AMERICAN HARDWOOD EXPORT COUNCIL

STRUCTURAL DESIGN IN AMERICAN HARDWOODS

Contents

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Front cover: Portcullis House, London, UK -
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Back cover: Haberdashers' Hall, London, UK -
American Hardwood Export Council.

Foreword

Engineers learn from their work on projects. The knowledge they gain is often disseminated in papers but it is unusual that one project should directly stimulate further testing and the publication of a reference work, which improves the utilisation of a whole range of products.

In developing the design for the long span roof over the courtyard at Portcullis House, Arup, working with BRE, developed detailed design information for their project and now the fruits of this work, with the support of the American Hardwood Export Council, are available for designers to use. Due to high density and straightness of grain, White oak is (at D50) roughly twice the strength of a high-grade softwood, enabling the very slender members at Portcullis House. Extensive strength testing on large-scale specimens by BRE now enables us to take full advantage of the tremendous strength of these American hardwood timbers. Because the results have been presented as both permissible and characteristic stresses, the information can be freely used across the whole of Europe.

Designers are sometimes confronted with a request to use a species for which little engineering data has been published. The range of timbers is vast and we can often make conservative assumptions, based on comparisons with other species, which enable us to proceed with design. In the late 1980s, the structural engineering could proceed for the design of the roof to the Queen's Building at Emmanuel College in Cambridge, a modern interpretation of a traditional tied truss roof using American white oak and stainless steel ties. But the design was challenging and it would have been enormously helpful to have been able to use this new guide, *Structural Design in American Hardwoods*.

For long span structures, particularly those in which slender elements are expressed in the architecture, if it is not possible to make full use of the strength of the material available, timber might not be considered appropriate as a structural material. Until this guide, the published standards gave information for only two temperate hardwoods (European oak and sweet chestnut); this guide provides information for a further four important temperate hardwood species.

Why are they important? Of course, the four species, American white oak, American red oak, American ash and tulipwood are widely recognised for their visual merits. The ability to extend their efficient use into structures increases the architectural palette. They also increase our opportunity to use sustainably sourced timber.

There is no other construction material that comes anywhere near timber in its potential to produce environmental benefit. Because both in growth and in use timber is a carbon sink, the use of timber, from whatever source, is always good environmentally and the more we use the better it is. The use of sustainably sourced timber is even better. In the past 50 years US hardwood forests have increased in area and the volume of standing timber has nearly doubled.

Combining strength, sustainability and great beauty, American hardwoods are a natural choice for high profile engineered roofs as well as smaller scale structures. This new guide enables us to make this choice and take full advantage of the strength and aesthetic qualities of these timbers.

Richard Harris
Buro Happold

Introduction


American white oak


American red oak


American ash


Tulipwood

The visual merits of American hardwoods have long excited the imagination of architects who have used these species, with their fashionable colours and grain patterns, to great aesthetic effect in building projects large and small. Traditionally within Europe, the use of American hardwood species has been largely limited to non load-bearing applications. But now a shift in fashion towards wood solutions coupled with a growing interest in temperate hardwood species, is fuelling a desire amongst specifiers to combine structural performance with aesthetic design. But without accurate structural data on the species to be used there is a tendency to over specify, to play safe, which has a negative impact on structural efficiency and forest yield.

In 2000 a high profile structural use of hardwood in the UK set in motion a chain of events that has culminated in the creation of this publication and new data on four commercially important American hardwood species. The project was Portcullis House, the new parliamentary building in London, designed by Hopkins Architects.

The building encloses a central courtyard with a large barrel vaulted roof of glass supported by a lattice work of laminated American white oak timber, designed by Arup. It is one of the most complex timber roof structures in Europe. In order to achieve this ambitious design Arup carried out detailed research and testing into the strength of American white oak and discovered that the material and grades available provided a better than expected D50 rating, allowing a more efficient design. Cost is an important consideration in structural design and this new research enables cost savings to be achieved with the use of standard grades.

The American Hardwood Export Council teamed up with Arup and commissioned the Building Research Establishment (BRE) in the UK to undertake testing of four American hardwood species including white oak in order to determine their characteristic values for structural design. These test results uncovered some surprising data and established that all four species have the potential to be more widely used structurally. AHEC now offer this information to architects and engineers all over Europe so they may have the confidence to use these species in load-bearing applications.

David Venables
American Hardwood Export Council

Environmental credentials

While there is an increasing volume of North American hardwood certified through such schemes as the Sustainable Forestry Initiative (SFI) and the Forest Stewardship Council (FSC), forest certification frameworks that rely on establishing traceability to specific forest management units are not always appropriate for the majority of North American hardwood forests. It is not the forestry practices which are at issue, but the nature of forest ownership.

Lack of certification does not imply lack of sustainability. In the case of American hardwoods, the forests are themselves living proof of sustainability. The United States Federal government has seventy years of national forest inventory data to provide ample evidence that the resource is thriving. To take just one headline statistic: over the last half century the volume of hardwoods standing in United States forests has increased by over 90% while the area of forest has increased by 18%. Detailed supporting information is available at the USDA Forest Service website:

http://www.fs.fed.us/pl/rpa/

Around 73% of hardwood forest land in the United States is privately owned, often by families whose ownership stretches back several generations. There are approximately four million private forest owners with an average lot size of 20 hectares. It is usual for a sale of hardwood logs to occur only once, perhaps twice, in any landowner's lifetime. Timber sales are a low percentage of lifetime expected income for these owners, so even a significant increase in timber value (which at present does not occur with certification) provides no real incentive for owners to achieve certification. The lumber that an American hardwood mill supplies to its customers will often come from thousands of these small landowners - and the next year it will be an entirely different group.


