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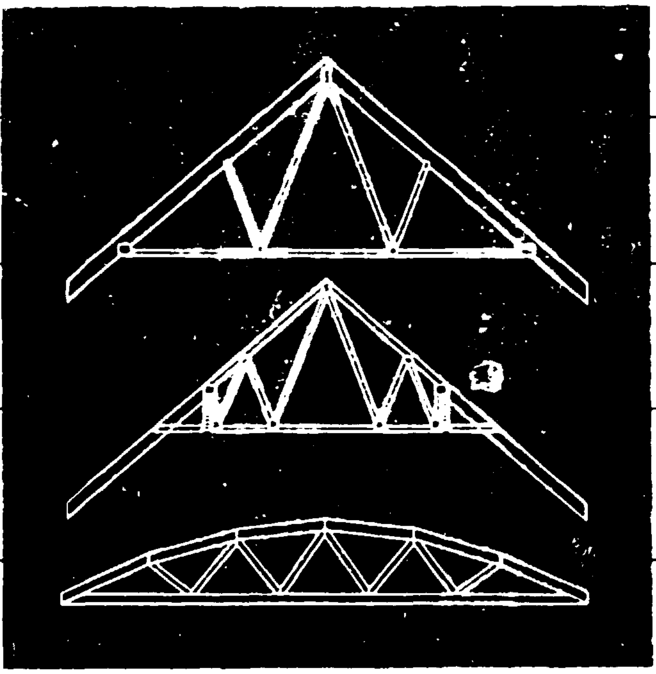
Timber Construction for Developing Countries



UNITED NATIONS INDUSTRIAL DEVELOPMENT ORGANIZATION

General Studies Series

TIMBER CONSTRUCTION FOR DEVELOPING COUNTRIES

Introduction to Wood and Timber Engineering

UNITED NATIONS INDUSTRIAL DEVELOPMENT ORGANIZATION
Vienna, 1995

ID/SER.O/6

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Explanatory notes

The term "billion" signifies a thousand million.

References to tonnes are to metric tons.

The following technical abbreviations are used:

DBT	dry bulb temperature
EMC	equilibrium moisture content
FSP	fibre saturation point
LP	limit of proportionality
MC	moisture content
MOE	modulus of elasticity
MOR	modulus of rupture

Abbreviations of standards institutes and other organizations:

ASTM	American Society for Testing Materials
CSIRO	Commonwealth Scientific and Industrial Research Organization
SAA	Standards Association of Australia

PREFACE

Whether grown in a particular country or not, wood is a virtually universal material that is familiar to people all over the world. It is used for many purposes but principally for construction, furniture, packaging and other specialized uses such as transmission poles, railway ties, matches and household articles. The United Nations Industrial Development Organization (UNIDO), which was established in 1967 to assist developing countries in their efforts to industrialize, has the responsibility within the United Nations system for assisting in the development of secondary woodworking industries and has carried out this responsibility since its inception at the national, regional and interregional levels by means of projects both large and small. UNIDO also assists by preparing manuals on topics that are common to the woodworking sectors of most countries.*

The lectures presented at the Timber Engineering Workshop (TEW), held from 2 to 20 May 1983 at Melbourne, Australia, are part of the continuing efforts of UNIDO to help engineers and specifiers appreciate the role that wood can play as a structural material. Collected in the form of 38 chapters, these lectures have been entitled Timber Engineering for Developing Countries, which forms part of the General Studies Series. Six of the chapters make up the first volume of this collection, Introduction to Wood and Timber Engineering. The TEW was organized by UNIDO with the co-operation of the Commonwealth Scientific and Industrial Research Organization (CSIRO) and was funded by a contribution made under the Australian Government's vote of aid to the United Nations Industrial Development Fund. Administrative support was provided by the Department of Industry and Commerce of the Australian Government. The remaining lectures (chapters), which cover a wide range of subjects, including case studies, are contained in four additional volumes, as shown in the table of contents.

Following the pattern established for other specialized technical training courses in this sector, notably the course on furniture and joinery and that on criteria for the selection of woodworking machinery,** the lectures were complemented by visits to sites and factories, discussion sessions and work assignments carried out by small groups of participants.

It is hoped that the publication of these lectures will lead to the greater use of timber as a structural material to help satisfy the tremendous need in the developing countries for domestic, agricultural, industrial and commercial buildings and for structures such as bridges. It is also hoped that the lectures will be of use to teachers in training institutes as well as to engineers and architects in public and private practice.

Readers should note that the examples cited often reflect Australian conditions and thus may not be wholly applicable to developing countries,

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*These activities are described more fully in the booklet UNIDO for Industrialization: Wood Processing and Wood Products (PI/78).

**The lectures for these two courses were collected and published as Furniture and Joinery Industries for Developing Countries (United Nations publication, Sales No. E.88.III.E.7) and Technical Criteria for the Selection of Woodworking Machines (UNIDO publication, Sales No. 92.1.E).

despite the widespread use of the Australian timber stress grading and strength grouping systems and despite the wide range of conditions encountered on the Australian subcontinent. Moreover, it must be remembered that some of the technology that is mentioned as having been new at the time of writing (1983) may since then have been further developed Similarly, standards and grading systems that were just being developed or introduced at that time have now become accepted. Readers should also note that the lectures were usually complemented by slides and other visual aids and by informal comments by the lecturer, which gave added depth of coverage.

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*For the reader's convenience the contents of the four complementary volumes are also given here.

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INTRODUCTION

Many developing countries are fortunate in having good resources of timber, but virtually all countries make considerable use of wood and wood products, whether home-grown or imported, for housing and other buildings, in both structural and non-structural applications, as well as for furniture and cabinet work and specialized uses. Although wood is a familiar material, it is all too often misunderstood or not fully appreciated since it exists in a great variety of types and qualities.

Some species, such as teak, oak and pine, are well known almost everywhere while others, such as beech, eucalyptus, acacia, mahogany and rosewood, are known primarily in particular regions. Still others, notably the merantis, lauans and keruing, which come from South-East Asia, have only recently been introduced to widespread use. Very many more species exist and are known locally and usually used to good purpose by those in the business. Also, plantations are now providing an increasing volume of wood.

The use of timber for construction is not new and, in fact, has a very long tradition. In many countries this tradition has unfortunately given way to the use of other materials - notably, concrete, steel and brick - whose large industries have successfully supported the development of design information and the teaching of methods for engineering them. This has not been so much the case for timber, despite considerable efforts by some research and development institutions in countries where timber and timber-framed construction have maintained a strong position. Usually the building methods are based on only a few well-known coniferous (softwood) species and a limited number of standard sizes and grades. For these, ample design aids exist, and relatively few problems are encountered by the very many builders involved.

Recent developments in computer-aided design and in factory-made components and fully prefabricated houses have led to better quality control and a decreased risk of site problems. Other modern timber engineering developments have enabled timber to be used with increasing confidence for an ever wider range of structures. This has been especially so in North America, Western Europe, Australia and New Zealand.

UNIDO feels that an important means of transferring this technology is the organization of specialized training courses that introduce engineers, architects and specifiers to the subject and draw their attention to the advantages of wood, as well as its disadvantages and potential problem areas, and also to reference sources. In this way, for particular projects or structures, wood will be fairly considered in competition with other materials and used when appropriate. Comparative costs, aesthetic considerations and tradition must naturally be taken into account in the context of each country and project, but it is hoped that the publication of these lectures will lead those involved to a rational approach to the use of wood in construction and remove some of the misunderstandings and misapprehensions all too often associated with this ancient yet modern material.

I. FOREST PRODUCTS RESOURCES

W. E. Hillis*

About one third of the earth's land surface enjoys conditions that are suitable for the growth of forests, and it is these same conditions that are usually also the most suitable for habitation. From the beginning, therefore, humans have been continually converting forests to other uses; only recently, however, has this conversion rate become significant. Large areas of forest have been removed in the temperate regions, but that situation has stabilized and the forests continue to satisfy a significant portion of local needs. Now, the removal of forests is accelerating in tropical and subtropical regions, where the population is increasing rapidly. These latter regions have provided and can continue to provide timber for local use and for export, but the properties of their timber species are different from those of temperate region species.

Forests provide both materials and energy. Over half of the wood felled globally is used for fuel. In some countries, the proportion is over 90 per cent, and the rapid consumption of trees is leading to the denudation of the soil and other changes. More than 1.3 billion people are reportedly suffering from an acute scarcity or deficit of fuelwood; by the year 2000, the number of people thus affected will increase to 3 billion. There is an estimated need for around 3 billion m^3 of fuelwood and an estimated shortfall of nearly 1 billion m^3 annually.

Forest products are the third most important commodity, by weight, in the United States and are a major commodity in all countries. Their processing consumes less energy than that of other materials; they are also less polluting and more renewable than other materials. The demand for forest products is likely to increase as attempts are made to replace materials that require large amounts of energy, that are non-renewable and that cause pollution.

World production of wood per capital peaked in 1976 at 0.67 m^3 and has steadily declined since then to less than 0.60 m^3, so that attention must be paid to the amount of resources available.

The recent publication by the Food and Agriculture Organization of the United Nations (FAO) of its forestry papers Nos. 29 (1) and 30 (2) marked a considerable advance in the availability of comprehensive information. Those papers point to the difficulty of gaining accurate, comparable data from complex situations and advise caution in dealing with their detailed figures. Since many of the data presented in the present paper are taken from the FAO papers, similar caution is necessary in the use of the data for some countries. Some of the discrepancies between figures may be due to the policy of the FAO team, in paper No. 29, to force a balance between consumption and supply in global terms, for the reason that a shortage of forest products would raise the price, which would in turn reduce demand.

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*Officer of CSIRO, Division of Chemical and Wood Technology, Melbourne.

Consumption in 1980, 1990 (projection) and 2000 (projection) of industrial wood products by the major regions is given in table 1, and the estimated demand for wood to make those products is given in table 2. The total estimated demand may be too high because residuals from the sawlog estimates are used in varying amounts to provide some of the needs for fibre. Nevertheless, some observers have estimated even higher demands for the year 2000. It is unlikely that current forest resources can provide, on a sustained basis, the higher estimates of global needs for forest products in the year 2000.

The availability of forest products differs from region to region (table 3), and international trade has been able, in the past, to meet demands. The needs will be greater in the year 2000 (table 4). The proportion of the supply of industrial softwood and hardwood from different regions is given in table 5.

Table 1. Consumption of industrial wood products

	Product								
	Sawnwood (million m^3)			Wood-based panels (million m^3)			Paper (million tonnes)		
Region	1980	1990	2000	1980	1990	2000	1980	1990	2000
World	455	520	570	109	141	169	180	256	357
Developed market economies	246	271	284	84	106	122	139	189	253
North America	118	129	133	41	50	55	70	92	120
Western Europe	74	81	86	30	40	49	46	61	79
Oceania	7	7	8	1	2	2	3	4	6
Other	47	54	57	11	14	16	20	32	48
Developing market economies	46	69	90	6	11	18	17	29	53
Latin America	17	22	27	3	5	8	9	15	26
Africa	5	6	10	1	2	3	2	3	4
Near East	6	8	9	1	2	3	2	5	11
Far East	18	33	45	1	2	4	5	8	13
Centrally planned economies	163	181	199	19	24	30	24	37	56
USSR, E. Europe	141	154	167	17	21	26	17	25	39
Asia	22	28	32	2	3	4	7	12	17

Source: FAO Forestry Paper, No. 29, 1982.

Table 2. Estimated demand for wood to supply industrial wood products
(Millions of cubic metres) a/

	Product											
	Sawnwood			Wood-based panels			Paper			Total		
Region	1980	1990	2000	1980	1990	2000	1980	1990	2000	1980	1990	2000
World	864	988	1 083	174	226	270	504	717	1 000	1 542	1 931	2 353
Developed market economies	467	515	540	134	170	195	389	529	708	990	1 214	1 443
North America	224	245	253	66	80	88	196	258	336	486	583	677
Western Europe	141	154	163	48	64	78	120	171	221	309	389	462
Oceania	13	13	15	2	3	3	8	11	17	23	27	35
Other	89	103	108	18	22	26	56	90	134	163	215	268
Developing market economies	87	131	171	10	18	29	48	81	148	145	230	348
Latin America	32	42	51	5	8	13	25	42	73	62	92	137
Africa	9	11	19	2	3	5	6	8	11	17	22	35
Near East	11	15	17	2	3	5	6	14	31	19	32	53
Far East	34	63	85	2	3	6	14	22	36	50	88	127
Centrally planned economies	310	344	378	30	38	48	67	104	157	407	486	583
USSR, E. Europe	268	292	317	27	34	42	48	70	109	343	396	468
Asia	42	53	61	3	5	6	20	34	48	51	92	115

Source: Calculated from data in FAO Forestry Paper, No. 29, 1982.

a/ Roundwood equivalent.

Table 3. Forest resources and utilization, 1974-1976

	Forest area in 1975 (millions of ha)		Apparent annual consumption (millions of m^3)		Net trade a/ (millions of m^3)		
Region	Closed forest	Other woodland	Industrial roundwood for processing b/	Forest products c/	Industrial roundwood	Processed wood c/	Total c/
World	2 860	1 070	1 185	1 185			
Developed market economies	693	243	732	763	-44	-31	-75
North America	510	120	412	390	+22	+22	+44
Western Europe	109	18	208	250	-18	-42	-60
Oceania	50	100	17	18	+3	-1	+2
Japan	25	-	86	95	-50	-9	-59
Other	-	5	9	10	-1	-1	-2
Developing market economies	1 222	642	109	100	+32	+9	+41
Africa	203	360	10	12	+5	-	+5
Latin America	695	180	47	47	-	-	-
Far East	310	35	46	32	+27	+14	+41
Near East	14	67	6	12	-	-6	-6
Centrally planned economies	945	185	344	322	+12	+22	+34
USSR, E. Europe	815	135	287	265	+12	+22	+34
Asia	130	50	57	57	-	-	-

Source: Adapted from FAO Forestry Paper, No. 29, 1982.

a/ Imports denoted by a minus sign, exports by a plus sign.

b/ Includes, in addition to wood for processing, roughly 10 per cent of miscellaneous industrial wood, e.g. pitprops, poles, pilings normally used in the round; more than half is consumed in centrally planned economies.

c/ In roundwood equivalent.

Table 4. Estimates of wood removals and utilization in the year 2000
(Millions of cubic metres)

Region	Removal of industrial wood	Apparent consumption		Net trade a/		
		Industrial roundwood for processing	Forest products b/	Industrial roundwood	Processed wood c/	Total b/
World	2 085	1 930	1 930	-	-	-
Developed market economies	1 093	1 138	1 190	-78	-52	-130
North America	642	617	581	+10	+36	+48
Western Europe	320	325	384	-16	-59	-75
Oceania	58	41	30	+16	+11	+27
Japan	58	143	175	-86	-32	-118
Other	15	12	20	-2	-8	-10
Developing market economies	365	274	238	+44	+36	+80
Africa	60	28	21	+10	+7	+17
Latin America	124	108	98	+5	+10	+15
Far East	161	128	96	+29	+32	+61
Near East	20	10	23	-	-13	-13
Centrally planned economies	627	518	502	+34	+16	+50
USSR, E. Europe	531	444	428	+34	+16	+50
Asia	96	74	74	-	-	-

Source: FAO Forestry Paper, No. 29, 1982.

a/ Imports denoted by a minus sign, exports by a plus sign.

b/ In roundwood equivalent.

Table 5. Supply outlook for industrial roundwood from different regions

Supply	Softwood		Hardwood	
	1980	2000	1980	2000
	Percentage			
Proportion supplied by:				
North America	38.8	34.2	23.0	24.0
Western Europe	17.7	16.4	16.0	14.0
Japan	2.5	3.5	3.0	1.0
Latin America	2.2	4.4	7.0	9.0
Asia, Africa, Oceania	2.5	5.0	30.0	35.0
Centrally planned economies	36.3	36.3	21.0	17.0
	Millions of cubic metres			
Interregional shipments				
Sawlogs	22.7	32.3	24.8	18.8
Pulpwood	18.6	28.0	6.7	24.4

Source: FAO Forestry Paper, No. 29, 1982.

A number of claims have been made for the potentially large "wood baskets" in tropical countries. However, many of the soils of these forests are thin and of low fertility, so that regeneration of the forests after harvest will be slow, and they are in that sense non-renewable. Decisions to remove trees will need to be carefully made. Also, the areas of productive forests are much less than expected. In 1980 there were in the tropical regions about 1.2 billion hectares of closed forest (97 per cent hardwoods) but only 670 million hectares of productive closed forests over 60 years of age (considered to be the minimum harvesting age), untouched and accessible for use. Few of the forests have reliable inventories, let alone management plans, so that the availablity of forest products is uncertain. Less than 15 thousand billion m^3 total growing stock exists in the productive closed forests, and their growth rates are mainly less than 2 m^3/ha/yr (table 6). The productivity of these forests is very low (table 7).

Table 6. Estimated total growing stock of closed forests
(broad-leaved and coniferous), end 1980
(Billions of cubic metres)

Location of tropical region	Productive			
	Unmanaged			
	Undisturbed	Logged	Managed	Total
North and South America (23 countries)	71.3	7.2	0.02	78.6
Africa (37 countries)	30.3	8.2	0.2	38.8
Asia (16 countries)	21.2	6.6	3.6	31.4
Total (76 countries)	123.0	22.0	3.8	149.0

Source: Adapted from FAO Forestry Paper, No. 30, 1982.

Table 7. Average annual production of sawlogs and veneer logs per hectare of productive closed forest, 1976-1979
(Cubic metres per hectare per year)

Location of tropical region	Closed broad-leaved productive forests	Productive coniferous forests	Closed broad-leaved and coniferous forests
Tropical North and South America (23 countries)	0.04	0.62	0.06
Tropical Africa (37 countries)	0 09	0.26	0.10
Tropical Asia (15 countries)	0.38	0.49	0.39
All the 75 countries	0.18	0.58	0.14
Europe without the USSR (25 countries)	0.62	1.40	1.08

Source: FAO Forestry Paper, No. 30, 1982.

Even when they are accessible for harvesting, few trees of the secondary tropical species yield logs of a shape or size suitable for economic conversion to solid wood products. Furthermore, big losses in recovery can result from poor wood quality, which takes a number of forms: decayed or discoloured wood; reaction wood, brittle heart and wood of very high and very low densities; the rapid deterioration of fallen logs in tropical climates; abrasive woods; and great variability within and between logs. Quality is, moreover, poorer in partly utilized forests. Lumber from secondary species also faces the problems inherent in marketing material of unfamiliar and variable properties and in meeting international standards that were formulated with reference to familiar species from temperate climates. All these obstacles result in the current wastages.

Tropical America has 68 per cent of the world's undisturbed productive closed broad-leaved forests (tropical South America accounts for 65 per cent, mainly in the Amazon Basin), and tropical Africa has 18 per cent; tropical Asia, with its huge population, has only 14 per cent. It has been estimated that the average annual production of industrial wood from tropical countries in the 1983-1987 period will be 215 million m^3, with 37.5 per cent coming from the western hemisphere, 24.1 per cent from Africa and 51.2 per cent from Asia.

Renewal of these forests is rapidly falling behind deforestation (table 8). While high growth rates exceeding 35 m^3/ha/yr have been achieved in some of the new plantations, the quality of the wood from these sources will differ from that obtained from slow-grown trees of the same species. In time, however, wood of superior quality should be obtained.

Table 8. Annual rates of deforestation and plantation, 1981-1985
(Millions of hectares)

Location of tropical region	Annual rate of deforestation Closed formation	 Open formation	 Total	Annual rate of plantation	Plantation: deforestation ratio
America	4.3	1.2	5.6	0.5	1:10.5
Africa	1.3	2.3	3.7	0.1	1:29
Asia	1.8	0.2	2.0	0.4	1:4.5
Total	7.5	3.8	11.3	1.1	1:10

Source: Adapted from FAO Forestry Paper, No. 30, 1982.

The need for forests and their products depends on population. The world's population of about 4 billion in 1975 was mainly in the Asian-Pacific region (about 56 per cent), followed by Europe (14 per cent), Africa (10.5 per cent), South America (7 per cent), the Union of Soviet Socialist Republics (6.7 per cent) and North America (6.3 per cent). It has been estimated that the world's population will grow to more than 6 billion by the year 2000 and to 10 billion by 2030. About 90 per cent of the population increase will take place in the poorest tropical regions, where half the global forests exist, mainly in Africa, followed by South America and then Asia (table 9).

The other major reserve of forest products is in the Union of Soviet Socialist Republics, which is the largest producer and consumer of softwood lumber and has timber reserves exceeding 75 billion m^3 with an annual increment of 575 million m^3. Most of this is in the taiga regions of Siberia and the eastern USSR, which contain an estimated 70 per cent of the world's conifers. These vast resources, which are being harvested at well over 1 million ha/yr, suffer from very slow growth rates, difficulties in regeneration, poor accessibility (for about 36 per cent of the area) and remoteness. Currently, more than 300 million m^3 of industrial wood are cut annually, mainly in the Ural region. The established plantations cover an area of 5.2 million ha, are being increased at a rate of 800,000-900,000 ha/yr and are being managed on 80- to 100-year rotations. The USSR plans to supply 447 million m^3 of industrial wood from all its resources in the year 2000.

Some tentative estimates of supplies available in other regions are given in table 10.

It is expected that the demand for softwood sawlogs will increase 1.2 per cent annually between 1980 and 2000. Supplies to meet the projected growth from 676 to 862 million m^3 in 2000 should be adequate, but they are expected to be tight in the developed economies. The demand for softwood pulpwood is projected to increase 2.3 per cent annually. Consequently the output of both softwood sawlogs and pulpwood is expected to be stretched close to their physical supply limits by 2000.

Table 9. Forest area and population in the tropical regions and subregions, 1980

Sub-region/region	Total area (millions of ha)	Tree cover (%)	Total population			Agricultural population	
			Total people (millions)	No. of people/ha of tree area	Rate of annual growth 1975-1980 (%)	Total people (millions)	Rate of annual growth 1975-1980 (%)
Tropical America							
Central America and Mexico	247	27	92.6	1.38	3.31	36.6	1.31
CARICOM	25	79	4.4	0.22	1.54	0.9	-1.26
Other Caribbean	45	59	22.2	0.84	1.95	9.6	0.69
Tropical South America	1 362	57	202.6	0.26	2.84	73.2	0.81
Subtotal	1 680	53	321.8	0.36	2.89	120.3	0.93
Tropical Africa							
Northern savanna region	424	10	29.6	0.68	2.65	24.5	1.99
West Africa	212	26	113.8	2.04	3.19	64.9	1.81
Central Africa	533	63	48.0	0.14	2.60	35.1	1.88
East Africa and Madagascar	881	25	149.7	0.69	2.95	116.1	2.23
Tropical southern Africa	140	36	1.8	0.04	2.81	1.2	1.68
Subtotal	2 189	32	343.5	0.49	2.95	241.7	2.09
Tropical Asia							
South Asia	449	15	895.4	13.45	2.46	580.4	1.57
Continental South-East Asia	119	40	83.0	1.75	2.71	54.2	1.84
Insular South-East Asia	225	58	216.8	1.47	2.55	119.4	1.22
Centrally planned tropical Asia	75	48	64.9	1.78	2.28	46.2	1.49
Papua New Guinea	46	83	3.0	0.08	2.54	2.5	2.08
Subtotal	945	36	1 263.2	3.75	2.43	802.8	1.53
Total 76 countries	4 814	40	1 928.5	1.00	2.63	1 164.9	1.58

Source: *FAO Forestry Paper*, No. 30, 1982.

