recognises that for serviceability limit states conditions, the partial factors γ_M for the properties of materials take a value of unity. This applies for all three of the serviceability limit states combinations of actions given in BS EN 1990³⁷, ie the Characteristic combination; the Frequent combination and the Quasi-permanent combination (used for long-term effects).

9 Load duration classifications and modifications

9.1 Load-duration classes

As indicated in Sections 3 and 8 of this Guide, timber is particularly sensitive to *load duration*. This is an expression conveniently reserved for use in conjunction with strength effects and ultimate limit states calculations. Also, significant long-term deformations may occur, ie *creep*, whose provisions are an important aspect of serviceability design.

³⁵ EC5/C1. 2.4.3

³⁶ EC0/C1.6.5.4

³⁷ EC0/C1.6.5.3

In terms of wood science and physics, the two effects are closely related (42), but for engineering purposes, it is convenient to separate them in this manner.

The load-duration classes are characterised by the effect of a constant load acting for a specific period of time in the life of the structure. In reality of course, this rarely occurs. The timber code indicates³⁸ that “for a variable action, the appropriate class is determined on the basis of an estimate of the typical variation of the load with time.” For ultimate limit states design, this judgement is finally left to the engineer, although advice is provided by assignments to load-duration classes, supported by further information in the National Annex, as discussed below. In the case of creep and vibrations, both aspects of serviceability design, there are codified formulations to assist the designer in “time-averaging” the accumulated variable actions. This is an area of improvement in the Eurocodes which users of the older national timber codes should study. These aspects are also discussed in the accompanying Guidance Document (43) in this series, GD 5 *How to calculate deformations in timber structures using Eurocodes*.

9.2 Assigning action effects to load-duration classes

Through the principle given in BS EN 1995-1-1:2004³⁹, involving code *Tables 2.1 and 2.2*, actions are allocated to one of the load-duration classes summarised here in Table 5. The code states that this is both “for strength and stiffness calculations,” but provides no further help at this point, however the associations of the assignments are as follows:

- Strength calculations – ultimate limit states – modification factor = k_{mod} ;
- Stiffness calculations – ultimate limit states – see “Applications of Stiffness Parameters for Analysis,” Section 7 above – modification factor = k_{def} ;
- Stiffness calculations – serviceability limit states – modification factor = k_{def} .

Note also that Table 5 of this Guide, whose third column incorporates information provided by the National Annex BS EN 1995-1-1:2006, refers to the *accumulated* duration of a “characteristic load.” This is an idea associated with the EC0 concept that actions are characterised probabilistically,⁴⁰ entailing a prescribed “reference period.” However in practice it is under the specific action combination for the particular design situation and load case in hand that the engineer is required to adjudge the load-duration class, and hence to look up the appropriate modification factors. This is an essential point to grasp in relation to timber design; the two vital modification factors being:

- Strength modification factor k_{mod} , dependent upon materials family, service class and load-duration class.
- Deformation factor, k_{def} , also dependent upon materials family and service class; in theory also variable with time, but for code simplification, calibrated to the longest load-duration period that is likely to be of practical significance.

Recognising that climatic loads (snow, ice and wind), are not uniform throughout the wide CEN geographic and climatic zones, the examples of load-duration assignment are permitted to vary between countries. Hence those indicated in Table 5 are in accordance with the UK National Annex *Table NA.1*. Consequently, engineers in this country using Eurocodes for projects that are to be constructed elsewhere may need to reference another country’s National documents.

9.3 Service class assignments

Service classes are already familiar to users of BS 5268. The system helps to assign appropriate strength values by defining environmental conditions. The Service class is an important parameter when calculating deformations, as well as for use in ultimate limit states calculations. Hence with BS EN 1995-1-1⁴¹, structures are to be assigned to one of the service classes whose definitions are given in Table 6 below - the table being a summary of the code recommendations.

³⁸ EC5/C1.2.3.1.2(1)P

³⁹ EC5/C1.2.3.1.2(2)P

⁴⁰ EC0/Annex C (informative)

⁴¹ EC5/C1.2.3.1.3

Table 5 Load-duration class assignments

Load-duration class	Order of accumulated duration of characteristic load	Examples
Permanent	More than 10 years	Self-weight
Long-term	6 months – 10 years	Storage loading (including lofts), water tanks
Medium-term	1 week – 6 months	Imposed floor loading
Short-term	Less than one week	Snow, maintenance or man loading on roofs; residual structures after an accidental event
Instantaneous		Wind; impact loading; explosion.

