Structural glued laminated timber – Design essentials

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Note: This document is also produced as:

Structural glued laminated timber – Designers' pocket guide

The alternative version is in "Railway timetable" format – approximately A7 size, on silk-folded paper. Copies are freely available on application to the Secretariat.

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PDF Version 1 – August 2010

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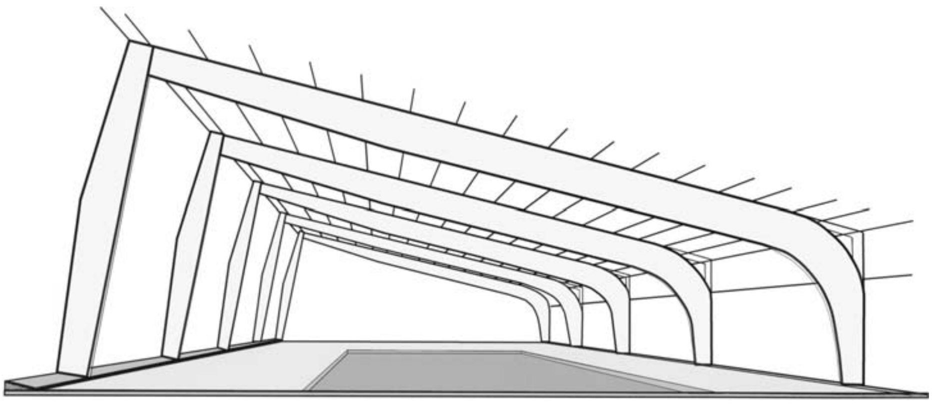

Structural glued laminated timber – Design essentials

Definitions

Glued laminated timber – *glulam* – is obtained by bonding together a series of *laminations* whose grain is essentially parallel[1]. Glulam members are larger and longer than those obtained simply by sawing a normal log. Except where a curved plan is required, *horizontal glulam* is the usual product. Fundamentally this is rectangular in section, but additional operations lead to a variety of other cross-sections and component shapes. For example, tapered profiles create pitched and shaped beams, portals and arches. Many types of curve are also fabricated, requiring thinner laminations bent on formers with bonding, clamping and curing arrangements. Uniquely this facilitates even three-dimensional curves.

Benefits

Glulam has exceptionally low mass, high strength and considerable stiffness, reducing foundation loads and easing delivery and erection. During its manufacture[2] every lamination is strength graded, end-jointed and dried, so that moisture content is uniform throughout the finished section. Eurocode 5[3] recognises this by assigning a lower partial safety factor for glulam compared with solid timber.

Glulam is well established - there are documented examples of its use in the UK around one hundred and seventy years ago[4], whilst some structures about one hundred and fifty years old are still standing. In its modern format, it uses waterproof synthetic resin adhesives, first introduced around 1929 and subsequently greatly improved. Consequently many sound examples remain in use from dates shortly after the Second World War.[5] In early 1947, the Forest Products Research Laboratory of the DSIR [6] commenced exposure trials on laminated softwoods for civilian applications, including many schools, colleges, telephone exchanges and other infrastructure re-building programmes.

The sustainable nature of glulam has recently come to be fully appreciated although this has been the case since its inception. Virtually all timber used in its manufacture is sourced from well-managed forests that are constantly being renewed.[7]

Updated design procedures backed by extensive tests and theories follow the Eurocodes basis of design.[8] Where necessary significant structural fire resistance[9] can be established. Glulam has high resistance in corrosive and exposed environments. The insulating properties of thick sections of solid wood, effectively created by the laminating process, may be used to advantage in thermal and condensation control calculations. Prefabrication in dry controlled workshop conditions is reflected in a range of well-tested and discrete structural connections, with alternatives both for pre-assembly and for the final site erection.

Production

Dried specifications of timber species known to be suitable for laminating are graded through both human inspection and automation,[10] assigning each lamination to a strength class. The subsequent operations include finer controls on moisture content, testing both means and ranges. Cutting and pressing finger joints converts the individual boards into long laminations. Then additional bonding machining and curing stages take place to complete the final product.

Production requirements cover all of the following:

- Adhesive types and performance.
- End joints in laminations – tensile and bending strength.
- Glue-line integrity and strength.
- For special components - bonded finger joints in complete glulam members.
- Production conditions and factory premises, staff qualifications and performance.
- Equipment standards for the actual manufacture and for the quality control operations.
- Record keeping, inspection and testing measures; responsibilities and documentation.