Table 10. Estimates of annual supply and growing stock
(Millions of cubic metres)

	Supply			
Region/country	Softwood/ hardwood	1980	2000	Comments
Brazil	S	5.7	32	
	H	24	-	
Canada	S	168 a/	217 a/	Growing stock 18 billion m^3
	H	21 a/	21 a/	
Chile	S	4.1	25	
China	-	-	-	Growing stock 4.6 to 7 billion m^3
Eastern Europe	S	-	55	
	H	-	36	Growing stock 3.9 billion m^3; increment 120 million m^3/yr in 2000
Far East	S	5	23	
	H	102	169	Large resources
Japan	-	55 a/	58 a/	
Latin America	S	27.4	71.3	Growing stock 100 billion m^3
	H	32	62	3.5 million m^3 plantations in 1980
Mexico	S	-	4.0	
Northern Africa and Middle East	-	9	17	
North America	-	-	-	Growing stock 38 billion m^3
Oceania	S	14 a/	38 a/	Will export 6.6 million m^3 in 2000
	H	12	20	
Sub-Saharan Africa	S	6.3	13	
	H	34	57	Large resources
USSR	-	-	447	Growing stock 75 billion m^3; increment 575 million m^3/yr
United States	S	267 a/	317 a/	Growing stock 20 billion m^3
	H	88	142 a/	
Western Europe	-	300 a/	387 a/	Growing stock 11.6 billion m^3 in 2000; increment 361 million m^3/yr

a/ Including residuals.

The world's consumption of industrial wood from hardwoods is expected to rise from 443 million m^3 to 673 million m^3 in 2000, or at a rate of 2.1 per cent annually; more than half of this will be for pulp preparation. It is expected there will be insufficient residuals to meet the demands for reconstituted boards.

In the absence of widespread disasters such as disease, insect attack and fire, there appear to be sufficient supplies to meet global needs in the year 2000, although some regional supplies will be inadequate. Beyond that time, the supplies of forest products for materials and fuel for different regions will become increasingly inadequate. Alternative materials are likely to be more costly. Accordingly, in view of the long growth period required for trees, greater efforts to increase the area and yield of forests and plantations for the sustained supply of wood are now needed. Furthermore, increased attention must be given to improving the conversion yields of wood from trees and to the efficiency of the use of wood in various applications.

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1. Food and Agriculture Organization of the United Nations, "World forest products; demand and supply 1990 and 2000", Forestry Paper, No. 29, 1982.

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II. TIMBER ENGINEERING AND ITS APPLICATIONS IN DEVELOPING COUNTRIES

John G. Stokes*

For many centuries wood was the structural material most widely used throughout the world, and it was used because it was available, was understood and could be easily worked. Additionally, there were no other options in many applications. Then, however, the onset of the Industrial Revolution in the developed world brought with it the increasing availability of wrought iron and, later, steel sections, and engineers were quick to devise effective ways of fastening these sections together.

Firstly bolts then rivets enabled iron bridges and tall steel buildings to be safely built. The evolution of welding brought an even more effective and predictable fastening system that appealed to engineers and enabled the design process to move from empirical data to a precise and predictable engineering basis. Likewise, reinforced concrete developed rapidly as a predictable material of construction to which similar methods of engineering design could be applied.

This was not so for wood, however, and while thousands of wooden bridges and buildings were still erected, engineers tended to move away from wood as a structural material, using it in the main for temporary structures, form-work and domestic houses of a permanent nature. The first reason for this shift in use was that the behaviour of wood is predictable to a degree that will satisfy knowledgeable engineers only when the wood is well sawn to a standard size; is free of such faults as would cause its strength to fall below agreed limits; is at or below a predetermined and agreed moisture content; and is of a known species or an agreed group of species whose characteristics are known, and, if not resistant to insect and fungal attack, has been treated to ensure an adequate structural life.

Wood has numerous virtues, many of which were well known to mediaeval timber engineers and their successors in the western world and to the ancient craftsmen of Asia and the Americas. Hence we have seen wood in the form of poles, piles and beams used as a material for round structures. Even today, excellent traditional houses can be seen in Borneo, Thailand, Laos, Cambodia, Polynesia and Micronesia, of which the main frame is based on poles or bamboos used in a most effective fashion. Likewise, some innovative architects in Australia, New Zealand and North America have built elegant and attractive houses based on treated softwood poles. Pole barns are widely and effectively built and used on farms in North America and, to a lesser extent, elsewhere.

Wood can be readily worked. It can be sawn, split, hewn, adzed, nailed, dowelled, screwed, carved, drilled, routed, planed, shaped, sanded, bent, finger-jointed, laminated, spliced and peeled. It can be changed and reconstituted by means of chemical preservatives or fire retardants, and it can be densified and impregnated with resins.

Likewise, it can be exploded or abraded into its constituent fibres and then reconstituted as hardboard or chip board or paper. It can be ground into explosive wood flour or mechanically converted into wood wool or chips or flakes, which, in turn, can be rebuilt into panel products using glue or cement as a bonding agent.

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From all of these elements, a vast family of building materials, papers and cardboards are reconstituted. Despite having all these virtues, however, wood lost ground as a structural material, and a number of factors were involved.

Many ambitious wooden bridge structures failed during the nineteenth century because of the lack of adequate fastening devices; the lack of a clear understanding of certain engineering fundamentals particularly important in timber engineering; and the lack of stress-grading facilities. These complicating factors were obviated by the use of iron and steel sections, which, within certain limits, did what they were expected to do and hence were attractive to engineers. Reinforced concrete quickly also showed itself to be reasonably predictable, providing that many criteria, some of them hard to achieve, were met. With wood, the criteria have been met only in the last two decades, and reliable, stress-graded, predictable wood sections are now available today throughout the developed world.

Another reason for the shift away from wood was that fastening systems for wood did not keep pace with those for steel. There was no way of welding wood until something akin to this was invented in the late 1950s. The first improved joint for wood was the Teco split ring connector, which was developed in the early part of the twentieth century. This was followed by the development of finger joints in the United States and Germany in the 1950s; finger joints revolutionized the glulam industry and are now used in the manufacture of trusses both as members and as a means of jointing trusses.

Improved glues emerged in the Second World War: the successful Mosquito fighter-bomber was a glued wood structure that reliably achieved design strength and life. While properly glued joints are equal to welded joints, the technical problems of mass-producing glued structural joints have not yet been conquered. A case in point is the concept of producing a custom truss using finger joints at the panel points. This is being done in parallel chord trusses for concrete form-work but has not been mastered for custom-built house trusses of varying pitch and profile.

Glue-laminated structures in wood, which became increasingly common and accepted after the Second World War, were made possible by the rapid improvement in glues and gluing techniques and in techniques for drying wood to allowable moisture contents without significant distortion. However, the not-so-favourable economics of glulam construction in most countries outside North America has slowed the widespread use of glulam despite its predictability and aesthetic attractions. Nevertheless, there has been an impressive expansion in the use of stock glulam beams in Australia and New Zealand and in Europe, where the material's high strength, predictability and aesthetic appeal are winning favour. Here in Australia, the CSIRO and the New South Wales Forestry Department's Division of Wood Technology in Sydney have contributed significantly to the successful growth of the market for engineered timber products, and their work in this field is world renowned.

If asked to define timber engineering, most people in the industry would say it is that segment of wood technology comprising the research, design, fabrication and erection of wood structures, whether the end use is a chair, a beam, a bridge or a roof structure.

It is becoming increasingly evident that today's timber engineer can no longer be only a researcher or a designer or a production person, for he or she lives and works in an environment where cost is a vital factor and alternative materials are constantly being developed. Thus, the timber engineer must have not only technical knowledge and abilities but also a strong commercial outlook that takes into account the many constraints of the real world. There must be an in-depth understanding of the materials and a keen sense of quality consciousness consistent with the clear knowledge that the end product, be it a table or a wooden bridge or a wall frame, must be slender, strong and economically affordable. The latter criterion is of particular significance in the developing world.

Before the details of timber engineering are discussed, the material itself and its production should be examined. In the presence of so many wood scientists and experts it would be presumptuous to expound forest technology, which has made enormous gains, nor will such subjects as the production and harvesting of genetically superior trees to produce more and better wood be dealt with.

Suffice it to say that trees are grown either in plantations or through programmes of regeneration of natural forests and that today bigger and better yields of wood are achievable. Virgin forests are rare and are now largely preserved as national parks, whereas operational forests are largely planted or regenerated.

It is of interest to note that the tree itself is a structure in wood and hence a fine example of timber engineering. Resilient and capable of resisting most storms and earthquakes, trees are the great survivors of this world, with living examples dating back before the times of Christ, Buddha and Muhammad.

Within a species, trees vary depending upon genetic background, soil type, rainfall and the location in which they are grown. The author remembers that, years ago, in the West Australian timber industry, orders were received from time to time for 60-ft (19.7 m) long keels for pearling luggers. The specification often read as follows: "12 in. x 8 in. x 60 ft ridge-grown quartersawn Jarrah, free of heart, bark and wane, the piece to be free of spring and bow". This specification could not be achieved today and was difficult to achieve 35 years ago. It is mentioned out of general interest and also in light of the earlier reference to variability between trees of a single species. It shows that, based on experience rather than research, builders of wooden boats knew that trees grown on exposed hills and ridges were more dense and, hence, stronger.

In timber engineering, the material is not a homogeneous one, as steel appears to be and as concrete is often thought to be, so that the successful development of mechanical stress grading for wood has been an important recent advance in timber engineering.

Later chapters will elaborate on what timber engineers have done to develop equipment that accurately and mechanically grades wood on a strength/stiffness basis. What will be emphasized in this paper is that timber engineering became a reliable science once ways and means of consistently drying it and then stress grading it had been developed. These innovations, coupled with methods of achieving improved durability, all paved the way for the introduction of improved gluing and fastening techniques and hence the rebirth of timber engineering.

Turning to the area that is of special interest to this workshop - the developing countries - the author does not think that glued structural joints will be of significance in these countries in the next decade. Frequent visits to many of these countries indicate that, whereas some advanced companies and government organizations are sawing and drying large quantities of wood with consistent precision for export markets in particular, most are not, and until there is major investment in kiln capacity and the local manufacture of glues, the use of glues for structural purposes outside of the plywood and particle board industry will not be significant.

There are many other timber engineering developments in the developed world, but few of them have immediate application possibilities in the developing countries. For example, factory mass-produced plywood and Microlam I-beams are excellent products but are volume-dependent and have not yet been developed using tropical hardwoods as the base material. Similarly, excellent I-beams are mass-produced in Sweden using long-fibred Masonite as a web in conjunction with kiln-dried softwood flanges.

Equipment has been developed in the United States and Sweden for the continuous assembly and gluing of truss joists of this type, but it will be more than a decade before this capital-intensive, volume-dependent engineered timber beam has a potential outside Europe and North America.

There are, however, some possibilities in the truss field for perforated structural nail-on plates with hand-applied nails hammered through the pre-punched holes in the plates. These so-called nail-on plates will be referred to in chapters XXXV and XXXVI. This is appropriate technology and is particularly applicable in remote villages, kampongs or barrios where a limited number of trusses are needed and transport is difficult or out of the question.

The disadvantages of nail-on plates are associated with the excessive area of steel that is necessary, owing to limitations on nail centres. Increased slip also occurs owing to the lack of fixity between the nail and the parent plate and to the frequent omission of nails by tired or careless workers, particularly towards the end of a gruelling day spent hammering, when concentration wavers and that elusive nail flies off into oblivion. Nail on plates, properly used, are, however, adequate for building shelter, particularly where small spans are involved.

Less susceptible to error than the nail-on plate is the grasshopper plate, in which the teeth are hinged from the parent plate and struck home by a hammer. Developed originally in the United States, grasshopper plates have been improved for use with New Zealand and Australian softwoods and, more recently, for use with tropical hardwoods. The only disadvantage of these connectors is that they are factory-produced and have to be transported from a producing centre to the point of use. This, however, must also be done with the steel for the local production of perforated nail-on plates. Additionally, because of the smaller centre distance between nails, less steel is used to make a grasshopper plate than to make a nail-on plate. This is a critical issue because heavily galvanized structural steel is expensive and is generally imported into most developing nations.

More efficient still is the multi-nail spiked connector plate, which has achieved by far the greatest success and has perhaps the greatest potential for the structural jointing of wood in the developing nations. Many kinds of truss plants have been set up, ranging from labour-intensive plants, each equipped with a cheap and very simple jig that uses a hand-rammer for the application of the connectors, to mass production plants that use a minimum of labour. Trusses made in this way have numerous advantages over hand-made nailed, bolted or nail-on trusses. Slip is minimal when the load is applied, trusses are identical owing to the use of production jigs, and performance can be guaranteed.

Even where labour is in surplus and inexpensive, such trusses have a relative cost advantage because of joint efficiency and speed of production, which cannot be ignored. In addition, spiked connectors are very efficient: with the nails rigidly connected to the parent plate, a much smaller area of steel is needed for the same loading.

Where desirable and the volume warrants, a joint venture within the developing nations to produce these connectors is generally the correct solution.

Structures made from these connectors range from farm gates and heavy-duty racks for the storage of steel, timber, pipes and so on, to roof trusses for agricultural, commercial and industrial buildings, with the latter being by far the biggest usage.

Stainless steel connectors are made for use in aggressive environments and marine environments, such as are encountered in plating works, fish co-operatives, acid plants, superphosphate and other fertilizer works, steam laundries and chemical plants. The unbeatable combination of rust-free stainless steel and corrosion-proof wood gives maintenance-free trusses of predictably high strength and long life.

Costs are all-important in today's competitive world, and recent studies in Malaysia have shown that spiked connector plated trusses are 15-30 per cent cheaper than similar bolted or hand-nailed trusses. For this reason, Malaysia's mass housing programmes utilize gang-nail trusses on a virtually exclusive basis. Mass usage is emerging in the USSR and Eastern European countries for agricultural buildings and in Mexico and South America for mass housing, frequently using green or air-dried wood, pressure-treated if necessary.

The splicing of long lengths of tile battens, purlins, girts and rafters from short lengths is finding rapid acceptance as a means of reducing waste and increasing recovery. This, too, is done with spiked connectors, appropriately sized.

Another important use of spiked connectors is to prevent the splitting of heavy wood sections such as logs, piles, poles, bridge and veneer flitches, wharf timbers and railway ties. For instance the application of a spiked connector to both ends of a railway tie has been shown to be the most effective and economic way of preventing splitting or of repairing an already split tie after the crack has been closed with a portable press.

In conclusion, it would be useful to examine the economics of the most commonly engineered timber structure in the developing world, namely, the domestic roof. Taking as an example the situation that prevailed in Malaysia in 1983, the cost of bolted timber trusses can be compared with that of gang-nail trusses of identical span and pitch. All costs are in ringgit ($M). For this comparison, profit has been excluded from both alternatives, i.e. totals are cost values.

Gang-nail trusses

- Cost of a gang-nail truss delivered to the site and lifted onto the roof by a crane. Timber quantity is 47.09 ft^3. Assuming 8 per cent wastage, timber quantity, including wastage is 50.86 ft^3, or 1.017 tonne. With treated timber at $M 410/tonne,

	$M	$M
Timber cost	417	
Gang-nail plates cost	187	
Fabrication	79	
Cartage	46	
Crane	35	
	764	764

- Cost of labour to erect trusses and install ancillary timber. With 11.0 squares required at $M 24/square,

Labour cost		264

- Cost of ancillary timber (assuming 15 per cent wastage on battens, 10 per cent on others)*

	$M	
Battens:		
2 in. x 2 in. x 1,100 FR x 1.15 = 35 ft^3 = 0.70 tonne at $M 380 =	267	
Wall plates:		
4 in. x 2 in. x 120 FR x 1.10 = 7.5 ft^3 = 0.15 tonne at $M 410 =	62	
Fascia board:		
10 in. x 1 in. x 102 FR x 1.10 = 7.8 ft^3 = 0.16 tonne at $M 540 =	85	
Mid-web tie:		
3 in. x 2 in. x 20 FR x 1.10 = 1.0 ft^3 = 0.02 tonne at $M 410 =	9	
	423	423
		1,451

The total cost of a gang-nail truss roof is, therefore, $M 1,451.

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*FR denotes running feet.

Bolted trusses

		$M
- Cost of timber. Timber quantity is 95.82 ft^3. Assuming 15 per cent wastage, timber quantity, including wastage is 110.19 ft^3, or 2.20 tonne. With treated timber at $M 410/tonne,		
Timber cost		904
- Cost of bolts and nuts, minimum 211 sets. With 250 sets required, allowing for wastage, at $M 0.70/set,		
Bolt and nut sets cost		175
- Cost of labour to fabricate and erect trusses and install ancillary timber. With 11.0 squares required at $M 35/square,		
Labour cost		385
- Cost of ancillary timber (assuming 15 per cent wastage on battens, 10 per cent on others)*		
Battens:	$M	
2 in. x 1 in. x 1,100 FR x 1.15 = 17.6 ft^3 = 0.35 tonne at $M 350 =	123	
Wall plates:		
4 in. x 2 in. x 120 FR x 1.10 = 7.5 ft^3 = 0.15 tonne at $M 410 =	62	
Fascia board:		
10 in. x 1 in. x 102 FR x 1.10 = 7.8 ft^3 = 0.16 tonne at $M 540 =	85	
Ridge board:		
6 in. x 2 in. x 10 FR x 1.10 = 1.0 ft^3 = 0.02 tonne at $M 470 =	10	
	280	280
		1,744

The total cost of a conventional roof is, therefore, $M 1,744.

The difference in cost of $M 293 represents a saving of 17 per cent with the gang-nail system.

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*FR denotes running feet.

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III. WOOD, THE MATERIAL

W. E. Hillis*

Introduction

Wood, unlike most other building materials, is a renewable material grown under a variety of conditions and obtained from a large number of species. As will be explained, wood is both chemically and physically heterogeneous, but with understanding it can be used at least as successfully as other materials in engineering structures.

Broadly speaking, woods are from two types of trees: (a) trees carrying needle-shaped leaves, such as the conifers, which yield the so-called softwoods and (b) broad-leaved trees, which yield the so-called hardwoods. The wood of the former is simple in structure and contains about 90 per cent or more fibres, with the remainder being the rays and a few other cell types. The wood of the latter is not always harder than the wood of the former, but it always contains a number of cell types, notably the vessels or pores, which are larger in diameter than the fibres.

A. The tree

The tree consists of three main parts: roots, stem or trunk and leaves. The roots anchor the tree in the ground and take in water and mineral salts from the soil. The trunk conducts these solutions from the roots to the leaves; it stores food materials and provides mechanical support to the branches and leaves. The leaves absorb carbon dioxide and, by means of the energy obtained from sunlight, synthesize the substances required for growth.

The trunk is the important part of the tree as far as the user of wood is concerned (figure 1). The outer covering of the trunk, the bark, protects the wood from extremes of temperature, fire and mechanical injury, and the inner layers of the bark translocate the food synthesized in the leaves to the regions of growth and of storage.

The cambium, a thin layer of tissue situated between the bark and the wood of the tree, forms a sheath covering the trunk and the branches. When the cambium is growing during the spring and summer or during the wet months, wood is produced on the inside of the layer and bark is produced towards the outside. The wood of trees grown under seasonal conditions consists of a series of concentric layers of tissue referred to as growth rings, and each layer comprises the wood produced by the cambium in a season of growth. A new ring of wood is added each full season, causing an increase in girth. In temperate regions and in some tropical countries, the yearly alternation between a growth season and a resting period results in the growth rings being annual rings, although sometimes interruptions to growth cause two or more false rings to be produced within one growth season.

The outer growth layers of the stem, known as sapwood, store food and conduct sap to the leaves. The sapwood is from half a centimetre to several centimetres wide, depending on species, age of tree and forestry practice.

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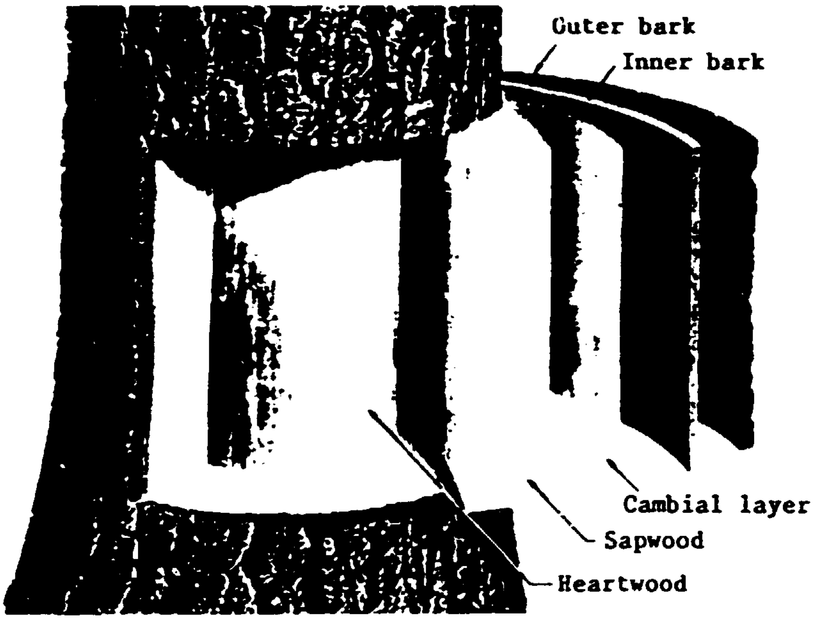
Freshly cut sapwood is lighter in colour than the wood towards the pith, or centre, of the tree; it is also less durable and usually contains more water than the heartwood. Its strength properties are similar to those of the rest of the wood.

Figure 1. Generalized structure of a tree showing orientation of major tissues including outer bark, inner bark, cambium, sapwood and heartwood



Source: St. Regis Paper Co.

B. Growth of the tree

1. Growth in height

The increase in the height of a tree or in the length of a branch is due to the division and growth of special cells at the tip. Elongation of the tip is the only lengthwise growth that occurs in the tree. In the young tree, vertical growth is rapid, but as the tree matures, growth continues to slow appreciably.

A short way back from the growing tip, the cells on the outside form the cambium layer whereas the inner cells form the pith, which extends through the centre of the stem and branches. The pith is of small diameter and, when noticeable, it usually consists of brown, spongy material.

2. Growth in girth

As the tree grows in height there is a corresponding growth in girth due to the division and growth of cells of the cambium layer. The soft, thin-walled cells of this fine layer extend around the stem from the roots to within a short distance of the growing tip. By division they give rise to cells that form the woody cylinder of the tree. As time passes, the stem or trunk increases in girth by the addition of new cells on the outside of those already formed.