The assignment of particular structures to service classes is a matter of national choice. Hence without altering any of the fundamental definitions, the National Annex to BS EN 1995-1-1:2006 adds a *Table NA.2*, reproduced in this Guide as Table 7, classifying common components and structures. These classifications are based in part upon long-standing experience in implementing similar recommendations in CP112 and BS 5268. The decisions have been supported by surveys on existing timber structures in the UK, carried out by authoritative bodies including TRADA and BRE.

Table 6 Service class categories

Service class	Definition	Notes
Service class 1	Characterised by a moisture content in the material corresponding to a temperature of 20°C and the relative humidity of the surrounding air only exceeding 65 % for a few weeks per year.	In Service class 1, the average moisture content in most softwoods will not exceed 12 %.
Service class 2	Characterised by a moisture content in the material corresponding to a temperature of 20°C and the relative humidity of the surrounding air only exceeding 85 % for a few weeks per year.	In Service class 2, the average moisture content in most softwoods will not exceed 20 %.
Service class 3	Characterised by climatic conditions leading to higher moisture contents than in Service class 2.	In this Service class, precautions against decay are essential. This can be by: • Constructional protection measures. • Use of a timber of adequate natural durability, ensuring that sapwood is excluded. • Adequate pressure preservative treatment.

Table 7 Classification of common components by Service class

Type of construction	Description	Service class
Roofs	Cold roofs	2
	Warm roofs	1
Floors	Intermediate floors	1
	Ground floors	2
Walls	Timber framed walls – internal and party walls	1
	Timber framed walls – external walls	2
External components and structures	Where members are protected from direct wetting	2
	Fully exposed	3

9.4 The strength modification factor k_{mod} for Service- and Load-duration class

Ultimate Limit States Design: The partial factor γ_M for material properties and its associated resistance expression has already been discussed and summarised in Table 4 and Section 8 of this Guide. To perform ultimate limit states calculations, the appropriate value of the strength modification factor k_{mod} has to be determined. Since timber is particularly sensitive to load duration and creep effects, it is essential in any design code to address both phenomena. In tabulating k_{mod} and k_{def} (see below) in matrices that combine the provisions for Service class (moisture related) and Load-duration class, underlying simplifying decisions had to be taken. Those requiring more background are directed to Hoffmeyer (2) and also Mårtensson (44), the latter providing a comprehensive review of wood rheology tests that were used to confirm the EN 1995-1-1 factors.

Not being subject to national choice, k_{mod} is thus unaffected by any National Annexes. Table 8 below gives a selection of the classifications of this factor. This covers common applications, but for the full range of parameters, reference should be made to BS EN 1995-1-1 itself.

Note carefully that BS EN 1995-1-1 states⁴² that if a load combination consists of actions belonging to several load-duration classes, a common situation, then a value of k_{mod} is chosen corresponding to the action with the shortest duration within the combination. For example, for a combination of dead load with a short-term load, a value of k_{mod} corresponding to the short-term load deals with the whole set of action effects for this particular combination. This is a well-established method, in principle no different to that given in BS 5268. However, non-specialists sometimes do not grasp it, thinking that the tabulated load duration factors are for one-off load-duration instances – in fact they are cumulative statistical estimates of the effect for the period over which the peak and near-peak actions are experienced throughout the design life of the structure.

⁴² EC5/C1. 3.1.3 (2)

Table 8 Selected values of strength modification factor k_{mod}

Material	Reference Standards	Service class	Load-duration class				
			Permanent action	Long term action	Medium term action	Short term action	Instantaneous action
Solid timber	BS EN 14081-1	1	0.60	0.70	0.80	0.90	1.10
		2	0.60	0.70	0.80	0.90	1.10
		3	0.50	0.55	0.65	0.70	0.90
Glued laminated timber	BS EN 14080	1	0.60	0.70	0.80	0.90	1.10
		2	0.60	0.70	0.80	0.90	1.10
		3	0.50	0.55	0.65	0.70	0.90
LVL	BS EN 14374, BS EN 14279	1	0.60	0.70	0.80	0.90	1.10
		2	0.60	0.70	0.80	0.90	1.10
		3	0.50	0.55	0.65	0.70	0.90
Plywood	BS EN 636						
	- Part 1, Part 2, Part 3	1	0.60	0.70	0.80	0.90	1.10
	- Part 2, Part 3	2	0.60	0.70	0.80	0.90	1.10
	- Part 3	3	0.50	0.55	0.65	0.70	0.90