© Corel

There can be no doubt of the sustainability of the American hardwood resource, which reflects the effectiveness of the existing regulatory framework on the federal and state levels, the natural resilience of the American hardwood forests, and the nature of forest ownership. The dominance of small non-industrial forest owners makes independent forest certification difficult. From a sustainability perspective it is a considerable strength, creating a strong link between rural communities and their forests.

Structural timber design in Europe

Eurocodes and standards

The publication of the Eurocodes, and their accompanying standards marks the culmination of a 20-year programme to provide a comprehensive unified set of documents which give design rules for the major structural materials, including timber, in a limit state format. Eurocode 0 sets out the basis of design, and Eurocode 1 and its various parts specify the loading criteria. Eurocode 5 gives the general rules for design in timber, and refers to various standards, among them EN 408, which specifies test procedures, and EN 384, which defines the method of determining characteristic values from the test results.

The main parts of the Eurocodes have now been published and the accompanying National Application Documents are due to be published in 2005, and to be ratified for design use in most European countries. There will be a transition period, in which designers may opt either for the Eurocodes or continue to use their national codes.

National design codes

Over the last 50 years many European countries have developed national design codes for timber and the other common structural materials, although the individual format of these codes varies. Existing national codes such as the UK timber code (BS 5268) generally give permissible stresses for various common species, which embody the whole factor of safety against failure. Other codes are in limit state format, where the total factor of safety is divided between the material strengths and the applied loads. These codes present material strengths as characteristic values. For this reason the design information in this publication is presented both as characteristic values and permissible stresses.

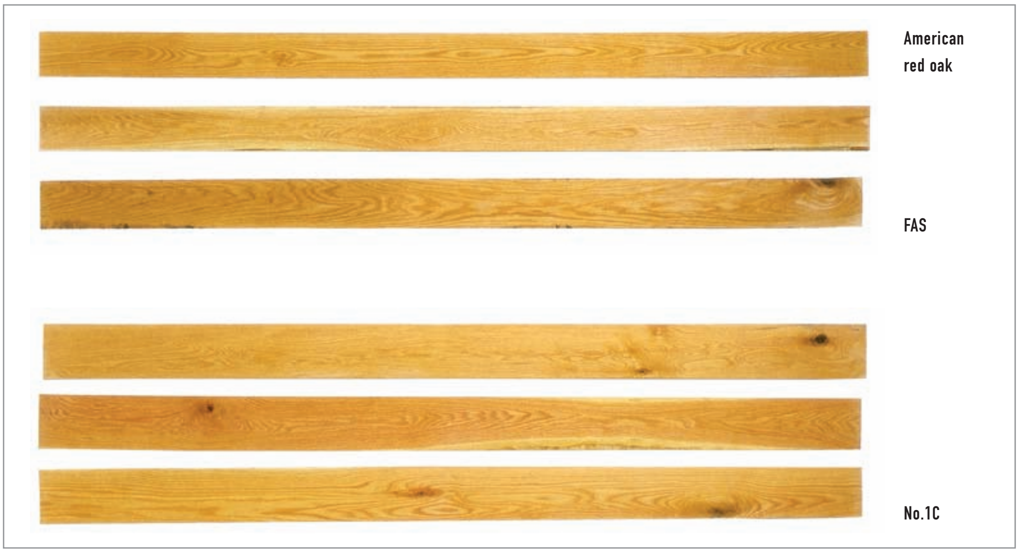
Strength classes and species properties

EN 338 defines a range of strength classes for timber: C14-C50 for softwoods and D30-D70 for hardwoods. For each class a profile of properties is defined, relating to strength, stiffness and density. The results from tests on a particular species/grade combination must pass the minimum values set for all the properties for the material to belong to that class.

The strength class system works well for softwoods, which overall are more closely related in terms of basic structure. The hardwoods, however, are a more diverse grouping, and not all the four species of American hardwoods which were tested fit neatly into strength classes. Although American white oak complies with all the requirements of D50, American red oak, although stronger than white oak in bending, has values of stiffness and density that will only allow it into strength class D40. And while American ash complies with the requirements of D35, tulipwood, while having D40 strengths and stiffness, is not dense enough to qualify for the lowest strength class of D30.

However, both Eurocode 5 and most national codes allow designs to be made using the species properties, as well as a strength class designation. In the following section on Material properties the species properties are given, and designers may use these values directly, in general with some advantage.

Grading



All the hardwood exported from America to Europe is graded by reference to the rules of the National Hardwood Lumber Association (NHLA). The rules are described in detail elsewhere*, but the two grades of relevance are 'First and Seconds' (FAS) and 'Number 1 Common' (No.1C). The higher of the two, FAS, will provide boards, each with between 84% and 100% 'clear' faces, that is, free of all knots (see above). The lower grade, No.1C, will provide boards with faces between 66% and 84% clear of knots. While these are high specifications, no limits are placed on the size of the knots when they occur, or the slope of grain, the principal two parameters of any structural grading system.

To use American hardwoods with confidence in structural applications, it is necessary to have design data which applies to material graded in accordance with a structural grading standard complying with EN 518. Currently, no single standard is accepted throughout Europe.

One such grading standard that does comply with EN 518 is BS 5756. It gives straightforward rules for grading hardwood into two grades, TH1 and TH2. The upper grade, TH1, is more appropriate to the American hardwood stock, maximising the quality of the individual pieces without producing unduly low yield rates, and was used to select the samples for testing. Thus the design data in this publication applies to American hardwoods RE-GRADED TO BS 5756, GRADE TH1. The yield rates for this re-grading from FAS and No.1C stock are given in the tables of properties (see Tables 1-4 on pages 9-12).

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* *The Illustrated Guide to American Hardwood Lumber Grades* – AHEC

Material properties

On the following pages are given design properties for the four species, together with additional design information under the following headings:

Availability

The following sizes are commonly available in the UK -

Thickness:

19 - 100mm

Width:

Random 152mm and wider for FAS

Random 102mm and wider for No.1C

Length:

Random 2.4m - 4.8m for FAS

Random 1.8m - 4.8m for No.1C

Notes:

1. Stock supplied to imperial sizes; approximate metric equivalents given.
2. Larger components can be achieved by glued lamination.