The growth in height is a function of the special cells located at the tip, whereas the growth in girth is a function of the cambium layer and does not influence the growth in height.

Cone-shaped sheaths are formed as the tree increases in height and girth. A board cut parallel to the bark along the length of the tree will contain wood of the same age throughout its length.

C. The cell wall of wood fibres

The cell wall is made up of a twisted skein of cellulose molecules bunched into elementary fibrils and ordered into microfibrils, which are embedded in a matrix of hemicelluloses and lignins.

1. Elementary fibrils

There is evidence that each elementary fibril consists of 40 cellulose molecules held in close association by hydrogen bonding. The cross-sectional dimensions are about 3.5 nm by a multiple of 3.5 or 4.0 nm (3.5 or 4.0 x 10^{-9} m). In the elementary fibril, ordered crystalline regions 300 nm in length are separated by amorphous regions where the molecules become less orderly. It is in these amorphous regions where water may move between the elementary fibrils of cellulose molecules and where degradation by acids or by heat can occur. Processes such as shrinkage and swelling occur preferentially at these places.

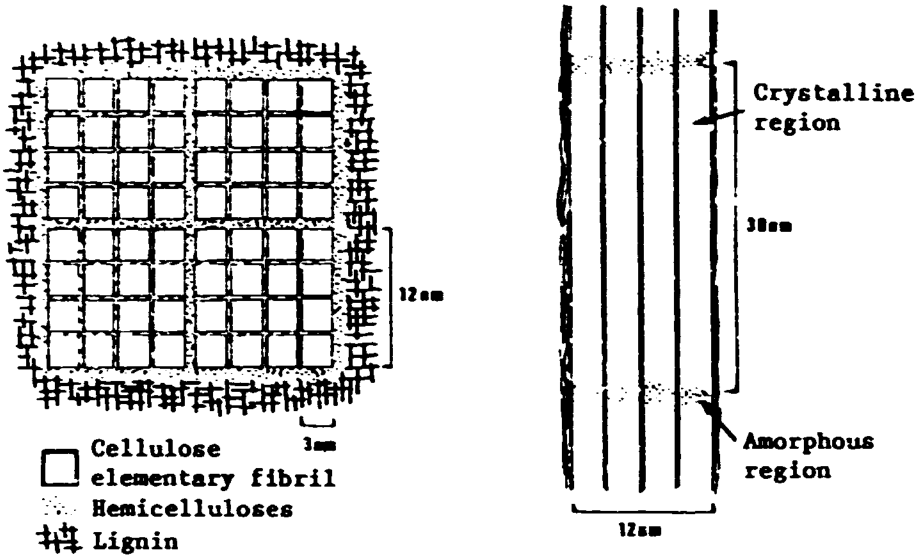
2. The nature of microfibrils

The cellulose elementary fibrils of about 3.5 nm width are embedded in a matrix of hemicelluloses and lignins. Different theories exist concerning the arrangement of the components of the fibre cell wall, and the situation can be exemplified by the proposal of Fengel (figure 2). In this model, a cellulose elementary fibril is surrounded by a few layers of hemicelluloses, which are considerably less crystalline, lower in molecular weight and less oriented than cellulose. The elementary fibrils are arranged in groups of 16, then into microfibrils containing a total of 64 elementary fibrils. These, in turn, are surrounded by hemicelluloses and lignin.

3. The arrangement of microfibrils in the cell wall

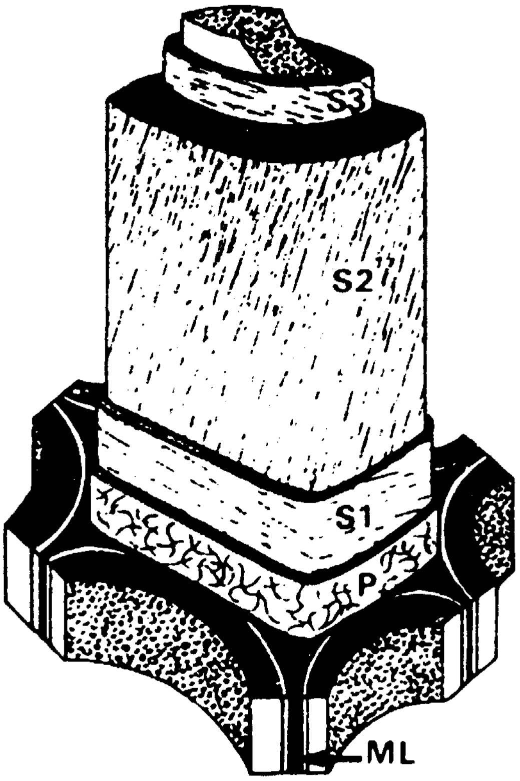
Wood cell walls are thus chemically heterogenous, being composed of several different substances; they are also physically heterogenous as they are built up of layers (figure 3). The wood cell wall consists of three morphologically distinct layers: the middle lamella, the primary wall and the secondary wall. The thin middle lamella, which is an amorphous, cellulose-free layer between the primary walls of adjacent cells, becomes heavily encrusted with lignin. During the growth of the cell, the thin primary wall is a flexible structure composed largely of cellulose, but towards the end of growth it becomes considerably lignified. Towards the end of the growing phase, the thick secondary wall begins to form in two or three layers in a process that continues after cell growth has stopped.

Figure 2. Model of the ultrastructural organization of a microfibril in wood; cross section on the left, longitudinal section on the right



Source: D. Fengel, "Ideas on the ultrastructural organization of the cell wall components", Journal of Polymer Science, Part C, No. 36, 1971.

Figure 3. The ultrastructure of the wood cell wall (ML = middle lamella; P = primary wall; S1, S2 and S3 = layers of secondary wall)



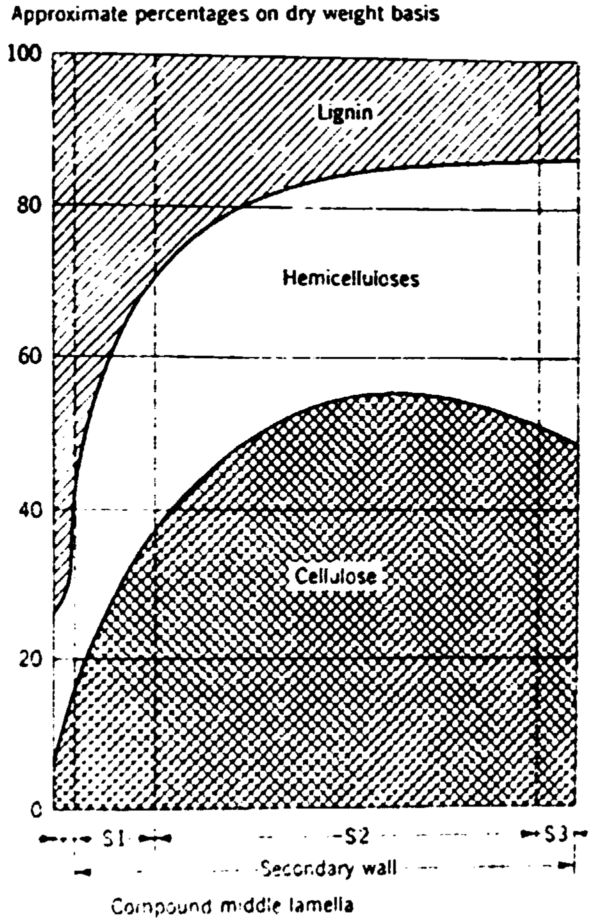
Source: W. A. Coté, "Ultrastructure - critical domain for wood behaviour", Wood Science and Technology, 5 (1981).

In the primary wall, which is about 0.06 x 10^{-6} m thick, the microfibrils are arranged in a multinet structure, and towards the end of the growth phase they tend to be oriented increasingly in a longitudinal direction.

The secondary cell wall in wood fibres consists of microscopically distinct outer (S1), middle (S2) and inner (S3) layers. The middle layer is by far the thickest at 1.5-8 x 10^{-6} m; the other two layers are about 0.1 x 10^{-6} m thick. The microfibrils in all the layers are helically arranged, but the pitch of the helices differs from layer to layer. In the S1 layer there are two or more helices of microfibrils that make large angles with the cell axis. The concentric lamellae of microfibrils arranged in helices in the S2 layer make a small angle with the axis. The inner S3 layer, which is sometimes absent, has a shallow-pitched helical organization with several lamellae.

Wood cellulose has a density of about 1.55; the amorphous hemicelluloses, 1.50; and lignin, only 1.33. The percentage distribution of these constituents is given in figure 4.

Figure 4. Distribution of the principal chemical constituents within the various layers of the cell wall in conifers



<u>Source</u>: A. J. Panshin and C. de Zeeuw, <u>Textbook of Wood Technology</u>, 4th ed. (New York, McGraw-Hill, 1980).

4. Porosity of the cell wall

The framework of microfibrils in the cell wall in sapwood encompasses "free" space containing water and other materials. The hydrated S2 layer of the tracheid cell walls in Pinus resinosa contains 25 per cent free space. The water in the capillaries of the wet walls of other woods has a volume of more than 40 per cent, on a dry wood basis, with about half the water being in the free state. The free space in wet cell walls is in capillaries having cross-sections of 16-60 x 10^{-10} m. Consequently, molecules of significant size can enter and act as fillers or modify to a considerable extent properties such as stability and durability. A dimensionally stable wood such as Sequoia sempervirens contains up to three quarters of its extractives in the cell wall.

The small voids in the dry cell wall affect its packing density, which is a more relevant indicator of the rate of penetration than is density. Packing density is higher in high-density woods than in low-density woods and higher in late and mature wood than in early and juvenile wood.

5. Distribution of constituents in the cell wall

Although the concentration of lignin in the middle lamella and primary wall can be over 50 per cent by mass, only 20-30 per cent of the total lignin is found there; the remainder is in the much thicker secondary walls, where it is present in amounts of 20-25 per cent.

D. Growth rings

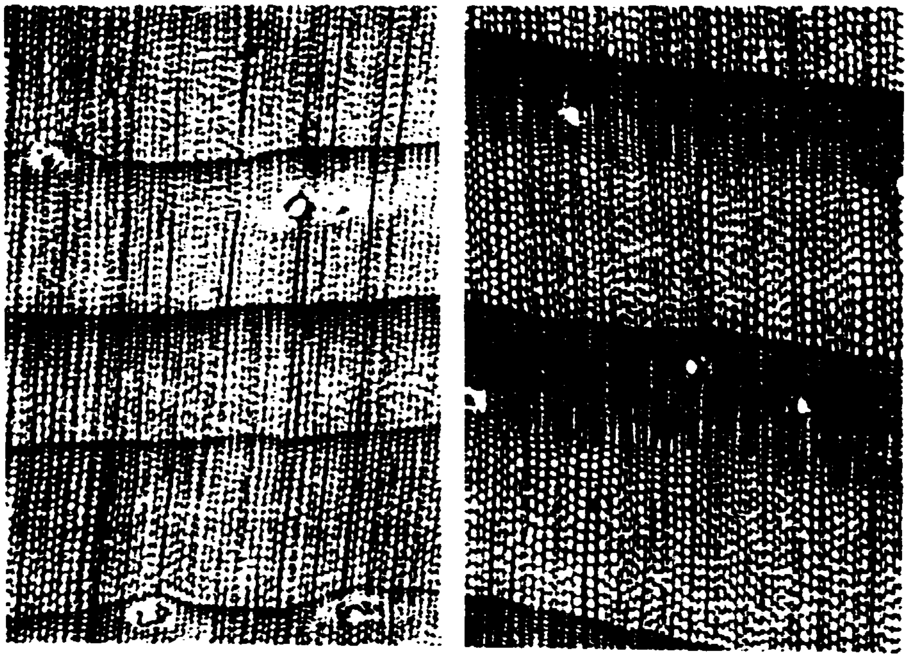
During each growing season, a new layer of wood is formed between the bark and the stem of trees over the entire length of stem. The demarcation of these growth layers or growth rings results from differences in temperature, moisture availability, the growing and non-growing seasons and also species. In most cases, growth rings are formed annually. In tropical and subtropical regions, the growth rings can be indistinct. In dry regions with relatively high temperatures and intermittent rainfall, several rings can be formed annually.

Growth rings are usually distinct owing to differences between the wood formed early in the growing season (i.e. earlywood or springwood) and that formed late in the growing season (latewood or summerwood). Earlywood has the thinnest cell walls and large lumens, whereas latewood, with its small lumens and thick walls, may appear as a dark zone (figure 5). There are variations in the contrast between earlywood and latewood, the relative amounts of them, and the abruptness with which earlywood stops forming. These variations depend on the species, the thickness of the cell wall and the age of the tree when the growth ring was formed.

Dry latewood has a higher specific gravity than dry, uncollapsed earlywood. However, in undried sapwood, the earlywood contains up to four times as much water by volume as the latewood due to the large lumens in the earlywood.

Some fast-growing species, such as Anthocephalus spp., produce great volumes of wood but the wood contains high proportions of cells with thin walls and large lumens which, when occurring in sapwood, are filled with water.

Figure 5. Variations in transition from earlywood to latewood in *Pinus* spp.: white pine (*P. strobus*, left) and Loblolly pine (*P. taeda*, right) (about x 30); note large diameter, vertical resin canal



E. Softwoods and hardwoods

1. Description

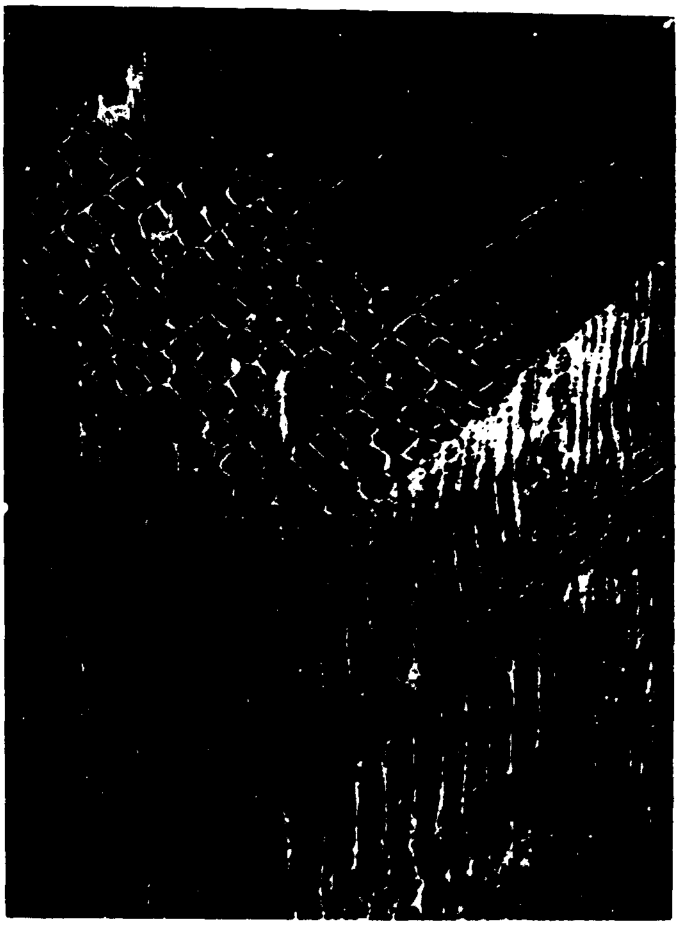
The two major groups of trees - softwoods (conifers, gymnosperms) and hardwoods (angiosperms) - are distinguished by the presence or absence of a cover on the seed. Whereas there are only about 40 genera and 600 species of softwoods, there are thousands of genera of hardwoods with widely differing anatomical structures. The average oven-dry specific gravity of softwoods is about 0.36, with a range of 0.25-0.60; that of hardwoods is 0.50, with a range of below 0.30 to above 0.80. Much of the wood available globally is from hardwood species.

2. Major anatomical differences between softwoods and hardwoods

The fibre is the single most important structural element in wood. In softwoods, the fibres also serve as the main translocation route for sap and are interconnected by openings known as bordered pits, which are called tracheids. In hardwoods, the fibres are usually thick-walled and have simple, slit-like pits. The characteristics of these elements vary within the tree, within the species and between species. Tracheids and fibres are considerably longer than they are wide, with ratios sometimes as great as 100 to 1. In commercial softwoods, the length of tracheids ranges from 3 to 4 mm. The diameters range from 20 to 80 x 10^{-6} m. The length of hardwood fibres ranges from about 0.5 to 1.8 mm and the diameter from about 10 to 25 x 10^{-6} m.

The major anatomical difference between softwoods and hardwoods is the presence of vessels, or pores, in the latter. These vessels, through which the sap is conducted in the living tree, vary widely in size, shape and arrangement. In ring-porous hardwoods, the vessels in the earlywood portion of a growth ring are of a different size from those in the latewood. In diffuse-porous woods, the vessels are the same size at all locations in the ring. The length of the vessel elements varies from 0.18 to 1.3 mm and the width from 20 to over 250 x 10^{-6} m. For a number of hardwoods the vessel diameter increases and vessel frequency decreases as the distance from the pith increases. The frequency of vessels per unit area varies according to the species, the size of the vessels, the position in the growth ring, the distance from the pith and growth conditions. The walls of vessels are thin, about 3-4 x 10^{-6} m. Figures 6 and 7 are scanning electron micrographs of, respectively, two hardwoods and a softwood.

Figure 6. A softwood Douglas fir (Pseudotsuga Menziesii) as viewed with the scanning electron microscope (about x 80), showing earlywood and latewood tracheids and rays



Source: W. A. Coté, "Ultrastructure - critical domain for wood behaviour", Wood Science and Technology, 5 (1981).

Figure 7. Scanning electron micrograph of a small cube of the hardwood *Eucalyptus citriodora* (top) and *E. regnans* (bottom) showing rays (r), fibre tracheids (f), vessels (v), tyloses (t) and axial parenchyma (ap) (unit distance 300 x 10^{-6} m)

3. Parenchyma

On the cross-sections of woody stems, the ray parenchyma extend as lines from the pith outwards to the cambium and are seen as lines between the fibres. In conifers and some hardwoods, the rays are 1-2 cells wide and 10-20 cells high. In other hardwoods the rays can be up to about 30 cells wide, sometimes hundreds of cells high and are tapered on their upper and lower edges.

Vertical parenchyma are also thin-walled cells and are interspersed between the fibres and arranged diffusely or surround the vessels in various patterns. In contrast to the fibres, the ray and vertical parenchyma remain alive across the sapwood zone. In the sapwood, they translocate or store primary metabolites such as starch or fats; in the heartwood, they frequently contain large amounts of extractives.

4. Resin canals

Coniferous wood contains resin canals about the same size as some vessels. They exist as anastomosing networks surrounded by epithelial cells, which form and exude resin into the canal. Frequently, the resin is under pressure so that when the canals are cut in the living tree, the resin exudes.

5. Pits and tyloses

When the pits, or openings in the cell wall, between the ray parenchyma and vessels are more than 10 x 10^{-6} m diameter, the parenchyma can form thin-walled, balloon-like extrusions - the tyloses - into the vessels. When the pit diameters are smaller, the rays secrete extractives. These changes occur when heartwood is formed or when sapwood is injured. In conifers, the bordered pits also aspirate or close during the transition of sapwood to heartwood. All these changes hinder the movement of fluids either into or out of the wood.

6. Proportion of non-fibrous elements

Whereas the proportion by volume of tracheids in conifers is usually over 90 per cent, the proportion of fibres to thin-walled elements in hardwoods is much lower (table 11). The proportion of the latter affects the water content and the density of the material.

Table 11. Proportion of tissue elements in various woods
(Percentage of total volume)

Species a/	Longitudinal fibres/tracheids	Parenchyma Ray	Parenchyma Axial	Vessels
Betula papyrifera	75.7	11.7	2.0	10.6
Erythrina vespertilio	16	80		4
Eucalyptus camaldulensis	58	25		17
Juglans nigra	48.7	16.8	13.5	21.0
Liquidamber styraciflua	26.6	18.3	0.2	54.9
Picea abies	94.1	5.9	-	-
Pinus strobus	93.0	6.0	-	-
Quercus rubra	41.3	15.9	23.4	19.5
Salix nigra	54.4	6.1	2.2	38.1
Ulmus americana	34.7	11.3	6.0	48.0

a/ Common names vary between countries.

7. Chemistry

The cellulose content of both softwoods and hardwoods is normally in the range of 42 $\pm$ 2 per cent (on an extractives-free basis). The hemicelluloses and lignin are found in complementary proportions and the woods with a high lignin content have a low hemicelluloses content. Generally, hardwoods contain less lignin (16-24%) than softwoods (24-33%).

F. Wood formed under abnormal conditions

Responses to abnormal growing conditions result in reaction wood with ultrastructures markedly different from those of normal wood. Reaction wood is frequently formed in leaning trees and bent stems. Because of the low density of juvenile wood in young trees and the flexible nature of fast-grown trees under windy conditions, there is frequently a higher proportion of reaction wood in the central portions of these stems than in the outer layers of mature trees. In addition, stressed wood can be formed along the periphery of trees, particularly hardwood trees. This results when the crown seeks the optimum opening in the forest canopy, causing the tree to lean in a certain direction.

Leaning trees and branches that are transversely eccentric in outline often contain reaction wood in the regions of accelerated growth. In softwoods, this is found in the underside of the trunk in the form of compression wood; in hardwoods, it is found in the upper side and is known as tension wood.

Stressed wood, and particularly reaction wood, has inferior properties for conversion into, or use as, solid wood products.

1. Reaction wood

Compression wood

Compression wood is readily detected in freshly cut log cross-sections (figure 8). It is generally much darker in colour than normal wood of the same species. Pronounced compression wood can occur over large areas and contain a number of characteristic anatomical features. Compared with normal wood, compression wood contains shorter fibres with thicker walls and a greater proportion of latewood in growth rings; its microfibrillar angle is much larger than in normal wood.

Compression wood is harder, heavier and more brittle than normal wood. It has a lower impact strength than normal wood and should not be used for scaffolding and ladder material. It shrinks and swells much more than normal wood in the longitudinal direction and less in the transverse direction. If there is more compression wood on one side than another, warp will occur on drying.

Tension wood

Eccentricity of growth and wider growth rings are often indications of the presence of tension wood. It is often found in bands that, compared with neighbouring normal wood, are usually darker in colour, harder and denser. The main anatomical features are fibres with a light-refractory inner layer, often termed the gelatinous layer. There is also a marked reduction in the size and number of vessels and a higher average wood density.

Figure 8. Cross-section of a log of *Pinus radiata* taken from a tree that had been blown over after approximately 10 years of normal growth; note the excessive development of compression wood on the lower side (scale in cm)

In most cases, the presence of tension wood is revealed by the extreme woolliness of sawn longitudinal surfaces of green timber. This feature can be extremely troublesome in sawing, because the fibrous mass may choke the saw cut and cause overheating of the saw. The woolliness of veneer surfaces is also indicative of their tendency to collapse on drying, and such collapse is of the non-recoverable type. Shrinkage in the longitudinal direction is high, radially it is normal, but tangentially it may be greater than normal. Its presence can cause twisting in boards on drying.