Table 9 Selected values of deformation modification factor k_{def}

Material	Reference Standards	Service class		
		1	2	3
Solid timber	BS EN 14081-1	0.60	0.80	2.00
Glued Laminated timber	BS EN 14080	0.60	0.80	2.00
LVL	BS EN 14374, BS EN 14279	0.60	0.80	2.00
Plywood	BS EN 636			
	- Part 1	0.80	–	–
	- Part 2	0.80	1.00	–
	- Part 3	0.80	1.00	2.50

Table 10 Additional values of deformation modification factor k_{def} , differentiated by load-duration class

Load-duration class	Reference Standards Solid timber and Glued Laminated timber - BS EN 14081-1; BS EN 14080	Service class		
		1	2	3
Permanent		0.60	0.80	2.00
Long-term		0.50	0.50	1.50
Medium-term		0.25	0.25	0.75
Short-term		0.00	0.00	0.30

9.5 The deformation modification factor k_{def} for Service class

The deformation modification factor for Service class is used mainly for serviceability limit states design, although as explained above in Section 7 of this Guide, load duration deformation effects are taken into account in some types of structural analysis, where strength is also under consideration. Neglect of k_{def} would usually have a less drastic effect upon safety than neglect of k_{mod} . However, estimating deformations, including creep deflection, is an important aspect of successful timber design – see also Guidance Document GD 5 (41). Section 3 Material Properties of BS EN 1995-1-1 introduces this modification factor very briefly⁴³. The choices of the deformation factor k_{def} are found in Table 3.2 of BS EN 1995-1-1, and, in an abridged format, in Table 9 of this Guide.

As with the load-duration modifier, k_{mod} , the deformation factor values really depend upon both service class (ie they are moisture related), and load duration class (also time-related, since they predict creep). However in the current Edition of the code, for simplicity, the values are only indicated for the permanent load-duration class, whilst the duration parameter is no longer provided for. This means that for temporary structures for example, estimates of long-term deformation may be somewhat exaggerated. Table 10 of this Guide is based on data provided by Table 4.1 of BS DD ENV 1995-1-1 (45). This is included for more advanced calculations, where the engineer has a thorough understanding of the code and its implementation. The factors remain appropriate, being based on tests reported in the above-cited references (2) and (44). As already stated, the further load-duration classes were only omitted from the current code for simplification.

Creep with drying under load: BS EN 1995-1-1 indicates⁴⁴ that for timber which is installed at or near its fibre saturation point, and which is likely to dry out under load, the values of k_{def} should be increased by 1.0. This may seem rather large, but it does realistically represent the behaviour of structural-sized beams under load, subjected to mechano-sorptive effects, meaning that flow of the wood fibres is accelerated by fluctuations in the environment accompanied by a gradual overall drying whilst the material is under strain. As long ago as 1951, Kingston and Armstrong (46) performed creep tests on initially-green beams of dense Australian hardwoods. These tests were of practical importance, because drying *in situ* was unavoidable, due to the slow air-drying rates of such timbers. These tests demonstrated creep of the order still now suggested. Later, Taylor *et al* (47) performed further experiments on structural-sized European spruce glulam beams. These were also modelled by Mårtensson, and reported in her reference cited above. Creep factors of around 2.8 over four years were indicated, both by tests and in theory, even when the starting point was with a quite dry type of glulam.

Information on the effects of drying under load is useful for designers of heavy carpentry, a method of building that has recently experienced significant interest (35). Here, the members are often of cross-sectional dimensions that cannot economically be dried in advance. Furthermore It is preferable to cut the joinery whilst the timber is still “green,” since in this condition it is much less hard. Under these circumstances, for a “green oak” building for example, the target service class indicated in the top row of Table 10 will usually be class 1 or 2, but the frame will be considered as drying *in situ*. Hence applying this clause, the appropriate value for factor k_{def} will be 1.60 or 1.80 (Service class 1 or 2), and this will lead to deformation predictions that match well with experience. More information on these aspects, together with a worked example, is to be found in the above-cited publication.