Appearance and working properties

Guidance on the appearance and general properties of the four species is given in the *Guide to American Hardwoods - Species* published by AHEC.

Durability

EN 350-2 defines five durability classes, ranging from 1 (very durable) to 5 (not durable). The appropriate durability class is given for the heartwood of each species. American ash and tulipwood are not included within EN 350-2, but approximate classifications are given based on *The Handbook of Hardwoods* (BRE 1997).

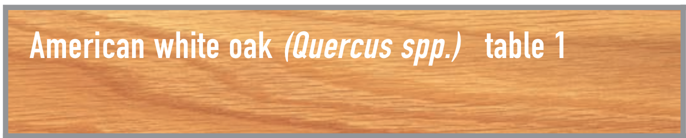
Yield on re-grading

As explained on the previous page, American hardwoods are exported as NHLA grades - FAS and No.1C. For structural use it is necessary to re-grade the material according to the rules of BS 5756, Grade TH1. The yield on re-grading is given for each species. (If the selection is done by the merchant, the non-selected pieces are not ‘rejects’, since they are still FAS (or No.1C) and can be put back into stock). It is, of course, important to specify the need for re-grading.

Structural properties

Strength, stiffness and density properties are given for each species in both limit state and permissible stress formats. The use of both formats is illustrated in the worked examples in the following section. As explained on page 6, three of the four species do not completely fit a single strength class profile. However, both Eurocode 5 and most National codes allow design to be carried out using properties which have been derived from testing, and this option will obviously optimise the potential of a particular species. As a basis for comparison, the strength class properties are put alongside the characteristic values.

Material properties



American white oak *(Quercus spp.)* table 1

Durability rating: 2-3 (durable/moderately durable - EN 350-2)

Approx yield on re-grading to TH1: FAS-70%, No.1C-50%

Material graded to BS 5756: Grade TH1

For design in accordance with Eurocode 5

Characteristic values for American white oak			(D50)
Bending - parallel to grain N/mm²	$f_{m,k}$	51.8	50
Tension - parallel to grain N/mm²	$f_{t,0,k}$	31.1	30
Tension - perpendicular to grain N/mm²	$f_{t,90,k}$	0.6	0.6
Compression - parallel to grain N/mm²	$f_{c,0,k}$	29.5	29
Compression - perpendicular to grain N/mm²	$f_{c,90,k}$	10.3	9.7
Shear - parallel to grain N/mm²	$f_{v,k}$	4.7	4.6
Mean modulus of elasticity - parallel to grain N/mm²	$E_{0,mean}$	15 000	14 000
5% modulus of elasticity - parallel to grain N/mm²	$E_{0,05}$	12 600	11 800
Mean modulus of elasticity - perpendicular to grain N/mm²	$E_{90,mean}$	1000	930
Mean shear modulus N/mm²	G_{mean}	940	880
Characteristic density kg/m³	ρ_k	688	650
Average density kg/m³	ρ_{mean}	811	780

For design in accordance with BS 5268

Permissible stresses and moduli for American white oak		
Bending - parallel to grain N/mm²	$\sigma_{m,adm,0}$	17.3
Tension - parallel to grain N/mm²	$\sigma_{t,adm,0}$	10.3
Tension - perpendicular to grain N/mm²	$\sigma_{t,adm,90}$	0.7
Compression - parallel to grain N/mm²	$\sigma_{c,adm,0}$	12.2
Compression - perpendicular to grain N/mm²	$\sigma_{t,adm,90}$	4.6
Shear - parallel to grain N/mm²	τ_{adm}	2.2
Mean modulus of elasticity - parallel to grain N/mm²	$E_{0,mean}$	14 100
Min. modulus of elasticity - parallel to grain N/mm²	$E_{0,min}$	10 700
Mean modulus of elasticity - perpendicular to grain N/mm²	$E_{90,mean}$	700
Mean shear modulus N/mm²	G_{mean}	880
Characteristic density kg/m³	ρ_k	709
Average density kg/m³	ρ_{mean}	835

Material properties

American red oak *(Quercus spp.)* table 2

Durability rating: 4 (slightly durable - EN 350-2)

Approx yield on re-grading to TH1: FAS-80%

Material graded to BS 5756: Grade TH1

For design in accordance with Eurocode 5

Characteristic values for American red oak			(D40)
Bending - parallel to grain N/mm^2	$f_{m,k}$	53.7	40
Tension - parallel to grain N/mm^2	$f_{t,0,k}$	32.2	24
Tension - perpendicular to grain N/mm^2	$f_{t,90,k}$	0.6	0.6
Compression - parallel to grain N/mm^2	$f_{c,0,k}$	30.0	26
Compression - perpendicular to grain N/mm^2	$f_{c,90,k}$	9.2	8.8
Shear - parallel to grain N/mm^2	$f_{v,k}$	4.8	3.8
Mean modulus of elasticity - Parallel to grain N/mm^2	$E_{0,mean}$	13 000	11 000
5% modulus of elasticity - Parallel to grain N/mm^2	$E_{0,05}$	10 900	9400
Mean modulus of elasticity - perpendicular to grain N/mm^2	$E_{90,mean}$	870	750
Mean shear modulus N/mm^2	G_{mean}	810	700
Characteristic density kg/m^3	ρ_k	615	590
Average density kg/m^3	ρ_{mean}	680	700