Wood formed under load stress

Peripheral growth stress can reach high levels in significant portions of the outer sapwood of hardwoods. The wood formed in those regions has an increased thickness of cell wall, a greater microfibrillar angle in the S2 layer and a higher intensity of lignification. The high peripheral stress results in high compressive stresses in the interior of the tree, so that compression failures occur in the fibres and the wood becomes brittle ("brash"). High growth stress causes logs to split open when felled or sawn.

Brittle heart

Brittle heart occurs in the central zone, which is not always symmetrically placed, and is characterized by wood of low strength and a brash fracture due to minute compression failures in the walls of some fibres. Its presence is due to the high peripheral growth stresses sometimes found in hardwoods or to forces such as severe winds, which are counterbalanced by a related compressive force in the interior of the tree. If these forces are sufficiently high and imposed on wood of low density so that the crushing strength is exceeded, then compression failures occur in the fibre walls. The wood has low impact strength and can be detected by its easier sawing characteristics and broken or foggy fibres on the end-grain, sawn surfaces.

2. Chemistry

There is a general pattern for both hardwoods and softwoods in that the wood on the lower side of any cross-section of a leaning or sloping stem has a higher lignin content and a lower cellulose content. There are gradations in composition and properties between severe reaction wood and normal wood within a single tree.

Compression wood

Compression wood can have substantially higher lignin and hemicellulose contents and lower cellulose contents than comparable normal wood. Because of the higher proportion of lignin, the cell wall density of compression wood is less than that of normal wood. On the other hand, because of the small proportion of earlywood and the thick tracheid walls, the gross density of compression wood is much higher and almost twice that of normal wood.

Tension wood

Tension wood contains a higher percentage of cellulose and a lower percentage of lignin and hemicellulose than normal wood.

G. Sapwood and heartwood

1. Volume of sapwood

Sapwood is the outer zone and the portion of the wood that, in the living tree, contains living cells and reserve material, e.g. starch. Fibres and tracheids die as soon as the lignification phase is completed, but the parenchyma remain viable for many years or until heartwood is formed or the wood is damaged.

The amount of sapwood in a mature tree can vary considerably, occupying the whole tree or only the outermost growth rings that surround an approximately conical central core of dead heartwood cells. In red oak (Quercus rubra), sapwood forms a bank of constant width of 1 cm or 5-6 growth rings around the heartwood; in pines, 15-50 growth rings of varying widths; in eucalypts, about 5 growth rings; in maple (Acer spp.), over 100 growth rings. The width of sapwood in a cross-section of a stem of a tree is not always uniform, and the number of sapwood rings can be greater at the stump than higher in the tree. Also, in some trees of mature or over-mature age, the width of the sapwood, and particularly the number of growth rings in it, is much greater than in young trees of the same species.

The mechanical properties of sapwood and heartwood of similar density and moisture content are practically the same.

2. The contents of sapwood

Most sapwood tissues in the living tree are involved in the translocation or storage of sap. The free water content of sapwood is determined by the lumen area of the elements after allowing for stored metabolites. The water content of sapwood can be high - over 200 per cent, on a dry weight basis in some cases; for softwood sapwood, it is usually between 110 and 170 per cent, whereas for hardwood sapwood it is between 60 and 110 per cent. Usually, the water content is maintained across the sapwood but decreases abruptly at the heartwood periphery.

Starch, fatty acids or esters of fatty acids are formed exclusively in the parenchyma, where they are stored as reserve material in the sapwood for growth or for extractives formation at the heartwood periphery. The storage material in the sapwood makes it prone to fungal and insect attack, so that chemical or preservation treatments are necessary to render it durable. In general, treated sapwood may be superior in durability to heartwood.

3. Heartwood

In most growing trees or shrubs, the inner layers of the stem or branches cease to contain living cells and the reserve metabolic materials are no longer present. This heartwood zone contains higher, sometimes much higher, amounts of extractives than the sapwood, and their composition is usually different. The zone is generally dark, with a colour range between light yellow and dark brown. Once the zone begins to form it is spatially continuous.

Less moisture is usually found in heartwood than in sapwood, and the decrease at the transition zone can be abrupt and considerable, coinciding approximately with the change in colour. This decrease in moisture content is characteristic of softwood species and most hardwoods. However, the heartwood can contain more moisture than the sapwood in some hardwoods species such as Populus (poplar), Ulmus (elm), and Eucalyptus, and in some cases this may be due to the formation of wetwood. The moisture content in the heartwood of softwoods is usually 33-95 per cent whereas in hardwoods it is usually 60-100 per cent.

Together with loss of water on heartwood formation, a marked aspiration or closing of the pits between tracheids restricts the transport of fluids. When heartwood is formed in many hardwoods, tyloses appear in the lumen of vessels. Aspiration of pits and tyloses formation also take place in sapwood in response to wounding.

Extractives are responsible for the distinctive colour of heartwood and are present in the parenchyma, vessels and some other cells, but also in the cell wall of the tissues. Extractives can hinder the movement of aqueous fluids. The amount of extractives increases from the pith to heartwood periphery and abruptly decreases in the sapwood. Large amounts can be present in the outer heartwood, e.g. over 30 per cent of polyphenolic extractives in old eucalypts. Usually, fast-grown trees of the same species contain significantly lower amounts of extractives than do the slow-grown counterparts. The composition of extractives in the heartwood varies considerably and depends on the genus to which the tree belongs. Some of the inorganic constituents of wood are in the cell wall, but larger amounts are translocated from the heartwood during its formation. The total mineral content increases from unblemished to discoloured wood and again to decayed wood. Potassium concentrations can increase 400-4,000 per cent, calcium significantly and other elements in a less pronounced manner. A number of organic extractives can, when present, convey durability to the heartwood.

Because the extractives or extraneous components are largely formed in the lumen of cells, they have little effect on strength.

The major classes of organic extractives in heartwood are as follows:

(a) Polyphenols, which are present in all woods although in some cases in small amounts. Some classes of polyphenols can affect adhesion with glues, others convey durability. Still others cause corrosion during sawing etc., discolour on exposure to sunlight or, with iron, affect paint films and other surface coatings;

(b) Resins are present mainly in the softwoods and include terpenes, resin acids and sterols. They are water-repellent and can affect applications where that property is involved;

(c) Fats exist as free fatty acids and their esters, usually in softwoods but also in hardwoods such as poplars and birch;

(d) Tropolones. Members of the Cupressaceae such as western red cedar (*Thuja plicata*) and other cedars (e.g. *Chamaecyparis* spp.) are the only tree species containing extractives based on this seven-carbon ring structure. They eadily react with copper and iron and convey a high degree of durability.

H. Juvenile wood

Natural stands and plantations of both pines and hardwoods are being harvested at increasingly younger ages, and greater use is being made of the formerly non-merchantable tops and branches. Also, there is the development and use of short-rotation, intensively grown crops of fast-growing species. These raw materials contain increasing amounts of reaction wood and juvenile wood.

The age of the cambium at the point of wood formation determines whether juvenile or mature wood is formed. Juvenile wood extends outwards from the pith about 6 to 15 rings, where it has gradually taken on the properties of mature wood. It comprises the major portion of the wood formed in the first 20 years of growth at a particular level in the tree. Juvenile wood also contains a high proportion of earlywood, and with increasing distance from the pith, the fibre length, density and cell wall thickness increase steeply in the first few years and more slowly in the mature wood. When present, spiral grain shows its maximum angle of inclination in the juvenile wood zone.

The moisture content varies widely with tree age and with the location of the sample in the tree. The considerable drop of moisture content with age is due to an increase in density and to the presence of heartwood. The amount of extractives is lower in juvenile wood.

There are different interpretations of the terms juvenile wood, core wood and heart-in material. Juvenile wood is an inner core of wood surrounding the pith in which the cells are smaller and/or less structurally developed than those of the outer layers. The characteristics mentioned above are genetically inherited and perhaps modified by growth rate. In addition, this clear wood may contain varying amounts of knots and branch stubs, depending on silvicultural practices, irregular grain around the knots, reaction wood and wandering pith. The central zone of core wood can be larger in diameter than juvenile wood and the material cut from it may not contain the pith. Heart-in material is taken from the core wood and contains the pith and associated defective wood. The pith consists chiefly of parenchyma or soft tissue, which impairs strength, wearing properties and appearance. Usually its actual volume is insignificant, but the pith can be particularly eccentric and affect the yield and quality of sawn wood.

I. Irregular features

1. Knots

Various types of knots affect the quality of wood in different ways, and knots are often rejected. The knots of conifers become highly resinified, whereas with hardwoods the branch stubs are not filled with extractives so that an entry point for insects and fungi is provided, leading to widespread discoloration and decay.

2. Wetwood

In freshly cut stems of some species, the small or large zones of wetwood (when present) are usually recognized by a darker or wetter appearance. They contain more water than the sapwood zone, and sometimes a gas can be present. The pH and density are higher than those of the surrounding tissues, and the occurrence of mineral stains or deposits, often of calcium carbonate, is frequently greater. The presence of wetwood causes problems during drying and penetration.

3. Discoloured and decayed woods

Some discoloured woods can be confused with heartwood because of their location and colour. They are, however, part of a sequence of damage to the living tree, which proceeds eventually to decayed wood. The zones are irregular in shape, colour intensity and location within the stem; sometimes they occur as coloured tubes within the stem. Often they occur longitudinally for a short distance as zones on one side of the tree.

4. Resinified wood and exudates

Cambial injury of many trees, particularly during the growing season, can result in the formation of organic materials that are confined to cavities - veins or pockets - in the wood or that exude onto the bark of the tree. The size of the cavity and the amount and composition of the exudate depend on the species and its conditions of growth. Conifers exude resins of the terpenoid type, eucalypts exude kinos, composed of polyphenols, and the Prunus, Acacia etc. genera yield carbohydrate gums. Pockets reduce strength, but veins have much less effect.

5. Spiral grain and interlocked grain

Spiral grain or inclined grain is an arrangement in which fibres or other longitudinal elements take a spiral course about the axis of the tree. Spiral grain can be severe in the juvenile wood of softwoods. It is low at the pith but usually reaches a maximum around five growth rings from the pith and usually decreases to a straight-grained condition in mature wood. A slope of grain of 6° can reduce bending strength by up to 25 per cent. Spiral grain causes twist in boards on drying unless high-temperature drying under restraint is used.

Interlocked grain, found in hardwoods, makes the wood difficult to split, and when it does split a corrugated radial surface is left. It causes distortion when veneer is dried.

J. The behaviour of wood under load

Studies of the behaviour of isolated, single fibres of wood under load have been confined to tensile loading because of the experimental difficulties involved in applying and measuring loads and deformations in specimens of very small dimensions. The large amount of work done on single fibres in tension and also on thin slivers of wood containing bands of fibres has established several interesting patterns of behaviour.

The tensile strength and modulus of elasticity of latewood fibres may be as much as three times that of adjacent earlywood fibres, and the strains at failure in both types of fibre appear to be similar in magnitude. The existence of constant strain at failure in whole wood under tension has also been observed in tests on a large number of species and lends support to a limiting strain concept. The tensile properties of single fibres are superior to those of whole wood. This may be due to the presence of medullary rays, other cell types, imperfect alignment of fibres and local variations in density in whole wood. Further, the transfer of stress from cell to cell in whole wood is through shear in the middle lamella. The properties of the single fibre appear to be influenced by the angle of orientation of the microfibrils in the thick S2 layer of the secondary wall of the fibre. The smaller the angle with respect to the longitudinal axis, the greater the tensile strength of individual fibres. In tension parallel to the fibres in whole wood consisting only of latewood, bundles of fibres appear to pull out from among others, which suggests that failure occurs in the region of the middle lamellae or the primary walls of the cells. In earlywood, failure appears to occur across the cell walls. In tension perpendicular to the grain, failure occurs either by the fibre breaking into two pieces along the length and exposing the lumen or by separation at the inside of the primary wall, leaving the remainder of the fibre intact.

In compression parallel to the fibres in whole wood, lines of buckling appear on the tangential face at an angle of about 60° to the longitudinal axis and on the radial face at about 90°, i.e. parallel to the medullary rays. The departure of the buckling lines from an angle of 45°, the angle of maximum shear, is due to the anisotropy of wood. Slip planes or compression crinkles appear to develop within the cell wall, and buckling of cells, together with separation near medullary rays, also occurs. In compression perpendicular to the fibres, the cells distort sideways and squash inwards towards the lumen, eventually separating at the outer boundary of the S2 layer.

Whole wood may be represented in a simple form by a model consisting of a series of long, parallel, hollow, tin-walled tubes cemented together. Small groups of thin-walled tubes may also be arranged horizontally (radially) to represent medullary rays. Under the action of longitudinal tensile forces, the system would be relatively strong, whereas in longitudinal compression, the system would be weaker because of the tendency to buckling of the long columns, particularly with initial curvature in the vicinity of the rays. In lateral tension and compression, the strength of the thin-walled tubes would be less than corresponding values in the longitudinal direction. Shear properties longitudinal to the fibres would also be low.

K. Important properties other than strength

1. Density

Because of its link with practically all of the mechanical properties of wood, including those of structural importance, density must be rated as one of the most important of the non-structural properties of wood. However, there are some tropically grown timbers that have a satisfactory density but consist of a small proportion of thick-walled high-density fibres and a large proportion of thin-walled, large-diameter vessels, parenchyma etc. These woods would fail more rapidly under load than woods of the same density but containing a large proportion of fibres with walls of medium thickness.

Except in special circumstances, the self-weight of a timber structure is seldom a serious design consideration. In cases where self-weight is important, it should be noted that, in general, timbers of low density are more efficient on a strength/weight basis than those of high density, particularly for beams and columns. The obviously much higher strength/weight ratio of dry timber, as compared to that of green timber, should not be overlooked.

The competitive use of timber as a material of construction depends on the effective use of wood's outstandingly high flexural rigidity per unit mass. This property can be capitalized in the design of relatively large yet comparatively lightly loaded structures such as single-storey buildings, all kinds of roof systems, towers, silos, bridges and curtain walls.

2. Shrinkage

From the time it is cut from the tree, wood exposed to normal atmospheric conditions dries and shrinks. The loss of dimension tangential to the growth ring is usually quite significant, particularly in hardwoods, and is about twice the loss in the radial direction.

In the first stages, shrinkage along the grain, except when abnormal wood such as compression wood is present, is usually small and of little or no practical significance. Generally, the changes in dimensions of softwood timbers on drying are not as great as those of hardwoods, although there are some high-density hardwoods, wandoo, for example, that exhibit a comparatively small shrinkage.

As the green timber dries to below the so-called fibre saturation point (at approximately 25-30 per cent moisture content), the normal shrinkage is more or less linear with change in moisture content.

In a number of hardwoods, normal shrinkage can be enhanced by an abnormal change in dimensions, called "collapse". This occurs when the moisture content of the timber is above the fibre saturation point. The phenomenon results from a collapse of the thinner walled fibres during the early stages of drying. It manifests itself macroscopically as an excessive shrinkage of the cross-section and a corresponding increase in apparent density. The surfaces of the timber are slightly to heavily corrugated, depending on the severity of the collapse, and internal checking can occur.

Hardwoods dried for joinery and similar uses are usually given a steaming or reconditioning treatment after drying. This treatment removes most of the collapse unless tension wood was present and restores the timber to the cross-section and density it would have had if only normal shrinkage had occurred.

Because shrinkage is a normal characteristic of wood, special consideration is required in the selection and use of timber for structures. Owing to the gross anisotropy of shrinkage, timber containing severely distorted grain or sloping grain may warp badly on drying from the green to the air-dry condition. Green timber in a joint containing two or more fasteners secured in such a way as to offer restraint to the normal shrinkage of the wood will probably split as it dries. Most of the technical aspects of the working of wood, i.e. its shrinkage and swelling as the moisture content changes, are fairly well understood, and suitable design and construction procedures have been developed to obviate the problems that might otherwise be caused by this particular wood characteristic.

Investigation has shown that for most structural grades of timber, the ultimate load-carrying capacity of individual members increases as the members dry from the green condition, in spite of the loss of cross-section due to the shrinkage. For large sizes and low grades of timber, there may be little or no significant increase in strength on drying due to the development of large splits and checks. The stiffness of hardwood members not subject to collapse increases on average by about 5 per cent on drying from the green to the air-dry state, a change which for structural purposes is not of practical significance.

Although air-dry timber responds to changes in relative humidity by shrinking and swelling, these small dimensional changes are seldom of structural importance; large sections are far less sensitive than small sections to changes in ambient conditions. Nevertheless it is desirable and, in extreme cases, essential, that timber in prefabricated structures, particularly if glued joints are involved, be conditioned before fabrication to the equilibrium moisture content for that timber in the place where the structure is to be finally erected.

3. Thermal properties

Since the thermal expansion of timber along the grain is only about one tenth to one third that of other structural materials, including glass, it need be considered only in relation to differential effects when used with them. Thermal expansion across the grain is, in general, larger than along the grain. In practice, the shrinkage and swelling with moisture change that often accompany temperature changes usually overshadow thermal expansion.

4. Corrosion resistance

Wood offers considerable resistance to attack by a wide variety of chemicals, including organic materials, hot or cold solutions of acid or neutral salts, and dilute acids. Direct contact with caustic soda, however, should be avoided. Strong acids and alkalis will destroy wood in time, but the action is not rapid. Chemical attack on wood rarely releases products harmful to an industrial process. Consequently, wood is superior to many other construction materials for certain industrial buildings.

Because wood resists atmospheric pollution and sea air, it is often better suited for construction uses near coasts. Timbers in roof trusses, beams and other structural members may be attacked by corrosive vapour, but the hazard is generally much less than with metals. Chemical attack in timber tends to be limited in depth, and conservative design practice when hazardous conditions exist will normally ensure an economic life for the structure.

5. Electrical resistance

Because its electrical resistance is high, wood is particularly suitable for such uses as poles and cross-arms for high voltage power lines. Since its electrical resistance also varies with moisture content, providing it is at least partly dry, it has been possible to develop electrical meters by which the moisture content may be readily determined by measuring the electrical resistance. The effect varies with species, so that special calibration factors are needed for each species.

6. Vibration characteristics

Wood has excellent damping characteristics, its specific damping capacity being 0.06 compared to a value of 0.003 for steel. Timber floors exhibit much less vibration than floors with metal joists and thus give a feeling of greater comfort during movement across the floor for a given deflection under load. The "softness" of wooden floors relative to concrete floors has been demonstrated to cause less muscle strain in a person walking.

7. Fire resistance

Timber is a very poor conductor of heat, and although the outside surface of a timber member may be burning, the temperature only a small fraction of an inch below the depth of the charcoal being produced is relatively low and the strength of the residual part of the member is retained. In general, the denser the timber, the longer it takes to ignite and the more slowly it burns.

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IV. MECHANICAL PROPERTIES OF WOOD

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Introduction

The engineer requires an accurate knowledge of the mechanical properties of the many different species of wood before he can utilize timber for engineering purposes. He or she also needs to know the mode of resistance of wood to various types of loading. The wood may be used in the green or air-dry condition, it may be subjected to various types of exposure and it may contain defects such as knots, gum veins, sloping grain, checks etc., all of which affect the mechanical properties.

An accurate determination of the strength properties of each species of wood can only be made under standard conditions of laboratory testing. The wood must be free of defects, i.e. it must be clear wood, its temperature and moisture content must be controlled to a selected value, and specimens of standard size must be subjected to accepted modes of testing under various types of loading. The number and type of standard tests carried out differ with various authorities, but in Australia it is normal practice to conduct strength tests in static bending, impact, compression parallel and perpendicular to the grain, hardness, shear parallel to the grain, both radial and tangential to the growth rings, cleavage and torsion. The test in torsion is not referred to in any standard. The influence on the elastic properties of wood of such factors as temperature, moisture content, duration of loading, defects etc. need to be determined separately and allowed for in deriving design stresses based on the mechanical properties of clear wood for each species.

The methods used in Australia for the testing of small clear specimens of timber to determine their strength properties have been described in detail. 1/ Methods of sampling and the procedures for the correction of strength properties for moisture content and temperature are also described.

In the present chapter, the standard tests carried out on clear wood and the typical behaviour occurring in each case will be described. The tests are made at 20° C on green wood cut from the tree and on wood dried to a moisture content of 12 per cent, based on the oven-dry weight, according to the standard testing procedures of British Standard No. 373-1957, 2/ and ASTM Standard D143-52. 3/ Nominal specific gravity and moisture determinations are made on each specimen. The method used in sampling timber for the evaluation of strength properties is described in CSIRO Forest Products Technical Note No. 5. 4/

A. The strength properties of wood

1. Tension

Tensile tests on wood are not included in standard mechanical testing procedures because it is difficult to obtain straight-grained, defect-free

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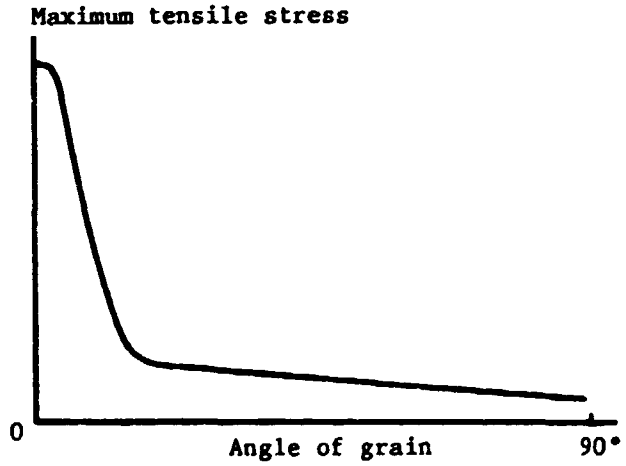
*Until mid-1982, an officer of CSIRO, Division of Building Research, Melbourne.

material and, further, because it is difficult to eliminate the effects of the end loading attachments on the test results. There is a tendency for the wood to crush or shear at the attachments. In practical applications, the full tensile strength of a member is rarely attained because of the poorer mechanical properties of the joints or attachments used to connect members.

Straight-grained, defect-free wood has a very high tensile strength parallel to the grain. For example, the average ultimate tensile strength parallel to the grain for dry hoop pine is about 130 MPa and that for dry mountain ash is about 185 MPa. In comparison, the yield stress for mild steel is about 250 MPa.

The tensile strength of wood is very dependent on the angle between the direction of the applied load and the direction of the orientation of the wood fibres, i.e. the direction of the grain of the wood (figure 9). The tensile strength perpendicular to the grain is about 1/25 of that parallel to the grain for green wood and about 1/45 for seasoned wood. Large reductions in tensile strength occur even with small grain slopes. When knots are present in the wood, the grain slope in the immediate vicinity of a knot is usually steep with respect to the general grain direction and the tensile strength of the material is considerably reduced. The effects of grain angle and knots are taken into account when timber is sorted for structural purposes by the application of grading rules.