⁴³ EC5/C1. 3.1.4 (1)

⁴⁴ EC5/C1. 3.2(4)

10 Effect of member size on strength

For relatively small solid timber members, BS EN 1995-1-1 permits the effect of member size⁴⁵ on strength to be taken into account beneficially. Simple expressions are given⁴⁶, to compute a strength *increase* modifier as the depth becomes smaller, namely k_h . The result of applying this factor to the characteristic bending strengths of two classes of solid timber is illustrated in Figure 3 of this Guide. “Widths” in tension are covered by the same factor – a somewhat confusing term that actually refers to the greater transverse cross-sectional dimension. For example, in a solid timber tie beam of 60 mm x 120 mm section, bending about the stiffer axis, the “width” factor k_h relates to the 120 mm dimension.

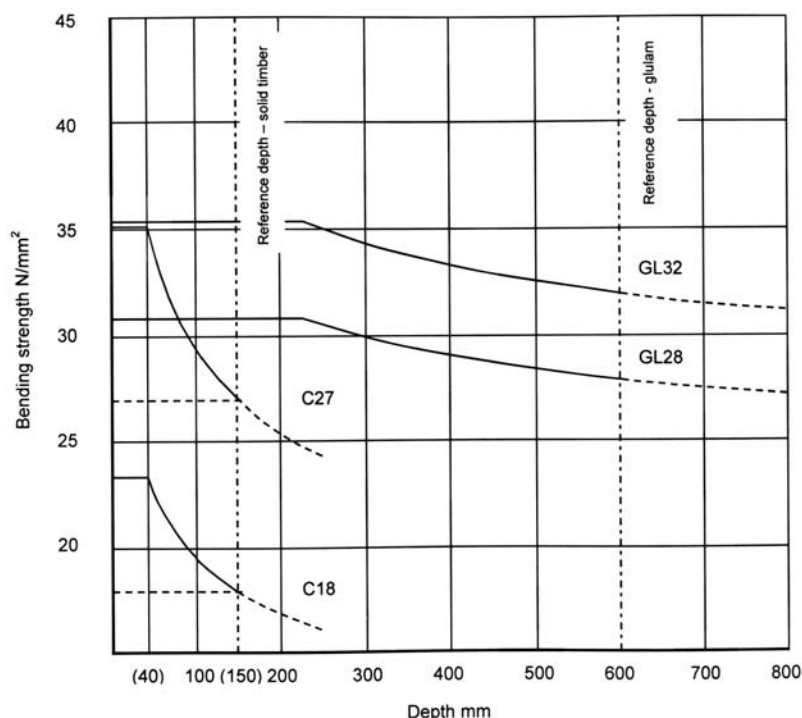


Figure 3 Depth (or width) factor k_h applied to the characteristic strength of two classes of solid softwood and two classes of glulam.

Two strength classes of glulam are also included in Figure 3 - others are treated similarly by the code. The format of the expression, giving an increase adjustment for bending or tension strength at lower sizes, is the same as that for solid timber, but the reference depth in bending or width in tension differs, being 600 mm. As can be seen from Figure 3, the benefit of the factor is less pronounced for glulam, compared with solid timber.

It can also be seen that for solid timber, the size factor allows a modest but useful increase in characteristic bending and tension strength over a relatively small dimensional range. Note however that in contrast to a similar factor in BS 5268, this applies only to the characteristic values for $f_{m,k}$ and $f_{t,0,k}$, not to the other strength properties. The size factor for solid timber applies in the range of depths (or widths for tensile members) of 40 mm to 150 mm. For depths of less than 40 mm, the factor remains set by the code at 1.3, since no test evidence is available. Also, above the reference depth of 150 mm, no reducing adjustment is provided. This is a code simplification, since experimentally the effect is probably capable of being extrapolated curvilinearly, as suggested by the dashed curves in Figure 3, and evidenced in earlier research, such as that by Freas and Selbo (48) and Comben, (49), for example. However, this does not necessarily mean that the strength will keep on reducing indefinitely with depth.

⁴⁵ EC5/C1. 3.2(2)

⁴⁶ EC5/C1. 3.2(3)

The limiting of the expression for the factor for solid timber to material with a characteristic timber density $\rho_k \leq 700 \text{ kg/m}^3$, arises simply because test evidence is only available for material in this density range. Although size effects on the more dense timbers, mainly of the tropical hardwood family, have yet to be investigated, the designer could apply judgement over whether or not to make similar adjustments.