Finished thicknesses and cross-sectional tolerances are prescribed [11]. Other strict controls include the temperature and humidity conditions throughout the operations; cleanliness and preparation; edge bonding and joint staggering arrangements; curing and conditioning regimes.

Curved glulam

Since it is necessary to reduce the thickness of the individual laminations, the designer can offset the manufacturer's costs, including those of setting up the formers, by aiming for a degree of replication of shapes rather than including many variations. Lightly cambered beams may be little more expensive than straight ones, but very tight radii, e.g. under about 4.0 m, may involve laminations of 20 mm thickness or less.

An expression in BS EN 386 [12] determines the required thickness for a given radius of curvature, depending in part upon the strength of the finger joints. Portal haunches would commonly require quite tight radii and therefore thin laminations, but nowadays there are several alternatives, including *"large finger joints,"* mentioned below.

Finger jointing

As part of the manufacturing process, individual laminations are finger jointed following BS EN 385.[13] A new standard is under preparation (prEN 15487) for other finger jointing applications and it is anticipated that a revised edition of BS EN 385 will be issued for glulam structures. At a later stage of glulam manufacture, other types of bonded joint, named "large finger joints" are also used. These are specified and approved through another standard,[14] designated BS EN 387.

Timber species

The designer is concerned with the species for two main reasons – appearance and durability. The overall appearance can be gauged by viewing small hand samples of the wood, taking into account that glulam structures involve large surface areas, usually seen mainly from a distance. Knots in proportion to the total surface seem much smaller than with solid wood, but they are definitely not excluded, particularly in the coniferous species. Factors such as availability, chain of custody of supply and amenability to finishes are also relevant, and these are discussed below.

Within a fully roofed structure with an interior that should remain totally dry, there is negligible risk of decay or insect attack, consequently Service class 1 conditions should be designated, using European whitewood.[15] The majority of standard glulam beams are produced from this species, which bonds and machines well, providing a clean bright surface and having an excellent strength-to-weight and stiffness-to-weight ratio. Whitewood glulam complying with the forest certification schemes of FSC[16] and PEFC[17] is readily available.

Ease of supply within FSC/PEFC is also the case with the common alternative of European redwood[18], preferred in conjunction with generally slightly heavier-duty finishes and sometimes with pressure preservative treatment. Where there is risk of occasional external exposure to moisture, or indoor wetting, Service class 2 conditions are stipulated. This also applies to parts of a structure beneath an open roof or given similar protection from direct weathering. Here, design details should ensure water-shedding and ventilation, to provide as much physical protection as possible, since there may for instance be short-term wind-driven moisture.

Softwood glulam manufactured from Larch[19] has come to be appreciated by specifiers wishing to ensure a greater degree of natural durability without the necessity for pressure treatment. The forest certification schemes cover larch from both European and Siberian sources. Its Durability class according to BS EN 350-2[20] is Moderate (3). There are a number of further alternatives, including hardwood glulam. However it should be borne in mind that as one departs from the timbers just mentioned, the glulam becomes more "bespoke" and a longer delivery time needs to be planned, together with discussions with potential suppliers.

Other softwoods that are laminated include Douglas fir[21], which may be imported or British grown. Its Durability class is Moderate (3) to Slight (2) depending on the source. Occasionally, use is also made of Caribbean pine[22] (similar to Pitch pine). This is laminated in large quantities in the USA, so its application in the UK is certainly technically feasible. It is of Durability Class 3 and its choice is normally an architectural preference since the economics of its import may restrict its wider use.

The temperate hardwood timber species regularly available in the UK for bespoke glulam include European oak[23] and Sweet chestnut,[24] plus American white oak.[25] The latter is used in prestigious buildings for its excellent architectural appearance and this has attracted other applications. Both of the European hardwoods just mentioned are rated Durable – Class 2 whilst American white oak has a durablity almost as high as European oak, and because of its availablity in high qualities, its glulam is strong.

External exposure is discussed in a later section, and this is likely to be the main reason for preferring one of the suitable tropical hardwood timber species. These include Iroko[26] and Kapur[27] – both Durable - Class 2. Other possibilities exist and amongst these some are now registered with forest certification schemes.

Dimensions

Beams: The following normal cross-sections are for beams, especially European redwood and whitewood, as straight members produced from ex Imperial-sized boards i.e. with laminations of 45 mm planed thickness. Sections indicated thus ■ are generally available "off the shelf."