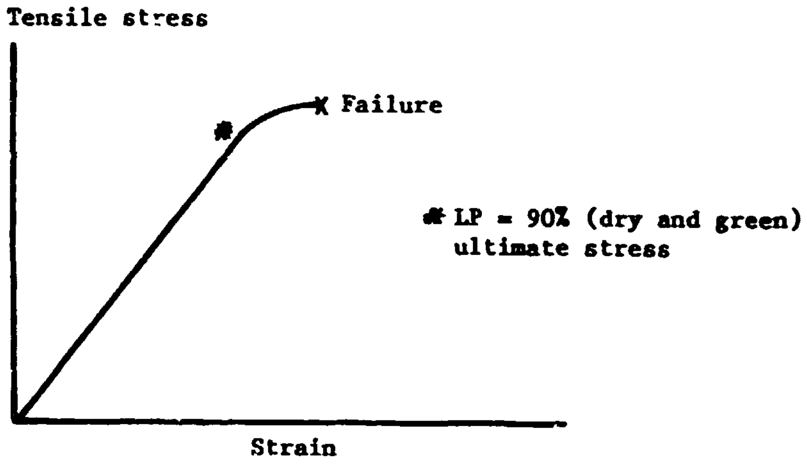
Figure 9. Relationship between maximum tensile stress and angle of grain



The stress-strain curve for wood in tension parallel to the grain is linear almost to the ultimate stress value (90 per cent level) with little plastic deformation (figure 10).

As wood does not deform rapidly at high tensile stresses, stress concentrations are not relieved to any appreciable extent; hence, stress concentrations should be avoided. Failure may be splintery in nature when thick-walled fibres fail near the middle lamella or brittle in nature when thin-walled fibres break across the cells.

Figure 10. Stress-strain curve for wood in tension parallel to the grain (LP = limit of proportionality)



2. Compression

Parallel to the grain

The standard specimen is 200 mm long by 50 mm square in cross-section. The rate of deformation during test is 0.6 mm/min. Longitudinal deformation is measured by means of a linear variable differential transducer and the load-deformation curve is plotted automatically on a chart recorder. Specimens in the green condition and at 12 per cent moisture content are tested at 20° C. Density and moisture content determinations are made on each specimen.

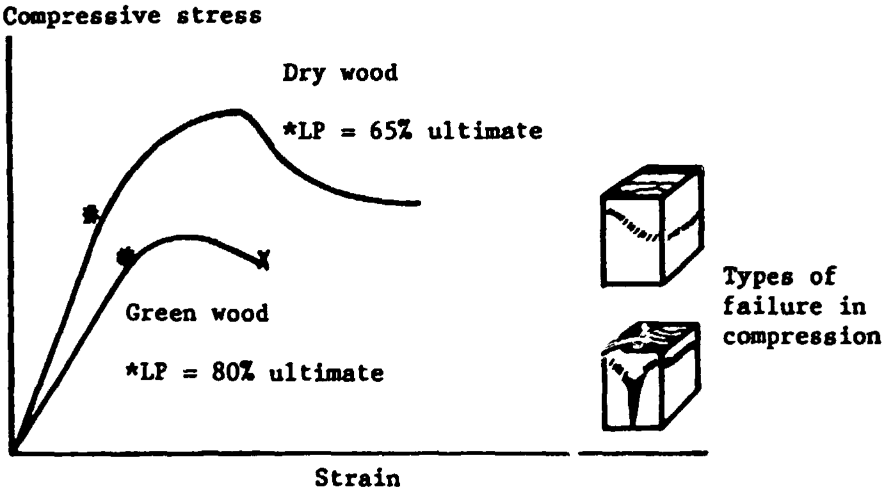
An alternative specimen sometimes used in compression testing is 60 mm long by 20 mm square; it is tested at a rate of deformation of 0.18 mm/min.

The maximum crushing strength of wood parallel to the grain is about one quarter of the ultimate tensile stress. The maximum crushing stress for green Douglas fir (Oregon pine) is about 27 MPa and for seasoned Oregon pine, 51 MPa. The values for mountain ash and grey ironbark, both hardwoods, at 12 per cent moisture content are about 63 MPa and 96 MPa, respectively.

The moduli of elasticity for wood in compression and tension parallel to the grain are approximately equal in value.

The stress-strain curve for wood in compression is different from that for wood in tension. The curve is linear to stress levels of 65 and 80 per cent of the maximum value in compression in dry and green wood, respectively (figure 11). Following the limit of proportionality, the strain increases at an increasing rate with stress; the curve reaches a peak and finally falls as considerable deformation occurs due to the slender wood fibres buckling laterally. The buckling of individual fibres is accompanied by separation in the vicinity of the medullary ray cells, which are disposed in a radial direction with respect to the growth rings of the wood. Whereas the longitudinal fibres lend lateral support to each other between medullary rays, the lack of such support in the vicinity of the radial rays permits buckling to occur. The line of failure on the face tangential to the growth rings is along the plane of maximum shear stress, which is about 60° to the direction of loading, compared with 45° for isotropic materials. The line of failure on the radial face is at about 90° to the direction of loading and is parallel to the medullary ray cells. A further mode of failure is that of the wedge and split, in which two included shear planes form a wedge towards the centre of the width of the specimen.

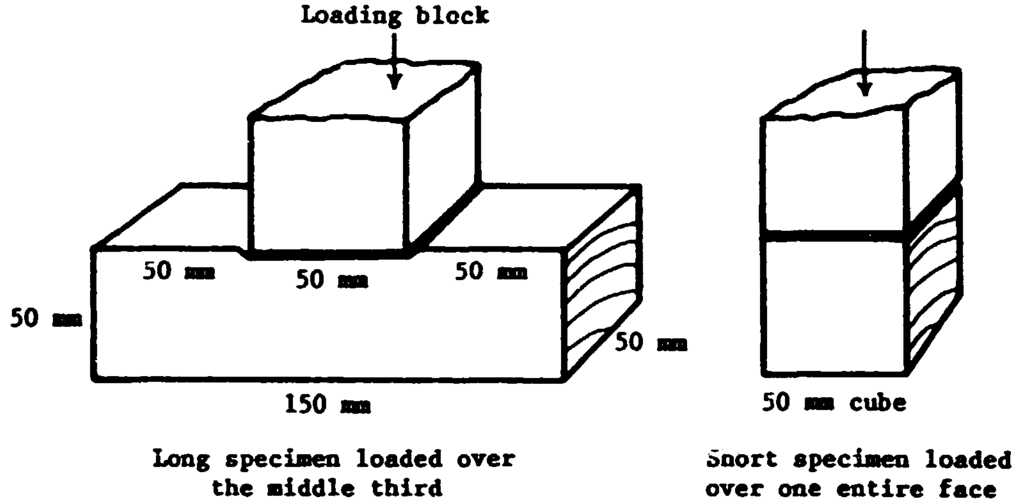
Figure 11. Stress-strain curves for wood in compression parallel to the grain (LP = limited of proportionality); the quantities measured are maximum crushing stress, stress at the limit of proportionality and modulus of elasticity



Compression perpendicular to the grain

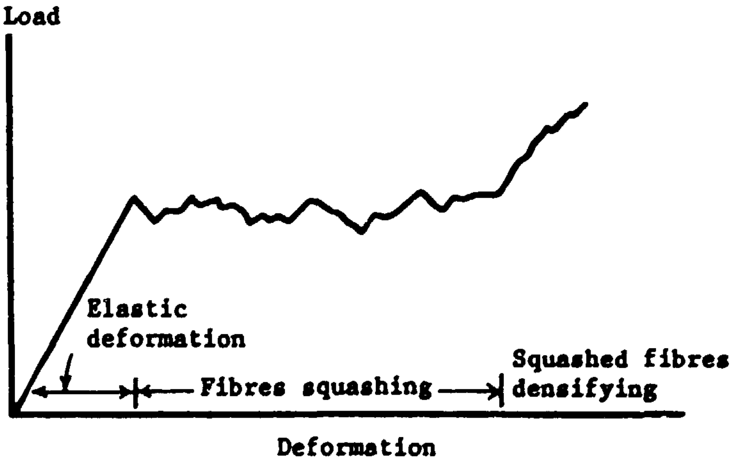
Specimens of two sizes are used to determine the properties of wood in compression perpendicular to the grain (figure 12). One specimen is 150 mm long and 50 mm square in cross-section (American standard). The specimen is supported on one of the long flat faces and a loading block, 50 mm square, is applied to the opposite face and over the middle third of the length of the specimen. The load is applied to the radial or the tangential face with respect to the growth rings and the specimens are initially machined so that perfect radial or tangential faces exist. The second type of specimen is a cube of 50 mm per side (British standard) tested in a similar manner to the long specimen with the exception that the loading block of 50 mm x 50 mm covers the entire face of the specimen under test. Both specimens are deformed at the rate of 0.3 mm/min to a total deformation of 2.5 mm. The load required to cause this deformation is accepted as the compressive strength perpendicular to the grain.

Figure 12. Compression test perpendicular to the grain



The load-deformation curve for wood in compression perpendicular to the grain is initially linear (figure 13). Beyond the limit of proportionality, the deformation continues to increase for little change in load. The hollow fibres squash flat and the wood densifies until the thickness of the wood is about one third of the original value. Following this, the load increases sharply with further compression of the densified material.

Figure 13. Load-deformation curve for wood in compression perpendicular to the grain



With the specimen loaded over only a portion of its area, the resistance to the load is proportional to the loaded area and the loaded perimeter. The material on each side of the loaded area lends support in opposing expansion of the loaded area in the direction at right angles to the direction of loading; in addition, support is provided to the loaded fibres in the direction of loading. Experiments have shown that where the loaded edges are sufficiently remote from the edges of the piece of timber, such as is the case when a specimen is loaded over the middle third of its length, the bearing stress, determined from a 50 mm cube loaded over one face, can be increased by a factor f, defined as follows:

$$f = 1 + P/A$$

where P is the loaded perimeter in inches and A is the loaded area in inches.

In the specimen loaded over the total bearing area, no perimeter effects exist.

For timber loaded in compression at an angle between 0° and 90° to the grain, the compressive strength may be estimated from Hankinson's formula, which is given in the SAA Timber Engineering Code. 5/

3. Bending

Because of the disparity between the compressive and tensile strengths parallel to the grain, neither provides a suitable basis for the design of beams. It is more convenient to determine the bending strength by test and to derive design stresses from the test results. An approximate value of extreme fibre stress at failure, the modulus of rupture (MOR), is calculated as

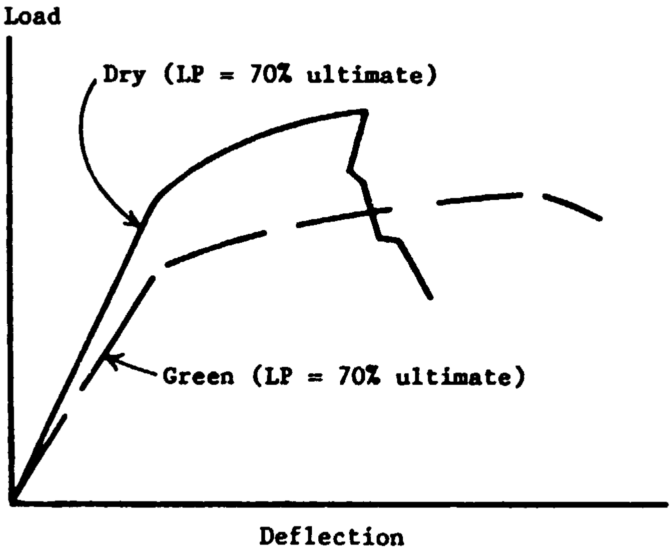
$$\text{MOR} = \frac{\text{Maximum bending moment}}{\text{Section modulus}}$$

Specimens of two sizes may be used in standard testing in centre-point bending. The dimensions are 750 mm in length x 50 mm square in cross-section, tested over a span of 700 mm, and 300 mm x 20 mm square, tested over 280 mm. The beams are freely supported and loaded in bending in the radial direction at the centre of the span. The rate of deformation is 2.5 mm/min for the larger specimen and 1 mm/min for the smaller specimen. Load-deflection curves are recorded on charts using linear variable differential transducer devices to measure deflection. Modulus of rupture, stress at limit of proportionality and modulus of elasticity are determined. The modulus of elasticity calculated from the data in this test may be up to 16 per cent lower than the true modulus because of the inclusion of deflection due to shear.

The load-deflection curve is linear in the early stage, and following the limit of proportionality, the deflection increases appreciably with a relatively small increase in load. After a maximum load value is reached, the load values decrease with increasing deflection until failure results (figure 14).

The mode of failure and stress distribution in a beam is largely determined by stress-strain relations for compression and tension parallel to the grain. As the load on a beam increases, the stresses increase linearly until the limit of proportionality in compression is exceeded at the extreme fibre on the compression side of the beam. The extreme fibres begin to buckle, but initially the deformation is small and their load-carrying capacity probably remains fairly constant. Fibres below the extreme fibre buckle in turn to produce a macroscopic wrinkle at one or more sections in the compression zone of the beam. As this load-sharing process continues across the depth of the compression zone, the compression wrinkle progresses towards mid-height of the beam and the stress over much of the compression zone is approximately constant and equal to the maximum crushing stress. The extreme fibre stress in tension steadily increases until the maximum tensile stress is reached at the extreme fibres and failure results. Just prior to failure, the stress distribution on the compression side of the beam is approximately rectangular over most of the section and equal to the maximum crushing stress, decreasing rapidly to zero value at the neutral plane; on the tension side of the beam, the stress distribution is approximately linear, varying from zero at the neutral plane to the value of the maximum tensile stress at the extreme tensile fibres. The neutral plane moves from the initial position at mid-height of the beam towards the tension face. The stress distribution assumed for calculating the modulus of rupture varies linearly from equal maxima values at the extreme fibres in compression and tension to zero at the neutral plane, which is assumed to be at mid-height of the beam. The calculated value of the modulus of rupture in compression is about twice the actual maximum compressive stress; in tension, the value is about half the actual maximum tensile stress.

Figure 14. Load-deflection curves for wood in bending parallel to the grain



The nature of the failure on the tension side of the beam varies with species and may be splintery or brittle in appearance. If loading is stopped just prior to failure on the tension side of the beam, even though compression wrinkles are present, and the beam is turned upside down and reloaded, the maximum load required to break the beam is nearly as great as that which would have been needed to break the beam in the first case. The buckled fibres in the previous compression zone are pulled straight in their new role in the tension zone, while compression wrinkles now occur in the new compression zone. The resultant fracture on the tension side of the beam is brittle in nature.

The modulus of rupture is dependent on the type of loading on the beam. It is lower for a beam subjected to loading at the quarter points (four-point loading) than for a beam loaded at mid-span (centre-point loading). The difference varies with species but is about 10 per cent on the average. In four-point bending, the maximum load depends on the weakest section between the load points where all sections are subjected to the maximum bending moment; in centre-point bending, the maximum load depends on the strength of the material at sections close to the centre of the span where the bending moment is at a maximum value. The chance that the weakest section of the beam is at midspan is relatively small, so the modulus of rupture of a beam in centre-point bending tends to be higher than that in four-point bending.

The centre-point values are taken as the basis for design stresses, appropriate consideration being given to other types of loading.

The modulus of elasticity in centre-point bending is calculated from the load-deflection curve for the full span and is up to 16 per cent lower than that calculated from the deflection in four-point bending, which is measured between the load points. This is because in centre-point bending the deflection over the full span is due to the effects of bending moment and shearing force, whereas the deflection between the load points in four-point bending is due to bending moment only, as the shearing force is zero in this region. The modulus of elasticity of wood parallel to the grain has the same value whether determined by tension, compression or pure bending.

Because beams, in practice, are generally subject to shearing force, the modulus of elasticity quoted for design purposes is that obtained from tests in centre-point bending, and thus no extra allowance for shear deflection need be made for solid beams. When shear deflection needs to be considered, as, for example, in the design of I-beams, an appropriate increase in the modulus of elasticity is made to bring it close to the value for pure bending.

4. Shear

A block shear test is made on 50 or 20 mm cubes in accordance with the British standard. The specimen is attached firmly in a steel loading block and tested in single shear in the direction of the fibres and over sections radial and tangential to the growth rings. The distance between the sheared edges is 3.2 mm in the 50 mm specimen and 1.6 mm in the 20 mm specimen. The specimen is deformed at the rate of 0.6 mm/min for both sizes. At CSIRO, a torsion test is also made on a cylindrical section of solid wood 38 mm in diameter.

The shear strengths from block shear and torsion tests are closely correlated, but the value from the torsion test is somewhat higher, probably because the torsion test is freer from the stress concentrations and tensile stresses perpendicular to the grain that are inevitably induced in the block shear test.

Wood is much weaker in shear parallel to the fibres than perpendicular to the fibres. Hence, in beams subject to excessive shearing force, failure is by longitudinal shear and not by transverse fracture.

5. Impact

The impact tests for wood tested in Australia are not included in the British or American standards. A toughness impact test, described in Technical Bulletin 479 of the United States Department of Agriculture, is made on a specimen 250 mm long and 16 mm square in cross-section. The specimen with the fibres parallel to the length is freely supported at each end and loaded at the centre in the radial or tangential direction by means of a high-speed pendulum. The work done in breaking the specimen is measured.

A further type of impact test, the Izod test, specified in British standards such as DTD-36B, 1939, is performed on a cantilever specimen of 22 mm square cross-section, notched as in the Charpy impact test for metals. Load is applied to the end of the cantilever by means of a high-speed pendulum. The fibres are parallel to the length of the specimen and the load is applied in the radial or tangential direction with respect to the growth rings.

Impact testing is useful as a means of estimating the ability of wood to absorb shock loads and further as a means of detecting the presence of certain defects in wood not obvious to the eye but which should be avoided in certain uses of wood. The impact strength of wood is sensitive, for example, to the presence of brittle heart and incipient decay.

6. Cleavage

The cleavage specimen is 45 mm long and 20 mm square in cross-section or 95 x 50 x 50 mm, with the fibres parallel to the length. A deep groove of special shape is machined across one end face of the specimen to permit loading perpendicular to the grain and in the radial or tangential directions. The remaining area, subjected to cleavage, is approximately 20 mm square in the small specimen and 76.2 x 50 mm in the larger specimen. The cleavage test is a combination of tension perpendicular to the grain and splitting. The rate of lateral deformation is 2.5 mm/min. The load necessary to split the specimen per unit width is referred to as the cleavage strength and is indicative of the splitting tendency of the wood. The result is of value, for example, in assessing nail and screw holding properties. Such factors as the orientation of growth rings, irregularities of grain, dimensions of medullary rays, the presence of resin canals and arrangements of the different tissues affect resistance to splitting.

7. Hardness (Janka)

The force required to indent a piece of wood with a ball 11.28 mm in diameter to a depth of 5.64 mm at a rate of 6.5 mm/min is known as the Janka hardness value. Hardness is determined for the radial, tangential and end surfaces. The specimen size is 150 x 50 x 50 mm.

The hardness value correlates closely with the density of the wood.

B. Factors affecting the mechanical properties of clear wood

1. Species

The mechanical properties of different species of wood vary considerably, some species being many times stronger than others. Within any one species, moreover, there is also a wide variation in properties. In species of low strength, some pieces of wood may be three or four times as strong as other pieces of the same species. In eucalypts, however, the ratio between the strongest and weakest pieces is about 2. The variation in strength within a species is such that great importance should not be attached to small differences, say, those of less than about 10 per cent, in the average properties of different species.

The variation in strength properties within a species is due to such factors as density, rate of growth, percentage of latewood and conditions of tree growth. Environmental factors affecting tree growth, such as height above sea level, geographical location, climate, soil conditions, aspect and spacing between trees, all have an effect on density. Because of the great number of factors involved and their interactions, little clear evidence is available on their separate influences.

2. Age

The age of the tree, at least in the early years of its life, has an effect on the strength of the wood. Strength increases fairly rapidly with age and after about 30 years full strength is achieved, although it will vary from year to year with seasonal conditions.

The rate of growth, that is the number of rings per inch, has been taken as an indicator of strength. Specifications often impose limits for rate of growth because very rapidly grown and very slowly grown wood are often weaker than wood having a more moderate rate of growth. During the early years of the life of the tree, growth is rapid and the wood is weak compared with that laid down during mature years. In the years following maturity, the rate of growth is very slow and the wood is also of low strength. It has been shown that the apparent high correlation between rate of growth and strength does not in fact exist. Instead, age rather than rate of growth appears to be the factor controlling the strength of the wood.

3. Position in tree

The way in which the strength properties vary with the height in the tree depends on the species. In softwoods, the wood from near the butt of the tree is usually denser, stronger and harder than that from near the top, but in some of the eucalypts the reverse holds true. The effect of height in the tree, however, is usually variable and only rarely of practical significance.

The variation in strength in the radial direction with distance from the pith is of importance: material from near the pith tends to be weaker in some species. Away from the pith, strength properties tend to vary erratically, presumably with seasonal growing conditions. In plantation-grown species, the variation of strength properties with distance from the pith can be very large. As an example, in 40-year-old trees of radiata pine, a twofold increase in density and a fourfold increase in bending strength have been observed in samples taken from pith to bark. A rise of 50 per cent in density and 100 per cent in bending strength is not unusual in 30- to 40-year-old trees of this species.

The zone of wood called brittle heart, which surrounds the pith in many hardwoods, contains wood fibres having compression failures in the walls. Such failures are believed to be the result of excessive compressive stresses arising at the centre of the tree during growth. The extent of this zone varies with species and with the diameter of the tree, but in general, it represents only a small proportion of the volume of the tree. The static strength properties of brittle heart are similar to those of normal wood provided no decay is present, but the impact strength is very low; hence, it is not usually used for structural purposes.

4. Percentage of latewood

The percentage of latewood is the proportion of dense wood laid down towards the close of each growing season to the total wood laid down for the year. Since it is closely correlated with density, a high percentage of latewood is generally a good indication of high strength. This fact can be used to advantage in the selection of wood with prominent bands of latewood.

In the United States, higher working stresses are permitted for Douglas fir, in which the latewood exceeds 35 per cent of the total wood.

5. Density

Density is highly correlated with strength. The specific gravity of wood substance is 1.5 regardless of species, but the arrangement of the substance in the cells and in the total structure reduces the density to a much lower value. Strength depends very much on the relation between the cell wall thickness and the width of the cell lumen. This relation varies with the growth conditions and the age of the tree. The following approximate relationship between strength and density of both green and air-dry material have been found for variability within a species:

$$\text{Strength} = K \times \text{density}^{n}$$

where n is 1.25 for modulus of rupture and maximum compression strength parallel to the grain, 2-2.25 for impact strength and 2.5 for compression perpendicular to the grain and hardness. K varies with the property and the moisture content of the wood. Density is calculated on the weight of oven-dry wood and the volume at the particular moisture content. The major strength properties (modulus of rupture and compressive strength parallel to the grain) increase approximately in proportion to density. Compression perpendicular to the grain, hardness and impact increase at a much more rapid rate.

Despite the high correlation, only about 80 per cent of the variation in strength is due to variation in density. Part of the discrepancy is due to extractives and deposits, which add to density but not to strength. Consequently, even density is unable to precisely predict the strength of a piece of wood. Nevertheless, density can be useful in reducing the chances of obtaining pieces of timber with strengths lower than particular values. Certain specifications, particularly for timber for aircraft use, set minimum densities for each piece to ensure that the required minimum strength is attained.