For LVL, the effect of member size on bending strength is again taken into account. Furthermore with this material, a length factor also affects the tension strength. This is unique amongst the structural timber materials that are included in the code, but it is necessary because of its sensitivity to the transverse veneer splices that are included in LVL manufacture. The reference depth is 300 mm, and the reference length in tension is 3000 mm. For other lengths, the characteristic value for $f_{t,0,k}$ should be multiplied by a factor that is computed in a similar way to the depth factor. The size effect exponent is declared in association with the harmonized standard⁴⁷. In the case of the Kerto material, according to the Type Assessment Certificate (50) which refers to BS EN 14374, the depth factor for bending⁴⁸ and the length factor for tension⁴⁹ are applied with the identical parameter s values, for both the standard type (Kerto-S) and the cross-veneered type (Kerto-Q). For this particular brand of LVL material, the parameter $s = 0.12$ in both instances.

11 Structural wood-based panels

For structural wood-based panels such as the appropriate types and grades of plywood, the essential harmonised standard for compliance⁵⁰ with BS EN 1995-1-1, is:

- *Wood-based panels for use in construction – Characteristics, evaluation of conformity and marking* – BS EN 13986 (51).

It is a little strange that the title of this code-related harmonised European standard does not begin with the phrase “*Timber structures ...*”. However, there is a great variety of wood-based panel material used in general construction and by no means all of it can safely be considered to be “structural.” Many types and brands do not have the appropriate quality control levels nor the associated characteristic values defined under BS EN 1990 and BS EN 1995. Wood-based panels are a complex topic, and reference to documents such as appropriate TRADA Wood Information Sheets (52) is strongly recommended. Further advice for BS EN 1995-1-1 design may eventually be expected in UK non-contradictory complementary information (*under preparation, to be designated PD 6693, see National Annex, 2006*). Meanwhile, reference may also be made to BS 5268 : Part 2 : 2002, *Clause 1.5*, for suitable materials specifications, even though Eurocode design should *not* follow other sections of that code - for example, the strength properties of the plywood types that it contains are inappropriate for limit states design.

Steck (53) gives a general introduction to plywood as a structural material, in the Eurocodes context. In the manufacturing process, rotary peeled, kiln dried and graded veneers are spliced together and sprayed with adhesive particles. They are laid up generally at an angle of 90° to one another, although special plywood including 45° veneers is known. Pressure and heat bonding is followed by stages that include curing, trimming, machine-sanding, inspection and marking. Special products having facings of materials such as epoxy films and metallic envelopes are produced, and these too may fall into structural use categories.

Characteristic values for plywood are derived in broadly the same manner as solid timber, see the general discussion of characteristic values in Section 4 of this Guide. However the layering arrangements add further orthotropy to that normal in all wood-based products. Hence generally plywood and similar structural wood-based panels have a far wider range of design properties. Consequently, separate standard test procedures are necessary, see BS EN 789 *Timber structures – Test methods – Determination of mechanical properties of wood based panels* (54).

⁴⁷ EC5/C1.3.4 (5)P

⁴⁸ EC5/C1.3.4(3)

⁴⁹ EC5/C1.3.4(4)

⁵⁰ EC5/C1.3.5(1)P

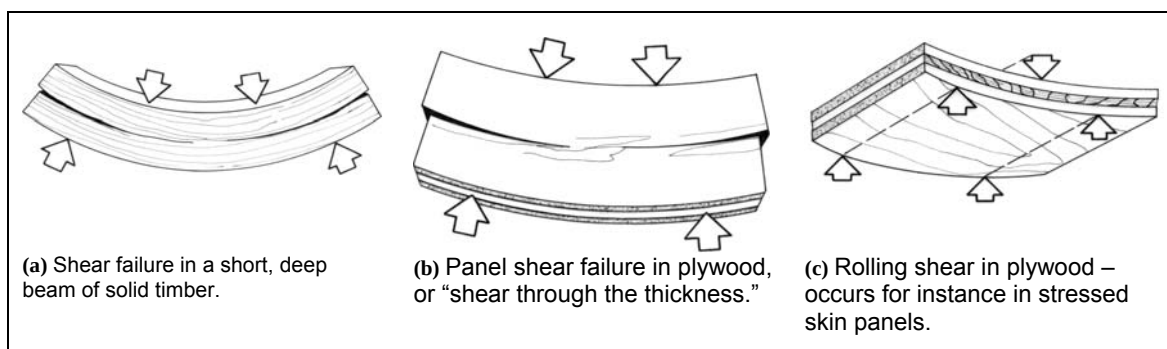


Figure 4 Shear in structural plywood.