For design in accordance with BS 5268

Permissible stresses and moduli for American red oak		
Bending - parallel to grain N/mm^2	$\sigma_{m,adm,0}$	17.6
Tension - parallel to grain N/mm^2	$\sigma_{t,adm,0}$	10.5
Tension - perpendicular to grain N/mm^2	$\sigma_{t,adm,90}$	0.8
Compression - parallel to grain N/mm^2	$\sigma_{c,adm,0}$	12.2
Compression - perpendicular to grain N/mm^2	$\sigma_{t,adm,90}$	4.6
Shear - parallel to grain N/mm^2	τ_{adm}	2.3
Mean modulus of elasticity - parallel to grain N/mm^2	$E_{0,mean}$	12 200
Min modulus of elasticity - parallel to grain N/mm^2	$E_{0,min}$	8400
Mean modulus of elasticity - perpendicular to grain N/mm^2	$E_{90,mean}$	610
Mean shear modulus N/mm^2	G_{mean}	760
Characteristic density kg/m^3	ρ_k	633
Average density kg/m^3	ρ_{mean}	700

Material properties

American ash *(Fraxinus spp.)* table 3

Durability rating: 5 (not durable; approx - *Handbook of Hardwoods*, BRE)

Approx yield on re-grading to TH1: No.1C-50%

Material graded to BS 5756: Grade TH1

For design in accordance with Eurocode 5				For design in accordance with BS 5268		
Characteristic values for American ash			(D35)	Permissible stresses and moduli for American ash		
Bending - parallel to grain N/mm^2	$f_{m,k}$	37.8	35	Bending - parallel to grain N/mm^2	$\sigma_{m,adm,0}$	12.5
Tension - parallel to grain N/mm^2	$f_{t,0,k}$	22.7	21	Tension - parallel to grain N/mm^2	$\sigma_{t,adm,0}$	7.5
Tension - perpendicular to grain N/mm^2	$f_{t,90,k}$	0.6	0.6	Tension - perpendicular to grain N/mm^2	$\sigma_{t,adm,90}$	0.6
Compression - parallel to grain N/mm^2	$f_{c,0,k}$	25.6	25	Compression - parallel to grain N/mm^2	$\sigma_{c,adm,0}$	10.5
Compression - perpendicular to grain N/mm^2	$f_{c,90,k}$	9.2	8.4	Compression - perpendicular to grain N/mm^2	$\sigma_{t,adm,90}$	3.3
Shear - parallel to grain N/mm^2	$f_{v,k}$	3.7	3.4	Shear - parallel to grain N/mm^2	τ_{adm}	1.8
Mean modulus of elasticity - Parallel to grain N/mm^2	$E_{0,mean}$	12 800	10 000	Mean modulus of elasticity - Parallel to grain N/mm^2	$E_{0,mean}$	12 000
5% modulus of elasticity - Parallel to grain N/mm^2	$E_{0,05}$	10 700	8700	Min modulus of elasticity - Parallel to grain N/mm^2	$E_{0,min}$	8000
Mean modulus of elasticity - perpendicular to grain N/mm^2	$E_{90,mean}$	850	690	Mean modulus of elasticity - perpendicular to grain N/mm^2	$E_{90,mean}$	600
Mean shear modulus N/mm^2	G_{mean}	800	650	Mean shear modulus N/mm^2	G_{mean}	750
Characteristic density kg/m^3	ρ_k	616	560	Characteristic density kg/m^3	ρ_k	634
Average density kg/m^3	ρ_{mean}	667	670	Average density kg/m^3	ρ_{mean}	687

Material properties

Tulipwood *(Liriodendron tulipifera)* table 4

Durability rating: 5 (not durable; approx - *Handbook of Hardwoods*, BRE)

Approx yield on re-grading to TH1: FAS-90%

Material graded to BS 5756: Grade TH1

For design in accordance with Eurocode 5

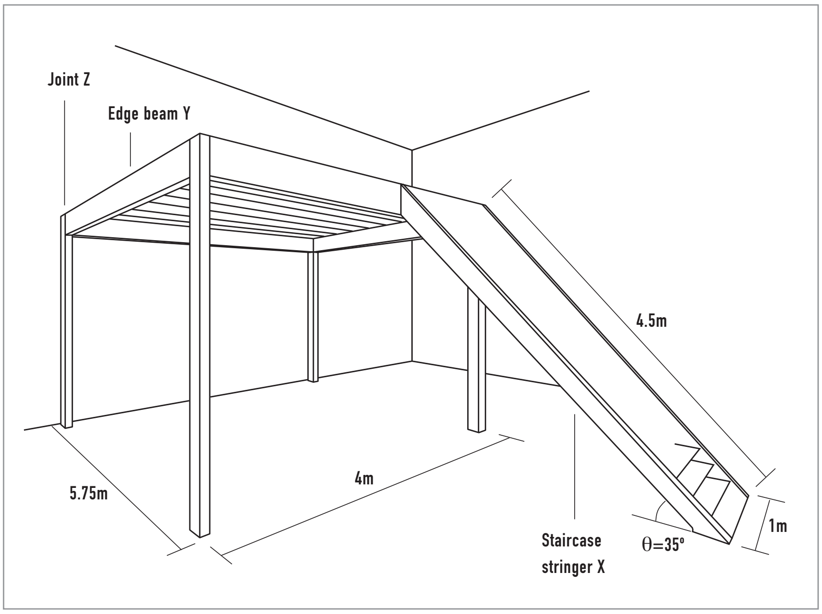
Characteristic values for tulipwood			Footnote*
Bending - parallel to grain N/mm^2	$f_{m,k}$	41.7	
Tension - parallel to grain N/mm^2	$f_{t,0,k}$	25.0	
Tension - perpendicular to grain N/mm^2	$f_{t,90,k}$	0.5	
Compression - parallel to grain N/mm^2	$f_{c,0,k}$	26.8	
Compression - perpendicular to grain N/mm^2	$f_{c,90,k}$	6.8	
Shear - parallel to grain N/mm^2	$f_{v,k}$	4.0	
Mean modulus of elasticity - parallel to grain N/mm^2	$E_{0,mean}$	11 900	
5% modulus of elasticity - parallel to grain N/mm^2	$E_{0,05}$	10 000	
Mean modulus of elasticity - perpendicular to grain N/mm^2	$E_{90,mean}$	800	
Mean shear modulus N/mm^2	G_{mean}	750	
Characteristic density kg/m^3	ρ_k	456	
Average density kg/m^3	ρ_{mean}	552	