Breadth mm	**Depth mm**				
	135	180	etc. - standard to 495	+Increments of 45 mm to 990*	1035* and beyond
65	■	■	■	▒	▒
90	■	■	■	▒	▒
+Increments of 25 mm to 140 then : -	■	■	■	▒	▒
165 (160)** etc. to: -	■	■	■	▒	▒
215 (210)**	▒	▒	▒	▒	▒

Notes: * for depths beyond around 810 mm early consultation regarding delivery is essential. Articulated vehicle lengths rarely exceed 25 metres although extending trailers may allow up to about 43 metres. ** Manufacturers' practices vary for the machining of the wide faces (resulting in the finished breadths).

The following cross-sections are for beams in a rational metric range of depths. Whilst less common than the above, they are also available using all of the main species of softwood including Larch. Hardwood glulam such as Oak (from European and American white oak) and Iroko (sourced from West Africa) also generally follows this system. For applications in Service class 3 (external), it is obligatory according to BS EN 386 to restrict the original board thickness to 35 mm, again giving similar finished sizes. Sections indicated thus ■ are more likely to be available "ex stock."

Breadth mm	**Depth mm**				
	100	133	etc. - standard to 500	+Increments of 33.3 mm to 1000*	1033* and beyond
90	■	■	■	▒	▒
+Increments of 25 mm to 140 then : -	■	■	■	▒	▒
165 (160)** etc. to: -	■	■	■	▒	▒
190 (185)**	▒	▒	▒	▒	▒

Notes: * and ** - similar to Table above.

Columns and posts: For appearance, designers may prefer revealed columns and posts, particularly in circulation areas of schools and similar open-planned situations in public and amenity buildings. Several manufacturers have specific production equipment. Following the popular strength classes such as GL 24 and GL 28, and the main species, round and polygonally-sectioned members are "semi-standard" items. Typical diameters are from 115 to 185 mm, in lengths between 1.60 and 6.00 metres, but further sizes, shapes, and lengths are possible. To prevent wastage caused by re-cutting rectangular beams, square-sectioned posts are also offered.

Special columns of various shapes including tapers and hollows, are possible.[28] For example, "T" and "H" sections are reasonably common, and struts may even be double-tapered along their length. Tempted architects should always be aware that advanced consultations are advisable – these items are not "off the shelf."

Shaped components: The industry offers a wide variety of major components including tapered and pitched-tapered roof shapes, whole portal frames, various typical forms of arch – round and parabolic, two- and three-pinned. There are plenty of illustrated, built examples, also showing for instance barrel vaults, gridshells and domes.

To provide an effective response to preliminary proposals, general structural concepts should be developed in terms of pitch, frame spacings and spanning capacity. Design manuals and texts are becoming available referring to the latest Eurocodes and accompanying standards. Mentioned further below are delivery and transport load configurations and these should also be borne in mind.

Appearance and surface finishes

A largely superseded British Standard[29] contains guidance for purely non-structural or *appearance* aspects. Its intermediate Appearance Class is usually completely satisfactory, corresponding to the industry norm and ensuring ease of supply. The surfaces are fully planed and consistent with the structural grading requirements, significant knot-holes, small fissures and machining irregularities are repaired. Additional aesthetic prescriptions including fully sanded surfaces and factory-applied finishes are accepted by individual manufacturers, but are a matter for contractual negotiation. A former lower "regularised surfaces" grade, intended for industrial applications, is no longer produced.

There is a wide range of specifically designed applied finish coatings for wood. These are no longer based on traditional oil-based paints and varnishes, that should definitely be avoided. Modern finishes usually contain anti-mould agents, but should not be regarded as full preservative treatments. Colours may be translucent or opaque, and in natural wood tones or other tints. Even for interior structures, a light coating is generally recommended; this is usually applied before wrapping for delivery. The stage at which further decorative and water-repellent coats are added depends upon individual contract agreements.

Connections

Glulam framing often includes visible structure that is a feature of the architecture, placing an emphasis upon neatness and consistency in the connections. It is usual to carry matched and aesthetically logical node details throughout an internal space or across an external facade. Fastener types, connectors and connection arrangements are much more varied than when building with other framed materials such as steel, so it advisable for designers to consult with potential manufacturers at an early stage. Later revisions to the connection arrangement principles may well have an impact on the engineering design time.

Design data

The essential harmonised standard for use with Eurocode 5 is as follows:

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

Referenced through a "note" in the code[30] is the standard for the strength classes:

- *Glued laminated timber - strength classes and determination of characteristic values* – BS EN 1194.