6. Reaction wood

Compression wood, formed in bent or leaning trees of softwood species, has abnormally high shrinkage, is denser and somewhat stronger than normal wood but is very brittle. In a severe form, it is noticeable as dark-coloured bands; in a mild form, it is not readily detected by visual examination.

Tension wood, formed in bent or leaning trees of hardwood species, exhibits high shrinkage but has little effect on strength properties. It is detectable in sawn wood by the stringy appearance of the surface.

7. Variability of clear timber within a species

The variability in the mechanical properties of wood within a species makes it a time-consuming task to determine those properties. A sufficient number of specimens per tree and a sufficient number of trees must be tested to determine the species mean with adequate precision. To estimate the species mean to within + 5 per cent, between 5 and 20 trees are sampled.

The results of such tests show that, in each case, a large number of values for each property are distributed close to the mean value, with a small number distributed well above and below the mean value. The amount of the variability is defined from the mean value, $\bar{x}$, and the standard deviation, σ.

The greater the value of σ, the greater the dispersion of the individual values of a property about the mean value and the greater the probability of obtaining material exhibiting very high or, more important, very low values. Approximately 95 per cent of the material has strength values lying within the range $\pm 2\sigma$, so that the value $\bar{x} - 2\sigma$ will be exceeded by all but 2.5 per cent of the material of the species. An estimate of the variability from the mean is essential for deriving design stresses.

The value $\sigma/\bar{x}$, expressed as a percentage, is called the coefficient of variation and is often used as a measure of variability. Its disadvantage is that it is dependent upon the mean, so for two species with the same standard deviation, the weaker will have the larger coefficient of variation.

Coefficient of variation values for the strength properties of green wood of 50 species tested in the United States are shown in table 12. The values for air-dry wood may be assumed to be similar. Similar values have been found for Australian hardwoods.

Table 12. Coefficient of variation for the strength properties of 50 species of green wood (Percentage)

Property	Coefficient of variation
Static bending	
Modulus of rupture	16
Modulus of elasticity	22
Compression parallel to the grain	
Maximum crushing stress	18
Modulus of elasticity	29
Shear parallel to the grain	
Maximum shear stress	14
Compression perpendicular to the grain	
Stress at limit of proportionality	28
Tension perpendicular to the grain	
Maximum tensile stress	25
Hardness	
End	17
Side	20
Toughness	34

8. Moisture content

Water is contained in the wood cell as free water in the lumen and as combined water in the wood tissue. The total weight of the water in the wood may exceed the weight of the dry wood tissue. Removal of the free water during seasoning of the wood does not affect the strength properties of the material. The moisture content of the wood, expressed as a percentage of the oven-dry weight of the wood substance, is approximately 30 per cent after the free water is evaporated but while the cell wall is still saturated. This level is referred to as the fibre saturation point. As drying continues below fibre saturation with removal of the combined water, the strength properties increase 1.5-5 per cent for each 1 per cent reduction in moisture content. 6/ Conversely, as dry wood takes up water, its strength decreases correspondingly.

The average percentage changes in various properties per 1 per cent change in moisture content are shown in table 13.

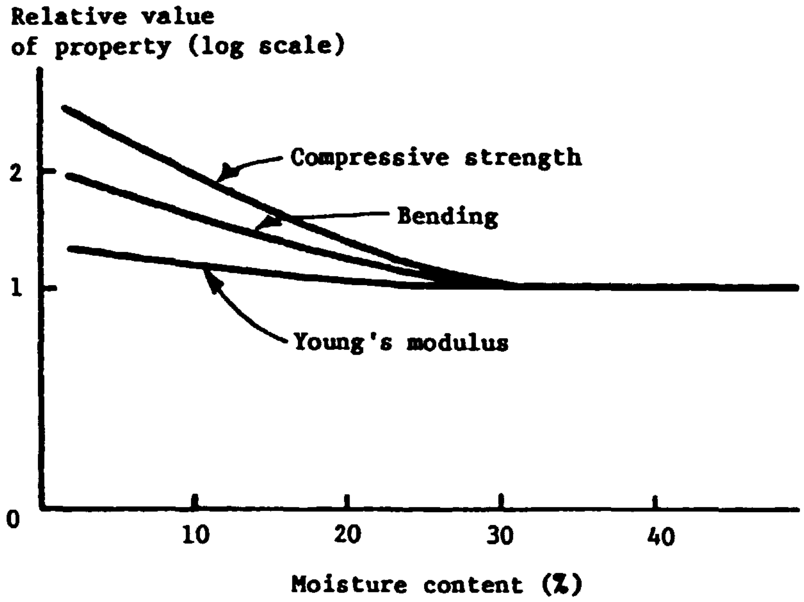
Table 13. Change in property for every 1 per cent change in moisture content
(Percentage)

Property	Change
Modulus of rupture	4
Modulus of elasticity	1.5
Maximum crushing strength	5
Maximum shear strength	3
Compression perpendicular to the grain	5
Tension perpendicular to the grain	2
Hardness	
End	4
Side	3
Torsion	
Maximum shear stress	3
Modulus of rigidity	2

Some species show an increase in impact strength with drying; others show a reduction at first, followed by an increase as the moisture content is reduced below 12 per cent. Still other species show a continuing reduction.

Figure 15 shows the change in some properties with change in moisture content.

Figure 15. Variation of mechanical properties of wood with moisture content



The following approximate relationships have been taken from figure 15:

$$\frac{\text{Maximum crushing strength at 12 per cent MC}}{\text{Maximum crushing strength at 30 per cent MC}} = 1.9$$

$$\frac{\text{Modulus of rupture at 12 per cent MC}}{\text{Modulus of rupture at 30 per cent MC}} = 1.6$$

$$\frac{\text{Modulus of elasticity at 12 per cent MC}}{\text{Modulus of elasticity at 30 per cent MC}} = 1.2$$

When the properties of different species or of individual pieces of wood are compared, they should be compared for wood of the same moisture content.

Since drying is a slow process in hardwoods and in larger pieces of softwoods, structural timber may be green or only partly dried when used. This applies also for imported timbers such as Douglas fir (Oregon pine), which is imported in large flitches that do not dry appreciably in transit or storage and that are resawn to smaller sizes on order. The unrestricted drying that usually occurs in structures may lead to checks and other defects in timber members that can offset the increase in strength due to drying. Consequently, working stresses are based on the strength of green timber.

9. Temperature and strength

Immediate effect of temperature

If other conditions remain the same, when the temperature of wood is raised, it generally becomes weaker in most strength properties, and when the temperature is lowered, it becomes stronger.

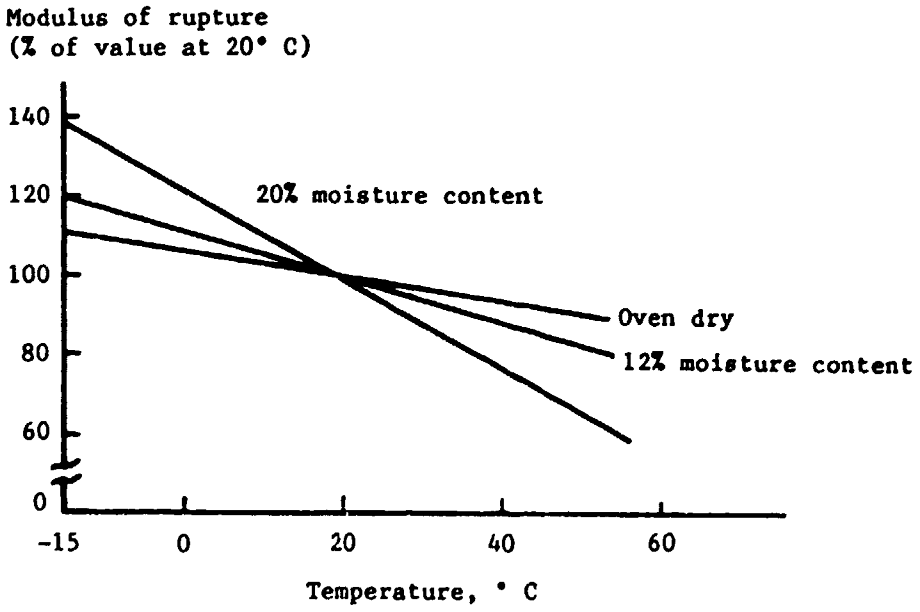
Temperature may also affect strength by altering the relative humidity of the atmosphere and, hence, the moisture content of the timber. Sometimes an increase in temperature is accompanied by a reduction in moisture content, and so the weakening due to temperature alone may be offset by the increase in strength that accompanies drying. At other times, high humidity may accompany high temperatures, and the weakening effects of higher moisture content and temperature will be additive. The following discussion will be limited to timber at constant moisture content.

The effect of temperature alone on strength is immediate, and its magnitude depends upon the moisture content of the wood and, when the temperature is elevated, upon the time of exposure. For most structural uses under ordinary atmospheric conditions, wood exposed to above-normal temperatures, if the exposure is for a limited period and the temperature is not excessive, can be expected to recover essentially all its original strength when the temperature is reduced to normal. Experiments indicate that air-dry wood can probably be exposed to temperatures up to about 65° C for a year or more without sustaining an important permanent loss in most strength properties; however, its strength while heated will be temporarily less than its strength at normal temperature.

The approximate immediate effect of temperature on most static strength properties of dry wood (12 per cent moisture content) within the range -15° to 65° C can be estimated as an increase or a decrease in the strength at 20° C of 1 per cent per degree Celsius decrease or increase in temperature. 7/ The change in properties will be greater if the moisture content is high and less if the moisture content is low. In some geographical locations, high temperatures are common but the relative humidity is low. Wood exposed to such conditions will generally have a low moisture content, and the immediate effect of the high temperature is not so pronounced as in locations where wood has a higher moisture content.

Figure 16 shows the approximate temperature and moisture content relations that apply for modulus of rupture in bending.

Figure 16. Relationship between modulus of rupture and temperature for wood at various moisture contents

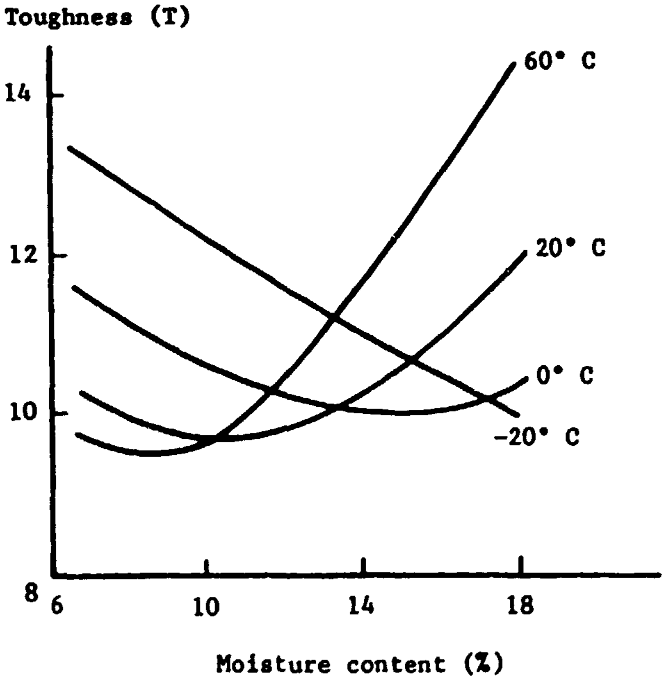


Tests conducted on wood at about -100° C show that the important strength properties of dry wood in bending and in compression, including stiffness and shock resistance, are much higher at that extremely low temperature than at normal temperature.

The compressibility of wood greatly increases when the wood is heated, providing the moisture content is not too low. The strain in partly seasoned wood subjected to steaming and loaded parallel to the grain is increased greatly at maximum load compared with strain under normal conditions. Steaming has much less effect upon the tensile properties, and the strain at maximum stress is not greatly increased.

As shown in figure 17, toughness generally decreases with rising temperature at low moisture contents and increases with rising temperature at high moisture contents. This may be because toughness is a function of strength and deflection. Below 12 per cent moisture content, the deflection of a beam does not increase much with rising temperature, so there is little or no increase in its ability to absorb impact loads. Above 12 per cent moisture content, the deflection of a beam increases with rising temperature, so toughness tends to increase, too.

Figure 17. Variation in the toughness of wood (impact resistance) with moisture content at various temperatures

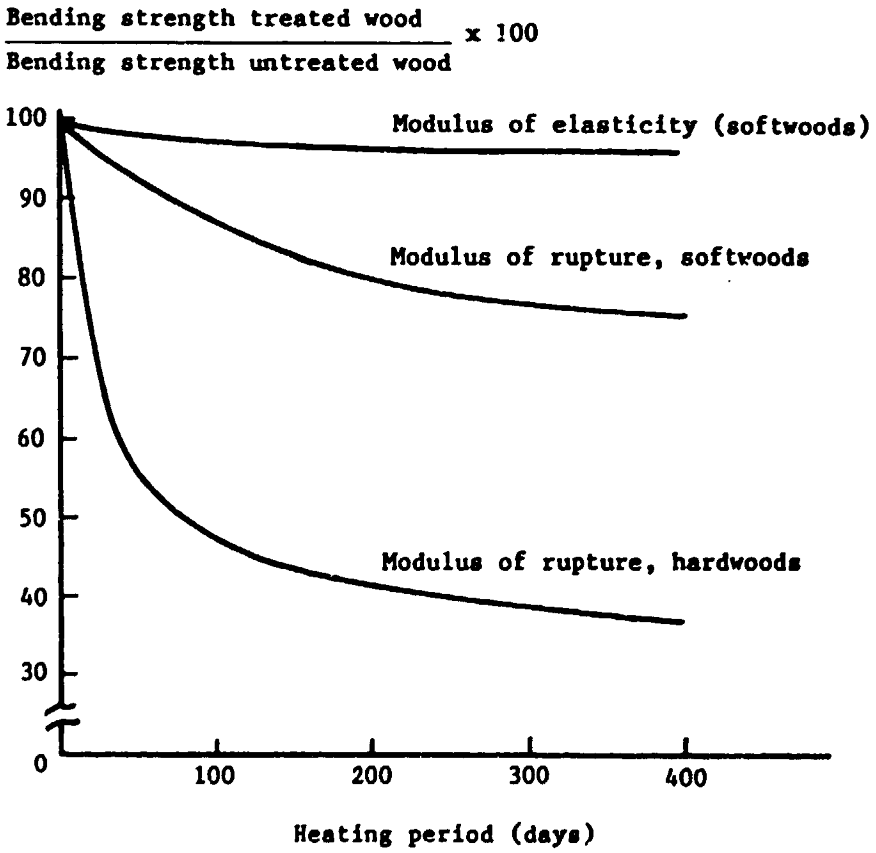


Permanent effect of exposure to high temperatures

When dry wood is exposed to temperatures above 65° C for extended periods of time, it will be permanently weakened, even though the temperature is subsequently reduced and the wood is used at normal temperatures. The permanent or non-recoverable strength loss will depend upon a number of factors, including the moisture content and temperature of the wood, the heating medium at time of exposure, and to some extent the species and the size of the piece. In the following discussion, losses in strength are understood to be permanent losses, measured at normal temperature, after exposure to high temperatures for various periods. Reductions in strength would be substantially higher if measured at the elevated temperature.

Broadly, the avaiable data indicate that wet wood will suffer a permanent loss in strength if it is heated above about 45° C. Exposure to higher temperatures will result in increasingly greater strength losses in shorter periods of time as the temperature is increased. Strength properties are affected differently by exposure to high temperatures. The shock resistance of wood, as measured by the area under the load-deflection curve (work to maximum load), is the first bending strength property affected to a measurable degree regardless of the species, temperature or heating medium. Modulus of elasticity, a measure of stiffness, is least affected. The effects of heating on the bending properties of wood exposed to water at 85° C for various periods are shown in figure 18.

Figure 18. The effect of heating on the bending properties of wood exposed to water at 85° C for various periods, then tested at 20° C and 12% moisture content



The effect of high temperature on various species is different but, in general, hardwoods are affected much more than softwoods.

The heating medium has a considerable bearing on the reduction in strength that results when wood is exposed at a particular temperature for various periods of time. At all temperatures, exposure to hot water causes a somewhat smaller loss of strength in a given period of time than does exposure to steam; exposure to a hot press has a considerably smaller effect than exposure to hot water, and the smallest effect comes from exposure to hot, dry air.

The effect of exposure to high temperatures on the strength of wood is cumulative. For example, if wood at a particular moisture content is exposed six different times to a temperature of, say, 65° C for one month each time, the overall effect would be approximately the same as for a single exposure of six months.

The shape and size of wood pieces can be expected to influence the overall temperature effect in relation to the heating medium, exposure time, moisture content and the strength properties considered. If the exposure is for only a short time, so that the inner parts of a large piece do not reach the temperature of the surrounding medium, the immediate effect on the strength properties of the inner parts will be less than the effect on those of the outer parts. On the other hand, the outer fibres of a piece stressed in bending are subjected to the greatest load and will ordinarily govern the ultimate strength of the piece; hence, the fact that the inner part is at a lower temperature may be of little advantage.

For long-extended exposures, it can be assumed that the entire piece reaches the temperature of the heating medium and will, therefore, be subject to permanent, non-recoverable strength losses throughout the volume of the piece, regardless of size. It should be recognized, however, that in ordinary construction service, such as in buildings, the temperature of the air surrounding the wood varies considerably during the day and the seasons of the year and that the wood itself, or at least any substantial part of a member, is not likely to reach the maximum temperature of the surrounding air. This is true particularly of the larger or structural members.

In designing a timber structure for exposure in the tropics, the engineer must allow for the combined effect of high temperature and high moisture content, and the SAA Timber Engineering Code provides for this.

Industrial buildings in which normal operations generate high temperatures and high humidities that may affect the structure must be designed to take into account the effects of these factors on the strength of wood.

10. Duration of loading

The permissible stresses and moduli of elasticity for structural timbers are derived from the results of standard mechanical tests on the various species, appropriate allowance being made for factors such as material variability, defects, type of engineering structure, service conditions and a factor of safety. Included in the service conditions are the effects of duration of loading on the strength and stiffness of the wood.

Most materials exhibit time-dependent behaviour when subjected to sustained loading, i.e. dead load, or continued restraint. Such rheological phenomena are important in the usage of the materials, particularly in engineering applications. The rheological behaviour of a material is influenced by its physical and chemical structure, its previous history, the type and magnitude of the loading and the environment in which it is contained. For hygroscopic materials such as wood, the moisture content and environmental fluctuations in moisture content may have a pronounced effect on rheological properties.

Creep in wood and wood products

When a wooden member is subjected to any type of sustained load, it undergoes an immediate deformation, which may consist of recoverable and irrecoverable components, depending on the magnitude of the stress and the time taken to apply the load. For low stresses, i.e. stresses less than two to three times the permissible stresses used in engineering design, and very short times of loading, i.e. times similar to those occupied in performing standard mechanical tests in a laboratory, the deformation that results from application of the load may be considered to be elastic in nature. As the time under load is increased, the deformation continues to increase, but at a gradually diminishing rate; it consists of a delayed elastic component, which is recoverable when the load is removed, and an irrecoverable component. This time-dependent behaviour is referred to as creep. At low stresses, the creep rate may gradually approach zero.

Factors such as temperature and moisture content affect the amount and rate of creep; increases in these factors lead to greater deformation.

After removal of the applied load, an immediate elastic recovery occurs that is similar in magnitude to the immediate deformation that occured when the load was applied. A further gradual reduction in deformation occurs with time and continues for a considerable period, the rate of recovery gradually approaching zero. An irrecoverable component, i.e. a flow component, remains in the wooden member.

Typical creep behaviour in wood is illustrated in figures 19 and 20.

Figure 19. Creep-time curves for wood at constant conditions of temperature and moisture content

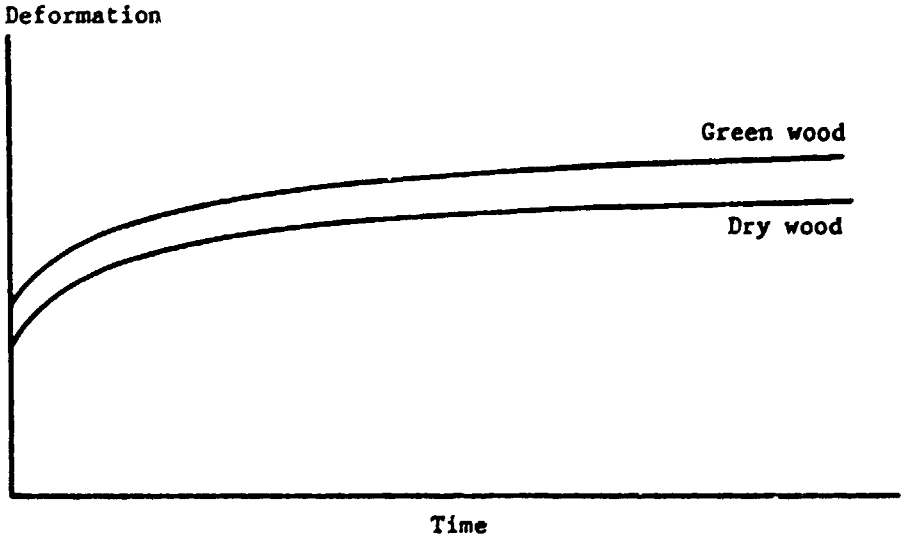
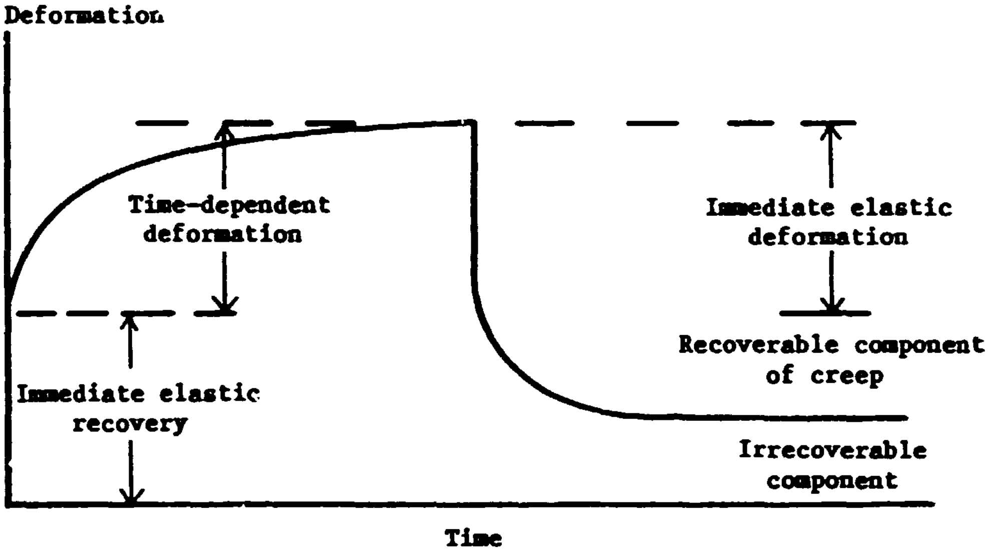


Figure 20. Components of creep



At high stress levels, i.e. at stresses above about 55 per cent of the short-term ultimate stress, the initial pattern of behaviour is similar to that already described; after a time, however, the deformation increases again at an increasing rate until failure occurs. It is possible that for very low stresses, deformations may vary in this way if the duration of loading is very extensive; however, the periods involved would greatly exceed the economic life of wooden structures. The influence of stress on creep in wood is illustrated in figures 21 and 22.