For design in accordance with BS 5268

Permissible stresses and moduli for tulipwood		
Bending - parallel to grain N/mm^2	$\sigma_{m,adm,0}$	14.6
Tension - parallel to grain N/mm^2	$\sigma_{t,adm,0}$	8.8
Tension - perpendicular to grain N/mm^2	$\sigma_{t,adm,90}$	0.7
Compression - parallel to grain N/mm^2	$\sigma_{c,adm,0}$	11.3
Compression - perpendicular to grain N/mm^2	$\sigma_{t,adm,90}$	3.9
Shear - parallel to grain N/mm^2	τ_{adm}	2.0
Mean modulus of elasticity - parallel to grain N/mm^2	$E_{0,mean}$	11 300
Min modulus of elasticity - parallel to grain N/mm^2	$E_{0,min}$	7800
Mean modulus of elasticity - perpendicular to grain N/mm^2	$E_{90,mean}$	570
Mean shear modulus N/mm^2	G_{mean}	700
Characteristic density kg/m^3	ρ_k	470
Average density kg/m^3	ρ_{mean}	568

*** As noted on page 6, tulipwood, while having D40 strength and stiffness, is not dense enough to qualify for the lowest strength class D30**

Design example



Mezzanine floor and staircase

As an example of the use of the design information given on the previous pages, consider the mezzanine structure shown opposite. All the structural members are exposed, and it is assumed that there are no requirements for a period of fire resistance. Calculations to Eurocode 5 and BS 5268 are made for:

- staircase stringer X
- edge beam Y
- joint Z

Assumed loads:

- Self weight = 0.3 kN/m^2
- Imposed = 1.5 kN/m^2

Solid member design

Consider the design of staircase stringer X.

Design to Eurocode 5

In Eurocode 5, imposed load is taken as 'medium-term'; this is reflected in k_{mod}. Try 38 x 175dp American white oak:

udl normal to member (ω)	= [1.35 Self weight + 1.5 Imposed] * loaded width * cos θ	
	= [1.35(0.3) + 1.5(1.5)] (0.5)(cos 35)	= 1.1 kN/m
Bending moment (M)	= $\omega L^2/8$	= 2.8 kNm
Applied bending stress	= $6M/td^2$	= 14.1 N/mm^2
Design stress	= $k_{mod} f_{m,k} / \gamma_M$ = (0.8)(51.8)/1.3	= 31.9 N/mm^2 OK

In practice, serviceability is likely to govern.

Design to BS 5268

BS 5268 is a 'permissible stress' code. The permissible timber stresses incorporate both the load and material factors. In BS 5268, imposed load is taken as 'long-term' and this results in a higher utilisation in bending compared with Eurocode 5. Since the reference depth in BS 5268 is 300mm (compared with 150mm in Eurocode 5), an enhancement (k_7) may be taken for shallower members:

udl normal to member (ω)	= [1.0 Self weight + 1.0 Imposed] * loaded width * cos θ	
	= [(0.3) + (1.5)](0.5)(cos 35)	= 0.74 kN/m
Bending moment (M)	= $\omega L^2/8$	= 1.9 kNm
Applied bending stress	= $6M/td^2$	= 9.7 N/mm^2
Permissible stress	= $k_3 k_7 \sigma_{m,adm,0}$ = (1.0)(1.06)(17.3)	= 18.3 N/mm^2 OK

Design example

Glulam design

Consider the design of edge beam Y. American hardwoods are primarily used for joinery and the maximum available length (4.8m - page 8) will be more of a limitation than for softwoods. Since edge beam Y is 5.75m long, it must be fabricated as a glulam.

Design to Eurocode 5

In the absence of more detailed guidance for the characteristic strength of hardwood glulam, properties of glulam may conservatively be taken equal to the properties of the solid timber laminations, taking the depth factor $k_h = 1.0$. While Annex A of EN 1194 gives formulae for glulam properties based on the strength of the laminations, this is strictly for softwoods, and if applied to say American white oak would actually yield bending strengths for the glulam lower than the strength of the individual laminates.

Try a 100 x 200dp American white oak glulam. For glulam, a slightly lower material factor (1.25) applies compared with solid timber (1.3).

udl normal to member (ω) $= [1.35 \text{ Self weight} + 1.5 \text{ Imposed}] * \text{loaded width}$

$= [1.35(0.3) + 1.5(1.5)]\,(2.0)$ = 5.3 kN/m

Bending moment (M) $= \omega L^2/8$ = 21.9 kNm

Applied bending stress $= 6M/td^2$ = 32.9 N/mm²

Design stress $= k_{mod}\, k_h\, f_{m,k} / \gamma_M = (0.8)(1.0)(51.8)/1.25$ = 33.2 N/mm² OK

A complete design would also need to consider serviceability.

Design to BS 5268

Permissible stresses may be calculated using the modification factors in Table 24 of BS 5268-2. For all combinations of American hardwood species and numbers of laminations, BRE recommend that the modifications corresponding to D35/D40 and 4 laminates should be conservatively taken. This corresponds to a 26% enhancement on bending strength and, as it happens, balances the conservatism in BS 5268 which designates imposed floor loads as 'long-term' (as discussed in the previous example), giving the same overall utilisation as Eurocode 5.

udl normal to member (ω) $= [1.0 \text{ Self weight} + 1.0 \text{ Imposed}] * \text{loaded width}$

$= [0.3 + 1.5](2.0)$ = 3.6 kN/m

Bending moment (M) $= \omega L^2/8$ = 14.9 kNm

Applied bending stress $= 6M/td^2$ = 22.3 N/mm²

Permissible stress $= k_3 k_7 k_{15} \sigma_{m,adm,0} = (1.0)(1.05)(1.26)(17.3)$ = 22.9 N/mm² OK

The white oak glulams for Portcullis House under construction.