Two other standards directly required in design are:

- *Glued laminated timber – performance requirements and minimum production requirements* – BS EN 386.

- *Glued laminated timber – sizes – permissible deviations* – BS EN 390.

At the time of writing, a revision of EN 14080 is being undertaken. Its scope may be expanded so that some of its auxiliary standards are included under the single cover.

Glulam strength classes: The allocation of a manufacturer's output to a particular glulam strength class is based partially on the strength class of the species or species combination used for the laminations (BS EN 338[31]). The performance of the finger joints is also stipulated and for the higher strength classes, this may control the assigned characteristic strength.

BS EN 1194 lists eight glulam strength classes. To distinguish them from the solid timber categories, they are designated "GLn." The material may either be of *'homogeneous'* lay-up, meaning that all of the laminations are of the same strength class, or *'combined'*, where the outer laminations (one-sixth of the depth on both sides of the neutral axis of a beam) are of a higher strength class.

Table 1 Characteristic strength and stiffness values in N/mm^2

and densities in kg/m^3 for selected strength classes of softwood glulam.

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					

For the "c" designations, the position of the lamination grades within the overall beam lay-up is controlled by reference to BS EN 14080. Use of these classes affects the engineering properties other than bending strength and stiffness, but it assists economy, so designation of "h" classes in certain parts of a structure and "c" classes in others may be worthwhile, generally on the advice of a specific manufacturer to ensure practicality of supply.

Glulam manufactured with alternative lay-ups of species and cross-section is permitted in accordance with BS EN 1995-1-1. Some of the combinations of lay-up and species discussed below under *durability* may lead to alternative design properties, for which there is some general provision within BS EN 1194.

External exposure

The risk of biological attack is seldom the same in all zones of a structure, hence five *Hazard classes* have been defined by BS EN 335-1[32]. These range from above ground, covered and dry, through the same but with a slight risk of wetting, then above ground but not covered and finally in the ground or in fresh water contact, plus in salt water – the most extreme class.

Glulam is used successfully in exposed conditions, but this entails protective design measures, with expressly designed covers to protect members and to maintain them in *Service class 2* conditions. On externally wetted structures, the acceptance of *Service class 3* exposure is required, having further consequent design decisions. In extreme situations, for instance major structures such as vehicular bridges, double pressure preservative treatment is applied to softwood glulam, at the same time protecting all of the key elements with non-corroding metallic covers.

Specifying laminating timbers that are classified as naturally "Durable" or "Very durable," and hence avoiding pressure treatment altogether, is certainly feasible. However it should be recognised that this restricts choice, since there must be experience in satisfactory bonding and laying-up, as well as precedents and records in achieving longevity. In the UK, this has been gathered with Iroko for example, used in situations such as the Thames Barrier roof structures, now some thirty years in service in very exposed conditions. Even here, well maintained water-repellent stain finishes are also essential together with rain screening and other protective measures. Accompanying metallic elements are protected through high duty galvanising or the use of stainless steel.

Fire resistance

Structural fire resistance is now established using BS EN 1995-1-2[9] . This addresses both the members and the connections. Fire is an accidental situation according to the basis of design – Eurocode 0; also referenced in the loading codes – Eurocode 1 series. More liberal partial factors apply to materials and connections, whilst characteristic strength and stiffness properties are more optimistic. The "reduced cross-section" method is one of the simpler approaches, likely to be followed in the majority of cases. No separate calculations are required for fire damage to bond lines, since these depreciate at the same rate as the surrounding timber. Following these methods[33], fire resistance periods of up to 90 minutes have already been approved in built glulam structures.

Adhesives

Adhesives must provide bonds of such strength and durability that their integrity is maintained in the assigned Service class throughout the expected life of the structure. This applies both for bonding the laminations and for making the finger joints.

Ambient temperature and relative humidity affect the timber's moisture content, whilst fluctuations in load and changes in the environment surrounding the structure also influence the long-term performance. Adhesives are therefore designated[34] by Service class: -

- Type I specification (BS EN 301) which may be used in all Service classes.
- Type II specification (BS EN 301) which shall only be used in Service classes 1 or 2 and not under prolonged exposure to temperatures in excess of 50°C.

All reputable glulam manufacturers in the European Standards zone use these classifications. Within each of them, performance is brand-specific, so specifiers may wish to check the individual manufacturer's technical information for evidence of independent certification.