Panel shear (b) is a similar effect to (a), when the material is acting as a plate on edge, eg in a web of a thin-flanged beam. For rolling shear, (c), where there are more than 3 plies (often the case), the strain distributions in the skins require evaluation to determine the critical interface, which may be adjacent to the stringers. LVL may also be subject to both panel shear and rolling shear.

In structural plywood design, shearing between horizontal planes needs to be considered, as well as “shear through the thickness,” see Figure 4. Also, flexural design needs to differentiate between in-plane bending – in directions parallel and perpendicular to the face grain; and bending as a vertical plate – one of the modes considered for example in the design of *Glued thin-webbed beams*⁵¹. *Glued thin-flanged beams*⁵² (stressed skin panels) also involve the use of various wood-based panel properties that differ from those of solid timber. Both types of component are addressed by Section 9 of BS EN 1995-1-1, whilst Solli (39) and Raadschelders and Blass (40), provide more detailed introductions and worked examples to the two types of component respectively.

For wood-based panel materials in structures, the durability needs to be carefully considered. This depends in part upon the inherent natural durability of the parent species. However further factors are at play, including the thickness of the veneers; their geometry, arrangement and surface quality; also the properties, quantities and chemical consistency of the adhesives. Clearly durability is an even more important issue in structural applications in Service class 3 conditions, and in association with the higher hazard classes as defined in BS EN 335-1 and 335-3. Further guidance on the specification and uses of wood-based panels in exterior conditions is provided in a TRADA Wood Information Sheet on the subject (55). Meanwhile, independent type approval for design with BS EN 1995-1-1 is gradually arriving, particularly for materials produced in the Nordic Region and in Canada.

12 Structural adhesives

12.1 Classifications

Structural timber adhesives are required⁵³ to produce joints of such strength and durability that the integrity of the bond is maintained in the assigned Service class throughout the expected life of the structure. As discussed in Section 9 of this Guide, the parameters that characterise Service class are mean ambient temperature and relative humidity. Their effect on the timber moisture content, as well as the inferred temporal fluctuations in loads and the surrounding environment, have a profound influence on the long-term performance of structural adhesives (56), (57), (58). For this reason, the code and its supporting standards distinguish adhesive performance by Service class, and it is essential that designers recognise this. The European standard referenced for adhesives, making strong Service class distinctions, is as follows:

- *Adhesives, phenolic and aminoplastic for load-bearing timber structures; classification and performance requirements* - EN 301:1992 (59).

⁵¹ EC5/C1. 9.1.1

⁵² EC5/C1. 9.1.2

⁵³ EC5/C1. 3.6(1)P

Emphasising the relationship between the code's application rules and the service conditions^{54, 55}

- Adhesives that comply with Type I specification as defined in EN 301 may be used in all Service classes
- Adhesives that comply with Type II specification as defined in EN 301 are only permitted for Service classes 1 or 2, and not under prolonged exposure to temperatures in excess of 50°C.

For timber structures, as opposed to the many other non-load-bearing applications of wood adhesives, these classifications are vital. Table 11 summarises the options that are likely to comply. However, as indicated by the key to the symbols in the Table, suitability within the classifications is brand-specific. Hence a symbol indicating *potential* suitability simply indicates this, rather than the certainty that all brands of the type are acceptable. Consequently it is essential to obtain the manufacturer's technical advice, as well as proof of independent certification regarding the use of an intended brand within a given Service class and exposure category.

Table 11 Classifications of the family of phenolic and aminoplastic adhesives for timber structures covered by BS EN 301.

Environment	Adhesive Type		
	RF/PRF	MUF	UF
Exterior	+	(+)	X
≥ 50 °C	+	(+)	X
≥ 85% r.h.	+	(+)	X
Marine	+	X	X
≤ 50 °C, ≤ 85% r.h.	+	+	+
Bondline colour	Dark – usually brown/purple	Light – usually white/clear	Light – usually white/clear
BS EN Class	301 - I	301 - I/II	301 - II
KEY: + Generally suitable, provided the specific brand conforms to Type I of the standard; (+) Some brands may be suitable - manufacturer's proof of certification essential; X Usually unsuitable; Abbreviations: RF/PRF - Resorcinol-formaldehyde (RF) and Phenol-resorcinol-formaldehyde (PRF); MUF - Melamine-urea Formaldehyde; UF - Urea-formaldehyde;			