Right: The cigar columns were turned from glulam blocks.

Far right: The laminated struts were pre-drilled and the ends shaped with hand tools.

Photographs © Kingston Craftsmen

Design example

Joint design

Consider the design of joint Z connecting the edge beam Y to the post. The diagram below shows one possible joint configuration, consisting of a two member bolted joint.

Design to Eurocode 5

For a thin steel plate, no more than half the bolt diameter, there are two possible failure modes as illustrated in *EN 1995 Part 1-1* (figures 8.3 a & b) and represented by the expression below. (*EN 1995 Part 1-1* expression 8.9)

Design capacity per bolt
$$(F_{v,Rd}) = (k_{mod}/\gamma_M)\ \min \begin{cases} 0.40\, f_{h,k}\, t_1\, d \\ 1.15\,(2M_{y,Rk}\, f_{h,k}\, d\,)^{1/2} + (0.25\, F_{ax,Rk}) \end{cases}$$

where

			Refs. to *EN 1995 Part 1-1*
Material factor	γ_M	$= 1.3$	(UK National Annex)
Modification factor	k_{mod}	$= 0.8$	(Table 3.1, MT, Service class 1)
Yield moment of bolt	$M_{y,Rk}$	$= 0.3\, f_{u,k}\, d^{2,6}$	(8.30)
Embedment strength	$f_{h,k}$	$= 0.082\,(1\text{-}0.01d)\,\rho_k$	(8.32)
Withdrawal capacity	$F_{ax,Rk}$	$= (3\, f_{c,90,k}\,)\,\pi(1.5d)^2$	(8.5.2, washer diameter 3d)
Tensile strength of bolt	$f_{u,k}$	$= 400$ N/mm^2	(UK Grade 4.6)
Timber thickness	t_1	$= 100$ mm	
Bolt diameter	d	$= 12$ mm	

These equations (above) feature only two properties of the timber - the characteristic density (ρ_k) and the compressive strength perpendicular to the grain ($f_{c,90,k}$). Reference to the other joint capacity equations in Eurocode 5 (for bolts, dowels, nails, screws and timber connectors) will show that these also depend either on density alone or a combination of density and perpendicular to grain strength.

In order to design a joint in American hardwoods, we can either input the species properties directly into the Eurocode 5 joint equations, or we can take the connection capacities from standard tables or design software, using the strength class which most closely matches the density and perpendicular to grain strength of the particular species, as shown in Table 5 (below right).

As previously noted, tulipwood has an unusually low density compared with strength, and only achieves density and perpendicular to grain strength equivalent to a ‘C50’ softwood classification. In this case, it would therefore be advantageous to use the actual species properties.

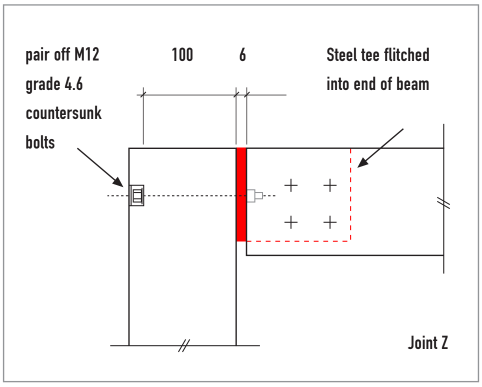


Table 5 - Species and matching strength class from tables 1-4	ρ_k [kg/m^3]	$f_{c,90,k}$ [N/mm^2]
American white oak	688	10.3
D50	650	9.7
American red oak	615	9.2
D40	590	8.8
American ash	616	9.2
D35	560	8.4
Tulipwood	456	6.8
(C50)	460	3.2

Design to BS 5268

Again, the connection capacities can be taken from standard tables or design software, using the corresponding strength classes given in Table 5 (above).

Portcullis House, London

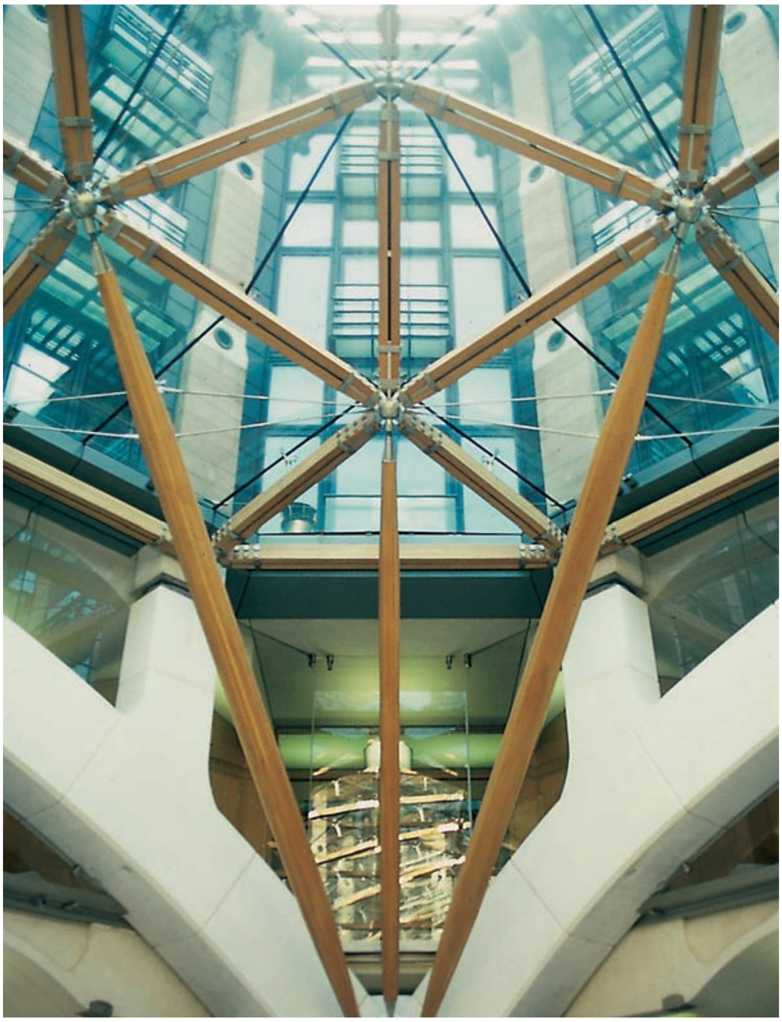
Portcullis House is situated in Bridge Street, Westminster. The building is a hollow rectangle, with a central courtyard approximately 50m by 25m covered by a glazed roof.