For Service classes 1 and 2, manufacturers frequently use types of polyurethane adhesive that are not included in some of the older standards[2]. One-component moisture curing PU types are permitted for laminating where the normal bondline thickness is not greater than 0.5 mm – virtually always the case. This is fully recognised in the more recent European Standards, for instance BS EN 14080 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."* Modified urea formaldehyde (UF) adhesives are also still in use for Service classes 1 and 2. Provided their brand has been approved, they remain perfectly satisfactory in these situations.

For structures in Service class 3, well-tried and tested brands of resorcinol-formaldehyde (RF) and phenol-resorcinol-formaldehyde (PRF) adhesive remain normal. Raknes[35] reported in 1997 on a large series of comparative ageing tests that began in 1964. He noted that the types available for fully exterior use were more or less the same as when the tests started. They may be recognised by their dark – usually brown/purple – bond lines.

Hardwoods generally differ from softwoods with regard to pH, extractives content and other factors. Consequently their successful bonding is a more specialised subject, so whilst conforming to the above general requirements, manufacturers' solutions may vary.

Bonded-in connection systems[36] may be considered and accredited manufacturers exist. These often involve formulations of epoxy resin adhesive, an extremely broad group found in other civil engineering applications.[37] However they are not yet generically classified for building structures, so evidence of the necessary individual approvals should be sought.

Marking and certification

In the UK, Ireland and Sweden, compliance with the Construction Products Directives[38] may be demonstrated via *Third Party Certification* from *Notified Bodies.* Elsewhere in the CEN Zone there are comparable systems (mainly in the non-EU countries), or others whereby "CE" marking on components and/or on the certificates accompanying deliveries has already been established. Further information on marking and certification may be obtained from the GLTA and from *BM TRADA Certification.* Where the finished elements remain visible in use, paper-based certification rather than direct product marking is permitted.

Delivery, site storage and protection

In terms of vehicle length and height for road bridge clearance, road transport constraints are similar to those for structural steelwork.[39] Dependent upon the destination, special arrangements for water transport may be feasible since glulam manufacturing plants are often in port areas. The arrival location should be secure, level and accessible, unless there are exceptional circumstances and special arrangements have been firmly agreed in advance.

During manufacture great care is taken over the moisture content and appearance of glulam, so it is important not to detract from them during delivery and storage. The ideal is to store components at site for as brief a time as possible, in a completely dry location or at least protected so that they are not soaked by rain run-off, ponding or splashing. On unloading, beams and other components should be evenly supported on clean, dry bearers at appropriate centres so that they do not deflect significantly under their own weight. Strips or blocks placed vertically between sets may assist subsequent lifting.

Manufacturers provide instructions for partial un-wrapping on delivery to retain protection but to avoid condensation within the parcels. Despite first coatings applied at the factory, strong sunlight and drying winds as well as precipitation detract from the timber's appearance. Discolouration can be remedied, but only by unnecessary work, so unless the members can be erected straight away, the best precaution is to cover stacks with dark sheeting, ventilated at the lower edges, and tented above, to avoid ponding. Such wrapping should be strongly guyed to avoid wind damage.

For subsequent lifting and handling, professionally written and approved methods statements are required, the aim being to ensure that the geometry of the completed structure meets design specifications and tolerances. During lifting, unintended strains must be avoided. Webbing slings are essential for lifting timber since it crushes quite easily across the grain. Normal advice on safety procedures applies, including the correct location and balancing of supports, the calculation of lifting forces, and the provision of stabilisation arrangements.

Glulam made from certain hardwoods may become stained through contact with ferrous items, including lifting equipment, so precautions should be taken. For bridge and other external structures, where mud and dirt may be a particular problem during construction, it is advisable to apply more than minimal protective coatings at the works.

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[16] http://www.fsc.org/ *Accessed 10 April 2010.*
[17] http://www.pefc.co.uk/ *Accessed 10 April 2010.*
[18] *Pinus Sylvestris* – known as *Scots pine* if British grown; Note : all the cited botanical and standard timber names are stated in BS EN 13556 *(Reference (15)).*
[19] *Larix decidua, Larix kaempferi; Larix x eurolepis, Larix occidentalis.*
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[21] *Pseudotsuga Menziesii.*
[22] *Pinus carribea and Pinus oocarpa.*
[23] *Quercus robur; Q. petraea.*
[24] *Castanea sativa.*
[25] *Quercus spp.* - American white oak comprises about eight commercial species – see http://www.americanhardwood.org/.
[26] *Milicia excelsa (formerly Chlorophora excelsa) and M. regia.*
[27] *Dryobalanops (spp).*
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