Figure 21. Deformation-time curve for wood at various stress levels

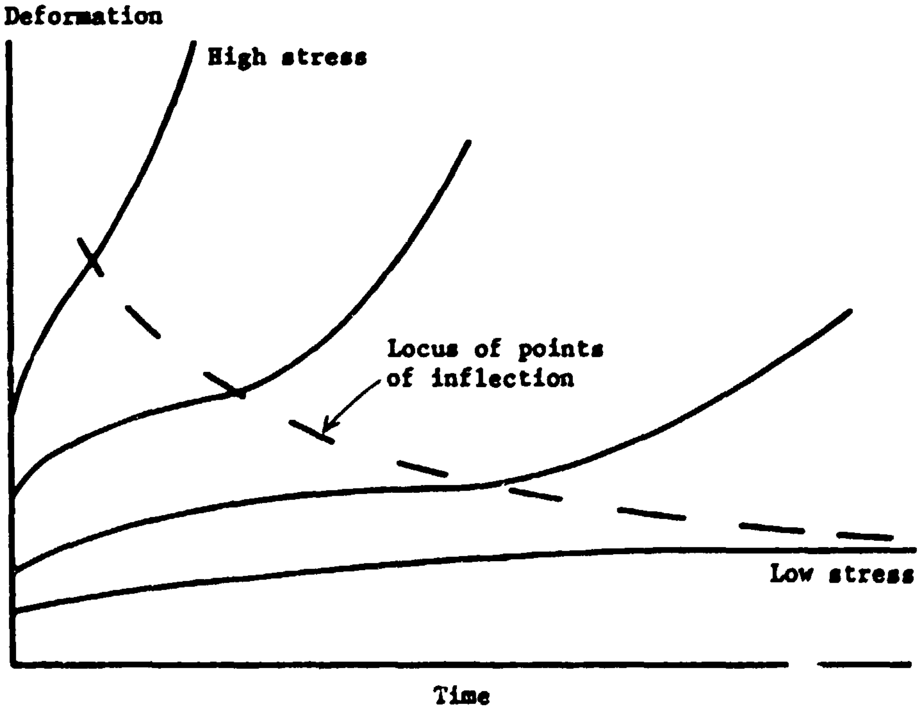
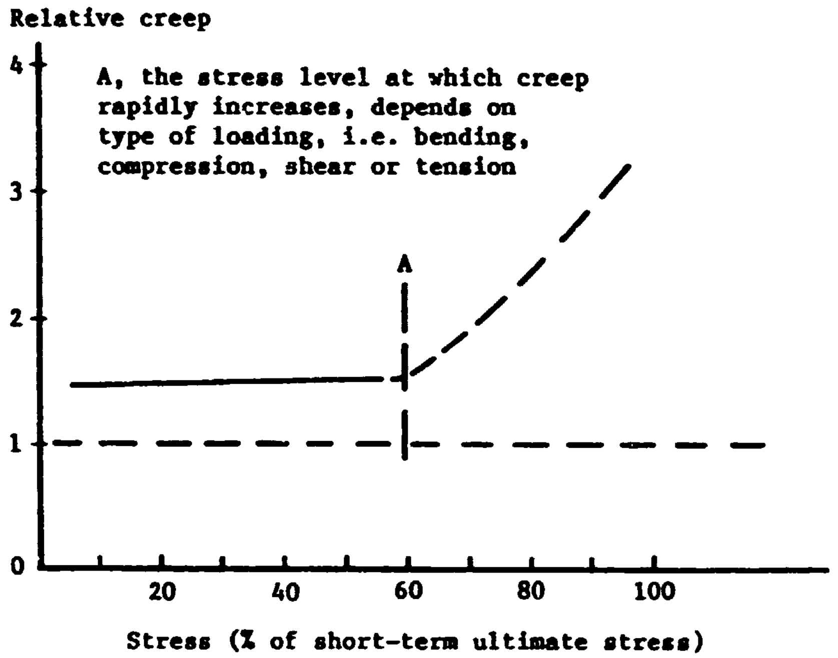


Figure 22. Effect of stress on relative creep



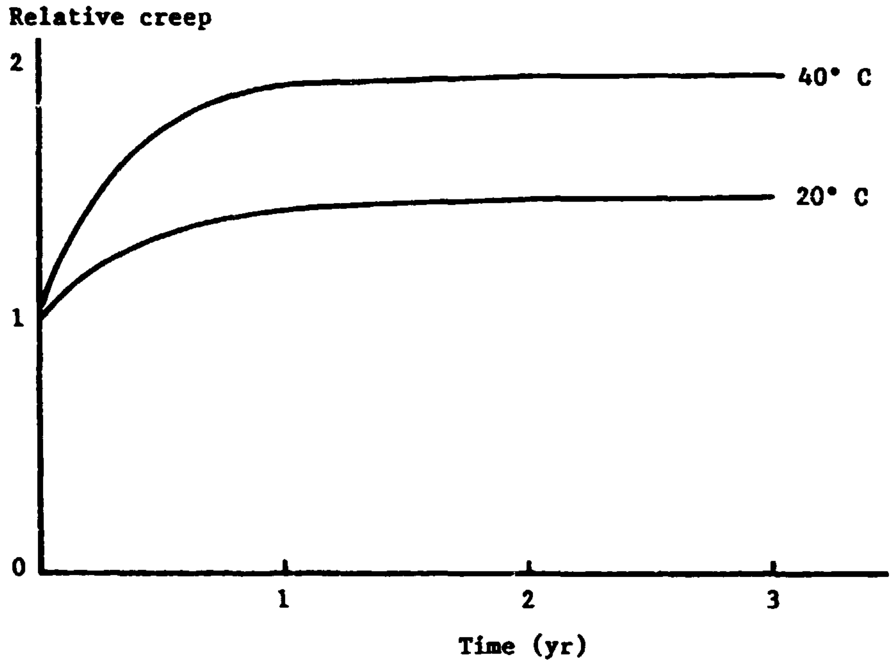
Relative creep, i.e. total deformation expressed as a multiple of the initial elastic deformation arising on the application of load, is little affected by stress level at stresses below about 55 per cent of the short-term ultimate stress; above this value, however, the relative creep may be greatly affected. The creep rate of wood in bending increases markedly at a stress level near 60 per cent of the short-term ultimate stress and in compression, at a stress level near 70 per cent. It is possible that the transition stress level is higher for wood in tension.

When wood is subjected to sustained loading parallel to the grain in bending, compression, shear or tension, at stresses of up to about half the short-term ultimate values, provided the moisture content is maintained constant at any value and the temperature is maintained constant at values of less than about 50° C, the total creep deformations over several years amount to between 50 per cent and 100 per cent of the initial elastic deformations. Most of the creep occurs within the first year, and the creep rate becomes very low after that time. In tests on five hardwood species and five softwood species, no marked differences in creep behaviour were evident. Relative creep increases markedly with increasing temperature, e.g. relative creep at 40° C is about double that at 20° C.

Relative creep is unaffected by the moisture content of the wood, provided the moisture content does not vary during the period that the wood is under load. Relative creep in green or dry wood in a constant environment is illustrated in figure 23.

Some work has been done on creep in wood in compression and tension perpendicular to the grain of the wood, and the amount of creep appears to be slightly greater than that in wood stressed parallel to the grain. After the sustained loads are removed from a wooden member that has been loaded for several years, up to half of the creep is recoverable. The irrecoverable component increases with increasing duration of loading.

Figure 23. Relative creep in green or dry wood in a constant environment



Although creep in plywood, at least in bending, appears to be similar to that in solid wood, wood products such as hardboard and particle board exhibit very much greater creep; in contrast to wood, relative creep in these sheet materials increases greatly at increased moisture contents. The difference in behaviour is probably due to the differences in the nature and degree of bonding of the components of the natural and processed materials. Creep values of between 40 per cent and 500 per cent of the initial elastic deformations have been measured over one month in hardboard and particle board at moisture contents from 10 per cent to 18 per cent. The creep behaviour of hardboard, particle board and wood is compared in figure 24.

Stress relaxation

In wood held at constant restraint, the stress in the material diminishes or relaxes at a decreasing rate, to about 60 per cent of its initial value, over a period of several months. This phenomenon is illustrated in figure 25. The rate of relaxation rapidly approaches zero towards the end of that period. The stress relaxation-time curve is similar in shape to the creep-time curve, but its mirror image (figure 26).

Provided it remains constant, the moisture content of wood does not affect the percentage of stress relaxation. Temperature has a marked effect on relaxation behaviour. No marked effect of stress is evident at stresses below half the short-term ultimate value. Relaxing wooden members can fail if the initial strains exceed about 70 per cent of the average strain at failure in a short-term mechanical test.

The rheological behaviour of wood may be studied by creep or stress-relaxation methods, and either behaviour may be predicted from a knowledge of the other.

Figure 24. Relative creep in wood, hardboard and particle board (MC = moisture content)

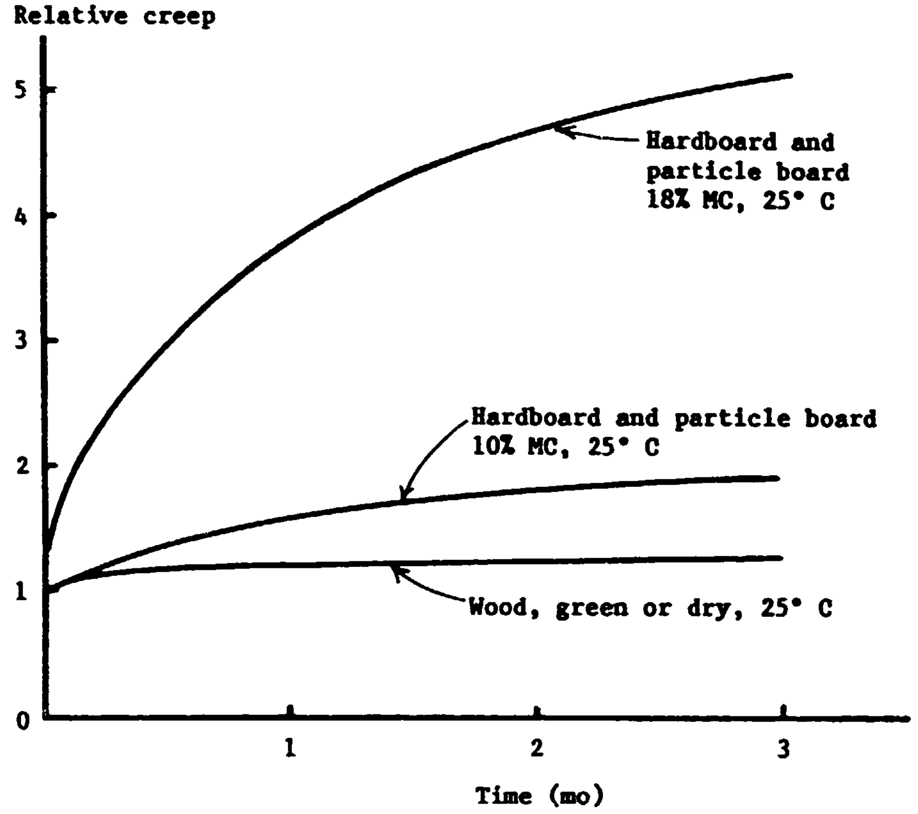


Figure 25. Stress relaxation in wood (green or dry)

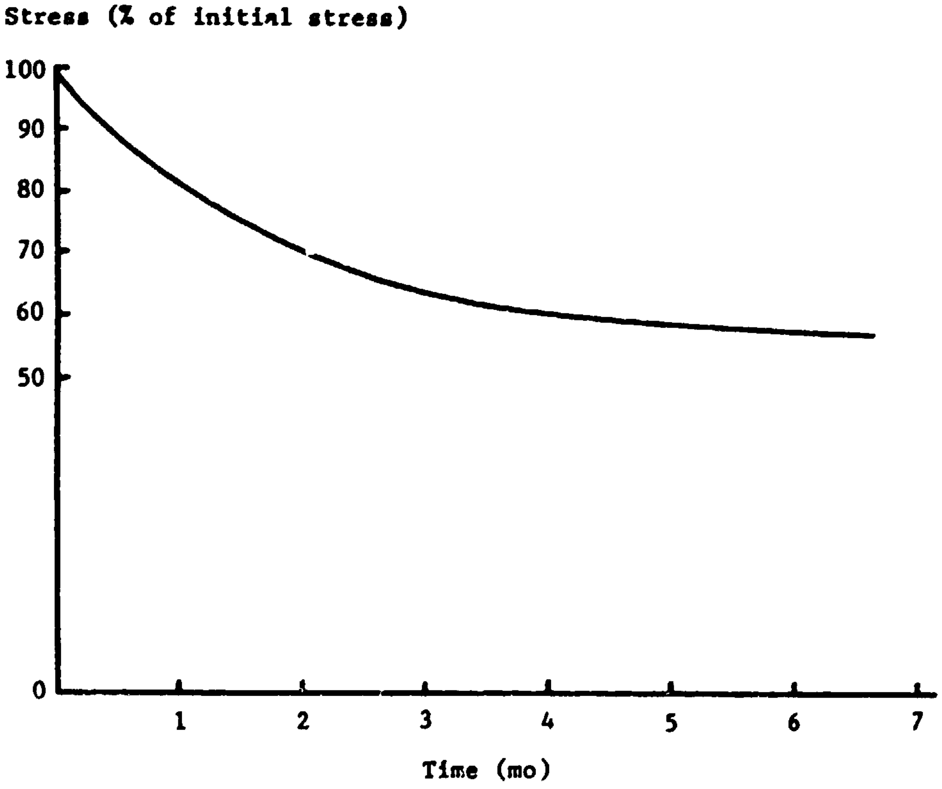
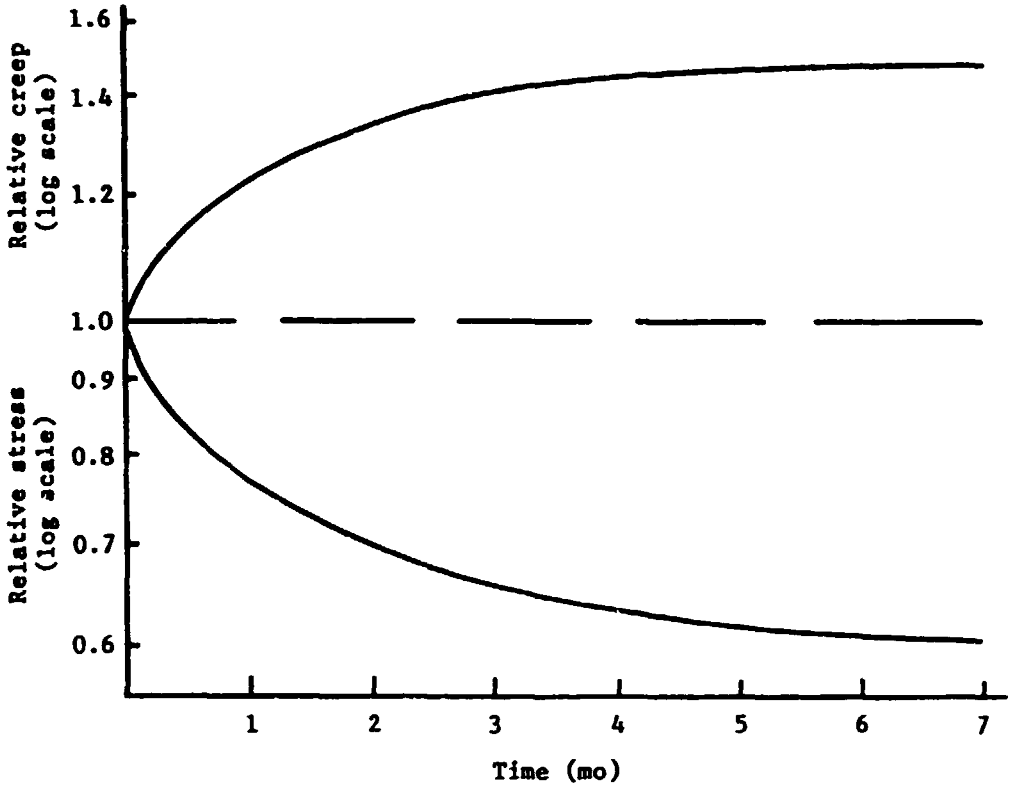


Figure 26. Creep and stress-relaxation in wood in a constant environment

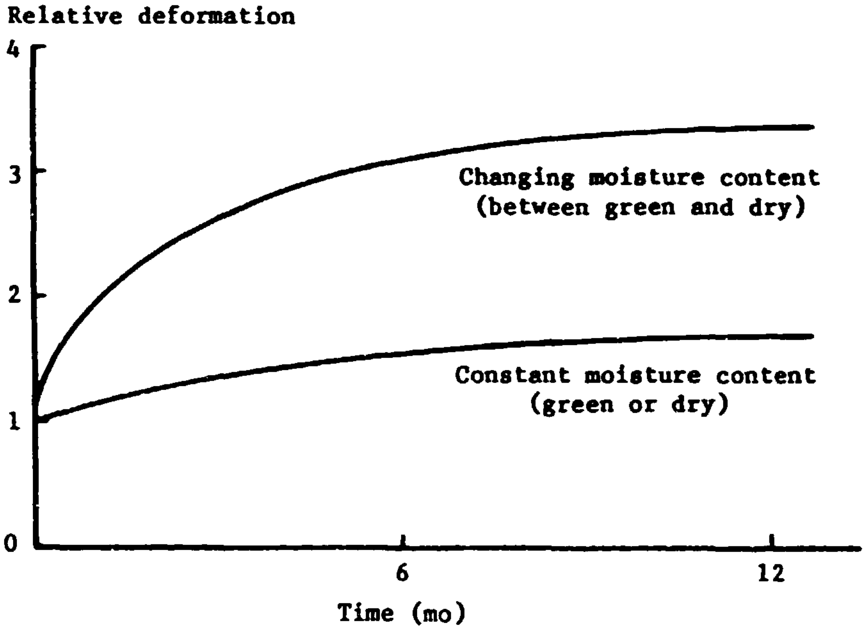


Mechano-sorptive deformation

Although the absolute values of creep deformation in wood are greater at high moisture contents, the relative creep values, i.e. total deformation at any time expressed as a multiple of the initial elastic deformation, are similar in magnitude in both green and dry wood. An extremely important phenomenon occurring in wood and wood products is the greatly enhanced deformation that arises during the simultaneous action of applied load and moisture content change. Mechano-sorptive deformation due to the interaction of load and moisture change probably arises in most hygroscopic materials. The behaviour of wood under prolonged loading in a constant and changing moisture environment is illustrated in figure 27.

When wood under any type of loading is subjected to an initial process of absorption or desorption of water, the deformation due to the applied load increases markedly during the period of moisture content change, with the amount of the increase being dependent on the size of the moisture content step. Depending upon the type of loading and the size of the moisture step, the initial deformation may increase by as much as 600 per cent or 700 per cent. In comparison, creep in wood in a constant environment may reach 100 per cent of the initial elastic deformation after several years. The largest mechano-sorptive deformations for a given moisture step arise in wood in compression; intermediate values arise in wood in bending and shear; and the smallest values arise in wood in tension. The behaviour of hardboard and particle board is qualitatively similar to that of solid wood, but quantitatively the effects are very much greater in the former materials. The quantitative effects in plywood appear to be in between those for solid wood and particle board or hardboard. Stress relaxation in wood under restraint is increased greatly during moisture changes.

Figure 27. Effect of moisture content change on the relative deformation of wood under sustained loading



When wood beams initially at a high moisture content are subjected to moisture cycling, i.e. alternate processes of desorption and absorption, the deflections increase during all desorption processes and show little change or small decreases during absorption processes. The result is a continuing increase in total deflection, as increases in deflection during desorption of water predominate. The wood can fail if the moisture cycling is sufficiently extensive. The mechano-sorptive behaviour of initially green beams drying under load, followed by moisture content fluctuations with climatic changes or other environmental effects, is shown in figure 28.

Wood beams initially at a low moisture content exhibit deflection increases during the first absorption process and during all desorption processes and exhibit no change or small decreases in deflection during absorption processes after the first one. The mechano-sorptive behaviour of dry wood during moisture content fluctuations following environmental changes is illustrated in figure 29.