The architects, Hopkins, defined the form of the roof as an arch with hipped ends, to be supported on a geodesic frame in timber. The aim was to create a very light structure to maximise the transparency of the roof, if possible using American white oak for its colour and texture.

The engineers for the project, Arup, found that little information on the structural use of American white oak was available. A conservative assessment of its strength would inevitably require larger member sizes, but the published results of tests on small sections showed that it was in fact stronger than European oak, and the material available as First and Second (FAS) grade would be of very high quality - straight-grained, and with few knots.

Arup therefore commissioned BRE to undertake a programme of testing (described in detail on page 18) which showed that D50 grade material could be obtained from commercially available supply.

This high strength enabled the basic frame members to be made of paired white oak glulams only 200mm by 100mm in cross-section. At each node the members are bolted to metal blades, in turn connected to a steel sphere, all in stainless steel. The perimeter flat, which allows access for maintenance, is supported by groups of 'cigar' columns, turned from a glulam block of white oak. The glazing panels are supported on a subsidiary diagonal grid of tensioned metal rods.

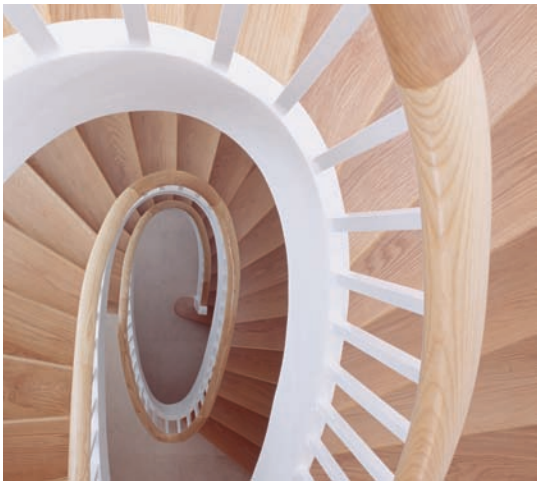


Photographs © Arup/Peter Ross

Award-winning projects

Right: Flame staircase, London
Using American ash (handrail) and American white oak (stair treads).
Joinery: E A Higginson, London.
HEAT Architects.
Engineer: NRM Consultants.

Far right: Hounslow East Tube Station, London.
The 'cigar' columns are formed from American white oak.
Acanthus Lawrence Architects.
Engineer: Buro Happold.



Left: Spiral staircase in American red oak, Cornwall, UK.
Designed and built by Devoran Joinery, Truro, UK.

Right: Haberdashers' Hall, London.
American white oak is used throughout. The ceiling diagonals are the top chords of the steel-tied roof trusses (see also back cover).
Hopkins Architects.
Engineer: Arup.

Far left: Queen's Building, Emmanuel College Cambridge, UK.
The roof trusses use American white oak.
Hopkins Architects.
Engineer: Buro Happold.

Left: New Heart for Bow Community Centre at St. Paul's Church, Bow, London.
Tulipwood cladding.
Matthew Lloyd Architects LLP.
Engineer: Price & Myers.

Photographs courtesy of The Wood Awards

Test procedure

Summary of the procedure for the derivation of strength and stiffness properties

The work was carried out by BRE at their Garston UK laboratories during 2001. There are three parts to the basic procedure, which were carried out for each of the four species:

- visual inspection of a large amount of timber, to establish the range and quality of material supplied commercially, and to select representative samples for testing
- the testing of the selected samples
- the derivation of strength and stiffness properties from the results of the tests.

Inspection and selection

Up to 1000 pieces of each species were examined in the yards of large suppliers. This established the general range of material available, and the variation within the supply. The aim was to assess timbers in relation to the grading rules of BS 5756, the UK hardwood grading standard.

Currently, no single visual grading standard is accepted throughout Europe. However, EN 518 sets criteria for grading standards in terms of measurable parameters, and BS 5756 complies with these requirements.

The temperate hardwood rules define two grades, of which the upper grade, TH1, is more appropriate to the generally high quality of the supply. It is important to select a grade which is set at a level which maximises the material properties, but which does not result in unacceptably high reject rates. The yield rates for the four species are given in Tables 1-4 on pages 9-12. These yields are for the whole of the material inspected for each species and not just for the material selected for testing.

During the inspection process, boards were selected to provide test specimens. These were chosen to represent the population as a whole, and to include pieces at the grade boundary, that is, containing defects which were close to the maximum values allowed by the grade rules. A total of 240 sample pieces were selected for testing from each species.

Testing

The tests were carried out in accordance with EN 408. In all, some 240 samples of each species were tested to determine moisture content, bending strength, modulus of elasticity and density, grouped into two samples of 120 pieces, differing in cross-sectional dimensions and geographical location.