12.2 New structural adhesives

Polyurethane adhesives: Major producers of glulam, and of the finger joints that this generic product contains, now make extensive use of types of polyurethane adhesive that are not yet included within the above categories. In particular, one-component moisture curing PU types are found in European glulam production, where they are widely used for the normal bondline thicknesses that are not greater than 0.5 mm. This practice is also beginning to be recognised in European Standards. For instance, BS EN 14080 *Timber structures – Glued laminated timber – Requirements*, (24), clause 4.5, indicates that “acceptable strength and durability can be achieved by the use of ... polyurethane adhesive tested and assessed in accordance with the requirements given in Annex C of this standard.”

⁵⁴ EC5/C1. 3.6(2)

⁵⁵ EC5/C1. 3.6(3)

Hence the Normative Annex C of BS EN 14080 gives the necessary tests and requirements for the production of glulam with these types of one-component moisture curing PUs. In several cases involving major manufacturers of both the adhesives and the glulam, these tests have already been conducted, providing the necessary independent certified approvals.

Epoxy systems: Certain formulations of epoxy resin adhesive have also been included in pre-normative research aimed at developing rules for the design of bonded-in rod connections in timber structures (60). Good results were obtained with the brands and formulations selected for the project, and in some cases, this family of adhesives is already used industrially for such purposes. Again however, adhesive manufacturer's advice is essential, particularly since the epoxy family is so diverse, both in formulation and purpose. Some manufacturers have obtained accreditation for bonded-in connection systems, and when contemplating these, the designer is urged to request the necessary proprietary assurance at an early stage.

13 Metal fasteners and connectors

Metalware items in timber engineering standards are generally confined to steel types, which are those predominantly used. BS EN 1995-1-1 calls for compliance⁵⁶ with two harmonised European Standards, each of which will contain the relevant Annex ZA – *information on addressing the provisions of the EU CPD*. These two new standards are:

- *Timber structures – Dowel-type fasteners – Requirements* - EN 14592 (61).
- *Timber structures – Connectors – Requirements* - EN 14545 (62).

At the time of writing this Guide, these standards are at an advanced stage of drafting, but are not yet published. Meanwhile, the brief *Section 4 Durability* that follows the code section on materials, contains a Table 4.1 that is of relevance. This table gives examples of minimum specifications for the corrosion protection of fasteners, related to ISO 2081 (63). This International Standard is expected to be generally compatible with the requirements of the above two harmonised standards. Note that within the broad categories provided, stainless steel types are included, and with the correct designation, these are clearly appropriate in certain applications, particularly in Service class 3 situations and in situations where it is intended to use acidic species of timber.

BS EN 14592 is expected to be published in 2008, and within this standard will be found ranges of dimensions, tolerances and other requirements for nails, staples, screws, plain dowels, and bolts and nuts. Procedures for Evaluation of Conformity will be given, along with Marking and Certification information. In BS EN 14545 will be found similar details for Shear connectors – plate, ring, and toothed plate forms; also for punched metal plate fasteners, and nailing plates.

The timber Eurocode, *Section 8 Connections with metal fasteners*, provides calculation expressions for the characteristic values of the yield moment in combined bending and tension for common standard types of nail, bolt, plain dowels and screws. These expressions are essential for the design of such connections, and also involve application of the factors for materials and load duration outlined above, as well as other considerations such as the embedment strength of the timber or wood-based material itself. The calculation of the yield capacity of dowel type fasteners may cause enquiry by engineers used to the differing yield strength procedures for bolts in steelwork. The basis for the current assumptions in timber engineering is given by Jorissen and Leijten (64).

At present, the yield moments of the fasteners are based on conservative assumptions of metallic material strength and ductility. Eventually, through the above-cited harmonised standards and their references, it will be possible to evaluate a wider range of fastener types, and these will be included in the design theory where appropriate. In the meantime, when unusual types or high-performance fasteners are proposed, enquiry should be made of the manufacturers as to their suitability with timber structures to BS EN 1995-1-1. An important point to note is that when the strength of the fastener is greater than normal, brittleness may be an issue, since the conventional mechanically fastened timber connections considered in *Section 8* are intended to deform significantly before ultimate fracture. This point is included by Hilson (65) in a general introduction to the theories used by the Eurocode drafting team.

⁵⁶ EC5/C1. 3.7(1)P

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