The derivation of strength and stiffness properties

The basic data from the tests was subject to adjustment in accordance with EN 384 to the reference depth and moisture content. From these, characteristic values for density, bending strength and mean modulus of elasticity parallel to the grain, were calculated for each species. The additional properties, calculated again in accordance with EN 384, gave the full set of characteristic values listed under each species in Tables 1-4 of this publication.

The characteristic values are for use when designing in accordance with EN 1995, the timber Eurocode, which is in limit state format.

Until about 2009, EN 1995 will run in parallel with the existing National codes. The present UK code, BS 5268, is a permissible stress code, and so grade stresses and moduli for use with this code have also been calculated and included in Tables 1-4.

Standards and references

EN 1990	Eurocode - Basis of structural design
EN 1991	Eurocode 1: Basis of design and actions on structures
EN 1995	Eurocode 5: Design of timber structures
EN 338	Structural timber - Strength classes
EN 350-2	Durability of wood and wood-based products - Natural durability of solid wood - Part 2: Guide to the natural durability and treatability of selected wood species of importance in Europe
EN 384	Structural timber - Determination of characteristic values of mechanical properties and density
EN 408	Timber structures - Structural timber and glued laminated timber - Determination of some physical and mechanical properties
EN 518	Structural timber - Grading - Requirements for visual strength grading standards (shortly to be replaced by EN 14081-1 Timber structures - Strength graded structural timber with rectangular cross section - Part 1: General requirements)
EN 1194	Timber structures - Glued laminated timber - Strength classes and determination of characteristic values
BS 5268	Structural use of timber
BS 5756	Specification for Visual strength grading of hardwood

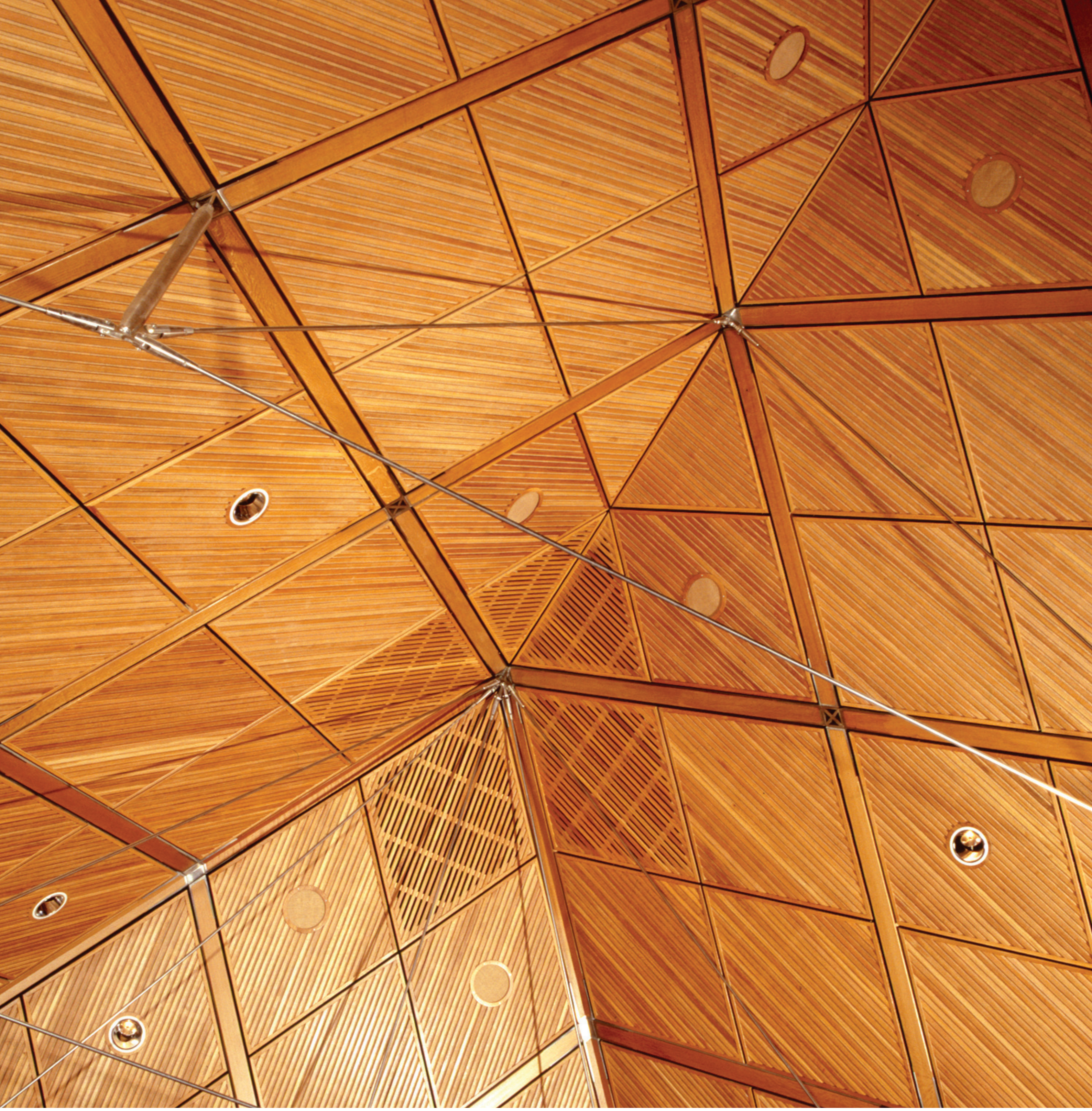
The Illustrated Guide to American Lumber Grades, published by AHEC

Guide to American Hardwoods - Species, published by AHEC

American Beauties, published by AHEC

Hardwood References, published by AHEC

Handbook of Hardwoods, published by BRE,
Centre for Timber Technology and Construction
ISBN: 1860814107



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