Figure 28. Mechano-sorptive deformation in wood beams drying from the green state, followed by small moisture content fluctuations due to climatic or similar environmental changes

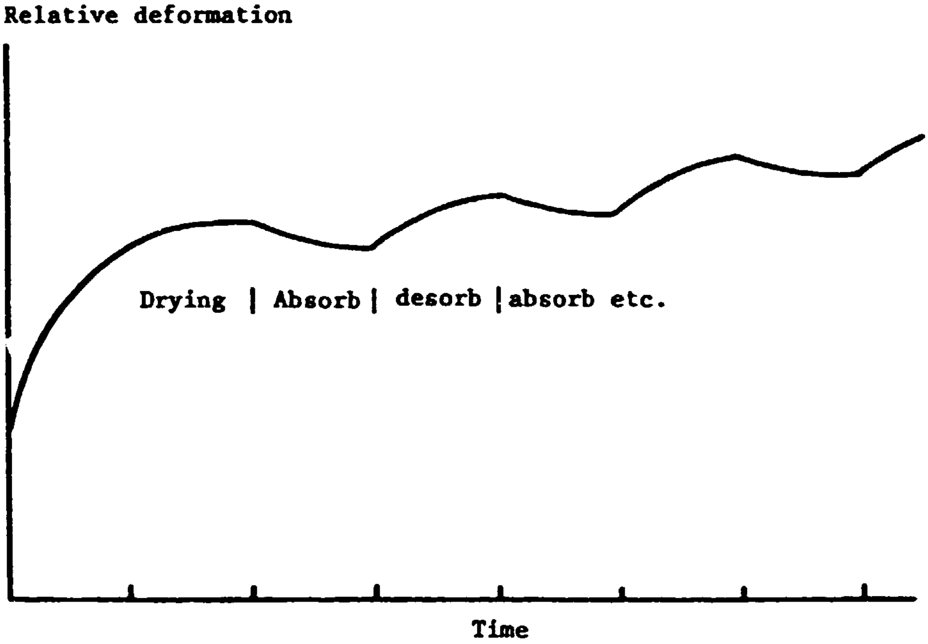
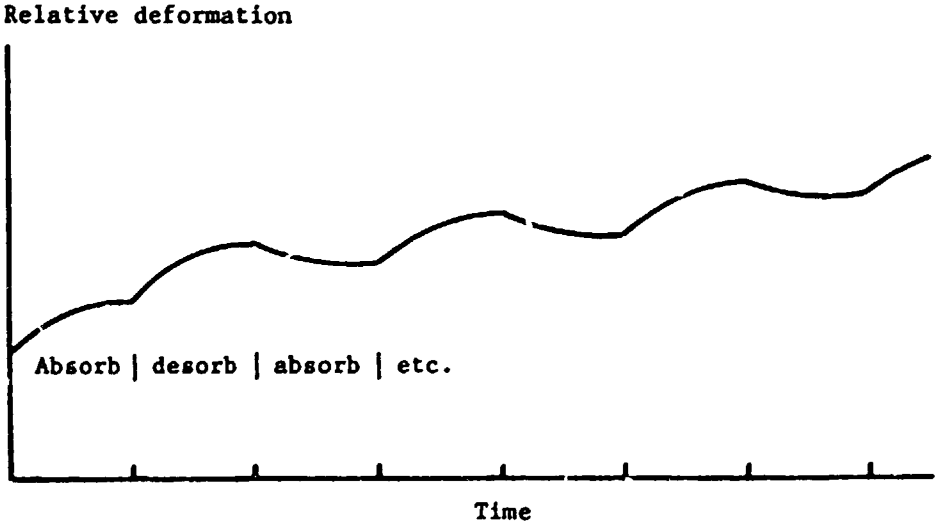
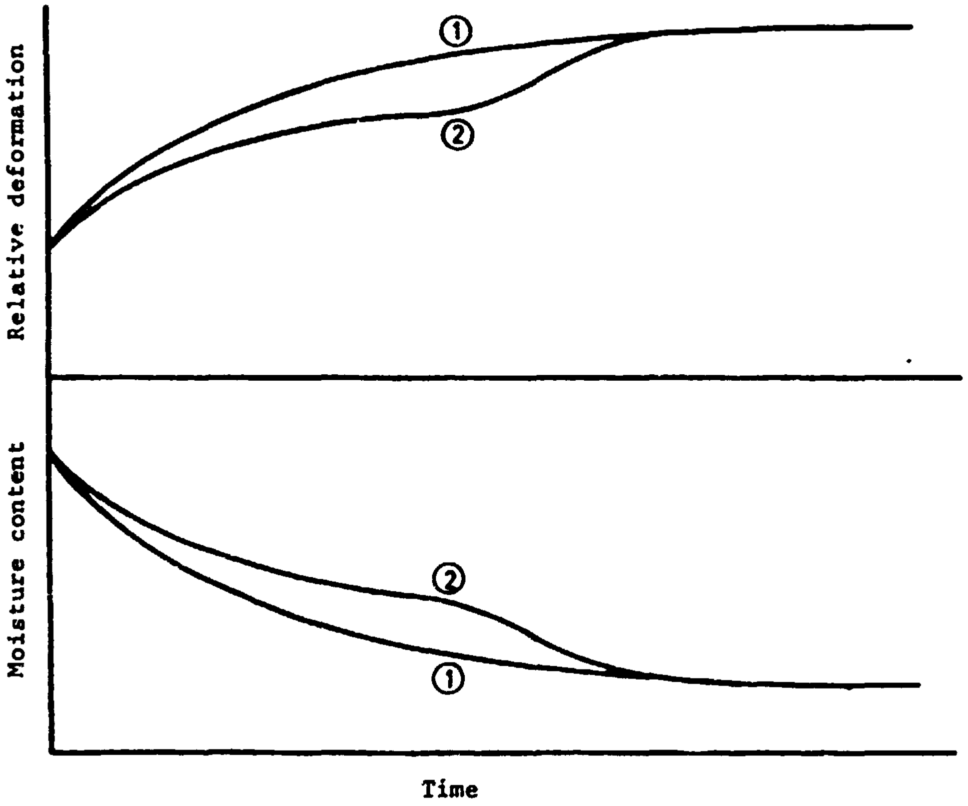


Figure 29. Mechano-sorptive deformation in beams of dry wood subjected to moisture content fluctuations with environmental changes



The magnitude of the increase in deflection is proportional to the magnitude of the change in moisture content, and although the rate of change in moisture content affects the rate of change in deflection, it does not affect the magnitude of the deflection. This behaviour is illustrated in figure 30. The transient effects on deflection are moisture-dependent and are not time-dependent. The behaviour described has also been produced in very small samples of wood in which cyclic changes in moisture content were induced in a few minutes; the magnitudes of the effects were similar to those in large samples in which the cyclic changes occurred over periods of days or even months.

Figure 30. Mechano-sorptive deformation in beams drying at different rates over a similar moisture content step



The phenomenon described cannot be explained simply in terms of swelling deformations, swelling stresses or changes in strength or in Young's modulus at different moisture content values; in fact, correction for some of these factors enhances the quantitative behaviour.

In wood species prone to collapse during drying, the mechano-sorptive deformations arise throughout drying from the green state, whereas in non-collapsible species, the deformations occur only during drying below about fibre saturation level. With collapsible hardwoods, mechano-sorptive deformations in structural timbers drying from the green state can reach two to three times those that occur in non-collapsible hardwoods and softwoods. A considerable reduction of mechano-sorptive deformations in collapsible species can be achieved if the timber is partially dried before it is installed in a structure, if it is allowed to dry in the structural frame before service loads are applied, or if it is given temporary support to reduce the influence of service loads during drying.

In a structure erected in green timber that dries under service loads, the mechano-sorptive deformation occurring during the large intial moisture decrease may amount to several times the initial elastic deformation. In subsequent years, the structure will continue to deform in small increments owing to the combination of creep and mechano-sorptive deformation that occurs annually with climatic changes.

In a structure erected in dry timber, the total deformation is very much smaller than that occurring in an initially green timber structure because there is no large initial change in moisture content with its corresponding large increase in deformation, although the increments in deformations due to time-dependent creep and mechano-sorptive phenomena will be similar in magnitude in subsequent years to those in green timber that has dried. The differences in behaviour of these two types of structure were illustrated in figures 28 and 29.

Under the conditions usually met with in Australia, annual increases in deformations of structures amount to less than 5 per cent of initial elastic deformations, but where abnormal moisture fluctuations arise under indoor or outdoor exposure, much larger increases in deformation can occur. Moisture fluctuations in timber can be reduced by applying surface coatings or impregnating the wood with water-repellent materials.

In the SAA Timber Engineering Code 5/ and the SAA Timber Framing Code, 8/ factors of 2 and 3 have been adopted in stiffness calculations for members in bending and compression to allow for the described effects of duration of loading in dry and initially green wood, respectively. In accepting the factor of 3 for initially green wood, account was taken of the fact that a substantial amount of drying occurs in green timber between the time a log is processed and the time at which service loads are applied to the sawn timber in a structure. Where practical conditions differ from this, the factors may need to be increased.

The phenomenon of the interaction between load and moisture change in wood may be used to advantage: moisture changes may be induced in restrained wood to help bring about desired deformations, e.g. the removal of distortions from buckled or twisted boards or panels, by the weighting of timber stacks during seasoning to reduce bow and twist in planks.

Reduction in strength under sustained loading

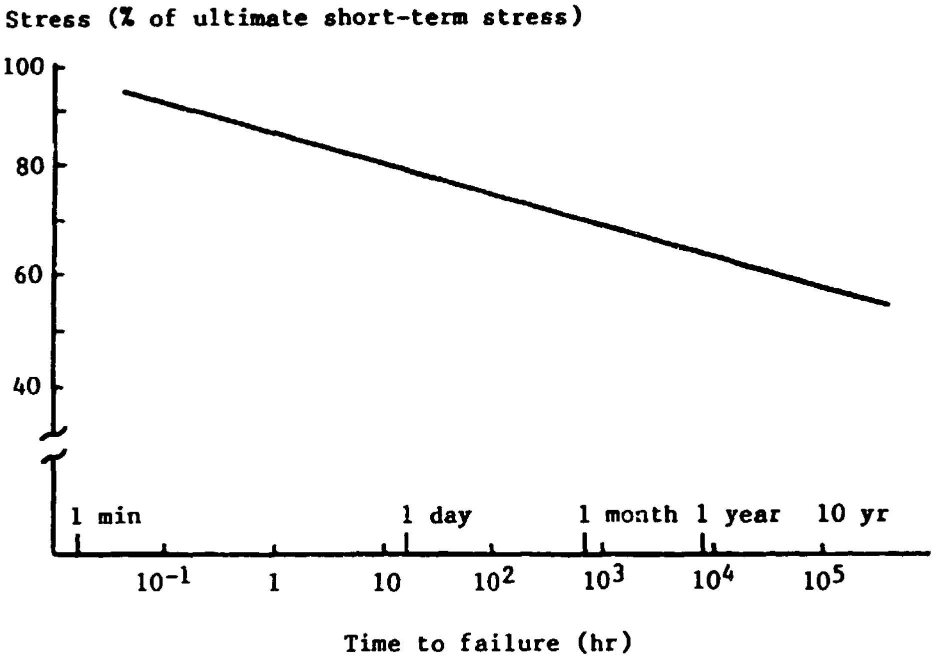
The strength of wood decreases markedly as the duration of loading increases. In bending, the long-term strength of wood for a loading period of about 50 years has been predicted to be approximately 56 per cent of the short-term ultimate strength. The amount of the reduction in strength appears to be similar in both green and dry wood.

In deriving permissible stresses for timber for design purposes, reduction factors are applied to allow for the effects of sustained loading on strength. For example, a reduction factor of 9/16 is used for bending. Where loads will be applied for periods of less than five years, the permissible stresses may be increased. The appropriate multiplying factors for various periods of loading are given in the SAA Timber Engineering Code. 5/

The relationship between stress level and time to failure in bending, as determined by Wood, 9/ is illustrated in figure 31. Unpublished work by Armstrong 10/ on green, initially green and air-dry wood loaded in bending, compression and shear, confirm Wood's results for bending but indicate significantly greater reductions in strength in compression and shear.

The derivation of basic working stresses from the results of mechanical tests and their modification to provide permissible stresses for structural timber are discussed in other chapters.

Figure 31. Effect of sustained loading on the strength of wood in bending



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V. CONVERSION OF TIMBER

Mervyn W. Page*

Introduction

To satisfy the world's current needs for forest products, approximately 3 billion m^3 of logs are extracted from forests annually. Most of this wood, in fact a little over half, is consumed as fuel, including charcoal, and most of the fuel is used in domestic situations. Of the remainder, approximately 30 per cent of the total extracted log volume is converted into sawn timber, railway ties and veneer, while approximately 18 per cent is employed for such uses as poles, piles, pit props, pulp, particle board and fibreboard and for tannin and distillation products.

The world production of sawn timber, the commodity that is of particular interest here, is approximately 440 million m^3. North and Central America are by far the largest producers of sawnwood, between them accounting for 38 per cent of the total production.

The contributions to the total supply made by the various regions (in one case, a country) of the world are as follows:

North and Central America	38%
Union of Soviet Socialist Republics	18%
Europe	18%
Asia	17%
South America	5%
Africa	2%
Oceania	2%

North and Central America and Europe both export up to 30 per cent of their production. Of the Asian countries, Indonesia also exports 30 per cent, while Malaysia and the Philippines export about 60 per cent of their total sawn output.

Approximately 77 per cent of the world's sawn timber supply is obtained from coniferous species, the large producers of coniferous timber being North America, the Union of Soviet Socialist Republics, Europe and Asia. The important producers of sawn hardwood are Asia, North and Central America, Europe, the Union of Soviet Socialist Republics and South America.

The uses of sawn timber are legion. In the larger sizes, normally up to about 360 x 360 mm in section, sawnwood is used in heavy construction, such as bridges and wharves, while in the smaller sizes, usually down to about 70 x 38 mm, sawn timber is probably the world's most widely used structural material for domestic house construction. In between these size limits, timber is also used extensively as framing for industrial buildings, in industrial flooring and roofing, in stairways and in similar applications.

Timber is also, however, an important material where decoration, as well as strength and stiffness, is required. It is used for wall panelling and

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trim, for furniture and joinery and decorative flooring. The sizes required for such uses are seldom larger than 75 x 300 mm but can be as small as 19 x 12 mm or even smaller.

Clearly, then, sawn timber must be produced to satisfy one or the other, but sometimes both, of two distinct quality requirements. Timber for structural purposes must have sufficient strength and stiffness, and for many such uses its appearance is of little consequence. On the other hand, appearance is the main consideration for timber intended for decorative uses, but at the same time the pieces must have sufficient strength for the intended end use.

World-wide, there are a confusing number of grades, particularly strength grades, but in actual practice most individual mills produce no more than two or three strength grades and two appearance grades at one time. However, many mills cutting for the general-purpose market produce a wide range of sizes and lengths, and in some of these mills the output is sorted and graded, according to size, length and grade, into as many as 120 classifications.

The logs from which these timbers are cut do themselves also vary in size, namely in diameter and length. In addition, they vary in quality in that they can contain a range of blemishes and defects, the presence of which cannot always be detected from the external appearance of the log. However, the size and location of these defects must be restricted in the final sawn sizes if these are to meet the specifications of particular grades.

The aim in sawmilling, then, is to convert the round, tapering cylinder of a log into rectangular pieces of various dimensions, each having a regular cross-section along its length, and to do this in such a manner that the growth ring orientation and the location and size of defects in each piece conform to a desired grade specification. In addition, the sawing should be efficient in respect to accuracy, speed and cut width.

As logs can contain a range of defects that usually become apparent only after sawing has commenced, it is not possible to produce every piece to a desired grade specification, particularly at the production tempo of modern industry; consequently, the mill output must be sorted and graded into the various qualities, sizes and length classifications after sawing.

High-capacity mills cutting small-diameter logs usually have sufficient time per log to saw each log to desired sizes only, and all quality grading is done after sawing. From small logs, the range of sizes that can be produced is limited by the small diameter of the log, and such logs are usually processed by high-speed, mass production techniques.

Mills cutting very large logs usually have sufficient time per log to produce sizes and grades according to the wood quality that is being revealed as sawing of the log proceeds. This practice has become known as "grade sawing" and is the process traditionally employed in mills producing a wide range of sizes from logs larger than about 450 mm diameter.

A. Characteristics of saw logs

Several defects occur naturally in trees, and consequently in saw logs, and have an influence on both the conversion process and the utilization of sawn timber.

1. Heartwood

Heartwood or corewood is the central portion of a log and includes the pith and the adjacent wood which is sometimes defective. In coniferous species it frequently appears to be quite sound. Often, however, it is less dense and less strong than normal wood and is unsuitable for uses where these properties are critical. In addition, the heart region contains a knotty core, even in logs from pruned plantations or from trees that have undergone some self-pruning.

In Australia, "heart" in softwoods is referred to as pith, and in the main plantation conifer, *Pinus radiata*, the pith region usually contains spiral grain. This fibre orientation causes twisting during drying and necessitates special seasoning techniques to produce straight dried products.

In hardwoods, the heart region is usually defective, although it may not always appear to be so. The two main forms of heart in hardwoods are:

(a) Brittle heart, which is wood near the centre of the tree. It has very low impact strength, although it may appear quite sound;

(b) Decayed heart and pipe, which is where the centre of the tree is either decayed or eaten away by termites, resulting in the well-known "hollow log", usually referred to in the industry as "pipey" log. Although the wood around the outside of the pipe may appear sound, it can be brittle and/or it can contain incipient decay.

Heartwood is not always in the exact centre of a log. It can be eccentric and it can wander about the geometric centre of the log along its length.

In hardwoods the "heart" or core must usually be excluded from sawn products and the sawmilling process must provide for heart material (defective portions around the pith) to be removed from the sawmill at various stages throughout the milling process.

2. Knots

Knots result when overgrown branch growth contained within the tree is cut across by rip-sawing and thereby exposed on the surfaces of the sawn timber. The presence of knots in sawn timber can reduce strength by causing deviations of the grain around the knot and in certain cases by loss of structural section. In addition, they can adversely influence appearance, particularly if they are not intergrown with the surrounding wood.

From the utilization point of view, it is important which way the included branch is bisected during conversion. If timber is produced with a back- or flat-sawn growth ring orientation, knots appear on the sawn surfaces as round knots, whereas on the faces of quartersawn timber they occur as spike knots. Generally, from both strength and appearance points of view, round knots are preferred. The conversion process must therefore provide a means of rotating the log to a wanted orientation before sawing commences and of turning flitches before subsequent resawing.

3. Bumps

When branches are pruned from a living tree, either mechanically or by the tree itself, the subsequent overgrowth of the branch stub can sometimes be associated with decay. Unfortunately, there is no means of determining before sawing commences whether or not decay is present.

The presence of an overgrown branch stub is usually indicated by a swelling on the surface of the log, the size of the swelling indicating the extent of the overgrowth but giving no indication whatsoever whether or not decay has taken place. As decay must either be excluded altogether from some products or strictly limited in others, the likelihood that decay will appear in a log during sawing requires the sawmilling system to be flexible enough to allow the sawing machine operators to change their production intentions during the conversion process.

4. Pinholes

Pinhole attack is caused by ambrosia beetles, which bore straight holes about 1.5 mm in diameter in green hardwood trees or logs. When the wood dries, the beetles die and the infestation ceases. Coniferous species are not attacked.

Unless the holes are very clustered, their presence in structural timber is usually not of importance, except where there is decay associated with the pinholes. For decorative timber intended for clear finishing, however, they are often completely excluded, while for timber that is to be painted, their occurrence is limited by specification.

Again, unfortunately, the presence and certainly the severity of pinhole attack is often difficult to determine from the external appearance of the log, so the milling system needs flexibility of operation to enable this defect in the finished product to be controlled.

5. Gum veins and pockets

Gum veins and pockets occur principally in a number of eucalypts. When susceptible trees are injured, either mechanically or by fire or by intensive insect attack or even sometimes by drought, the trees exude a gum or kino, which spreads like a shield over the injured tissue. In conversion, this material is revealed as pockets, veins or rings.

Gum is unsightly and is not permitted in timber to be used as panelling, feature flooring or the exposed parts of joinery or furniture. However, small gum veins can be permitted in timber to be painted or covered. In structural applications, gum veins and pockets mainly affect shear strength, and their size and location must be limited by specifications.

From the conversion point of view, logs that contain gum should preferably be converted into backsawn timber. This makes it possible to produce some pieces with one face clear of gum, which can be used in the many applications for which only one defect-free face is required, such as flooring, panelling and some joinery uses. On quartersawn timber, gum appears on both faces and there is a likelihood that corners will shell off.

6. Shakes

Shake is the partial or complete separation between adjoining layers of wood, due initially to causes other than drying. The two most common forms of shakes are the following.

(a) Star shakes, which are due primarily to radial and tangential growth stress gradients throughout the tree;

(b) Ring shakes, which are often caused by cambial damage to the growing tree and/or impact loads suffered by the tree when it falls. As shake constitutes an actual fracture of the wood, its influence in both structural and appearance applications is obvious.

In conversion the aim should be to confine shakes to the edges or corners of sawn pieces, so that they can more easily be removed during subsequent processing. This aim is best achieved if the first cuts in a log can be aligned along the major shakes, but this is frequently difficult because each end of the log exhibits a different shake pattern.

7. Spring

Spring is the longitudinal bending that takes place in both portions of a log or flitch as they are separated by a saw cut, the bending being towards the bark. This type of distortion takes place in most saw logs when they are sawn. However, it takes place to varying degrees and is not always troublesome. It is almost always more troublesome in hardwoods than in softwoods, in which it is seldom a problem. In particular it can be very troublesome in small, immature, fast-grown hardwoods.

Spring results from the release by ripsawing of growth stresses in the tree. In severe cases it requires making wasteful face cuts to straighten bent flitches and to reduce thickness variations. Sawn timber that is so distorted by spring to be beyond the limits of relevant specifications must be rejected. This influence on the utility of sawn timber can be substantially reduced if the pieces are produced to be backsawn rather than quartersawn. In this way the distortion is exhibited as bow, rather than spring, in the finished item, which is then much easier to straighten.

8. Log taper

As indicated earlier, one of the aims of sawmilling is to convert the tapering cylinder of a log into sawn rectangular pieces of uniform cross-section along their length. To achieve this, saw cuts can be made either parallel to the outside of the log, referred to as taper sawing, or parallel to the longitudinal axis of the log, referred to as parallel sawing. In practice, logs are sawn by a combination of both systems.

Taper sawing is somewhat slower to perform and therefore more costly than parallel sawing, but it results in straighter grain timber that distorts less during drying, machines better and has greater strength. Naturally the degree to which these advantages accrue depends on the amount of taper in the log. Some logs have such slight taper that little or no advantage results from taper sawing.

B. Sawmilling operations

The common types of equipment used in sawmilling will now be briefly described and any limitations in relation to dealing with the foregoing characteristics of logs will be discussed.

The primary or green sawmilling process can be divided into four distinct activities: (a) log sawing, (b) resawing, (c) docking and (d) sorting and grading.

1. Log sawing

Log sawing, which usually is the cutting from the log of flitches or other pieces for subsequent resawing to either width or thickness or both, is carried out on machines or combinations of machines called "headsaws" or "head rigs".

The most common head rig is a combination of either a band-saw or a circular saw and a log carriage that carries the log backwards and forwards past the saw, enabling a saw cut to be made on each forward trip or on both forward and backward trips ("double cutting").

The equipment used to load the log onto the carriage incorporates log-turning devices that permit the log to be rotated into the most favourable position for conversion before sawing commences and to be subsequently turned into new positions during processing.

The log is held on the carriage by headblocks, which can be accurately transversed across the carriage so that pieces of wanted dimension can be cut from the log. These headblocks can also be moved independently of each other, permitting the log to be oriented for taper sawing.

Carriage and saw combinations offer a very flexible production system that can cope with natural defects as they are revealed during sawing. However, as cutting is sequential even when double-cutting saws are used, the system is relatively slow compared with multi-saw machines and is therefore more suited to larger logs. Sawing speeds seldom exceed 1.5 m/sec.

Carriages vary in degree of mechanization, from very simple machines on which all adjustments are made manually to large, fast machines on which all the operations are remote-controlled. As well as being used with a headsaw, carriages can also be used with a chipping head, which operates in front of the saw to reduce the outside portion of the log directly into pulp chips.

The machine that offers the highest production capacity, but which lacks flexibility, is the high-speed gang frame saw. This machine consists of a reciprocating sash, which carries a number of saws and through which the log is fed. As sashes can carry twenty or more saws and as log feed speeds can be as high as 0.5 m/sec, productivity can be very high. However, as all cuts are made at one time, the ability to deal with defects hidden within the log is limited.

A third type of machine, which affords a compromise between flexibility and high production, is known generically as a log edger. It consists of a means of supporting the log, either along its length or at its ends, and moving it between two, and sometimes four, saws.

On simple machines, the spacing between the saws is fixed and the logs are passed through the machine once only. On more advanced machines, the log can be reciprocated backwards and forwards between the saws, the spacings between which can be rapidly and accurately altered between passes. On the very latest machines, chipping heads are located in front of the saws, which can be either circular or band.

Log edgers, particularly the two-saw machines, offer some of the production flexibility of a sequential sawing system coupled with increased productivity, due to the use of multiple saws. In material prone to spring excessively, log edgers overcome the problem of face cutting, but like the gang frame saw, they saw parallel to the longitudinal axis of the log, unless the saw is oriented to taper saw on one side of the log only. At times this may have some advantages, but it also has the disadvantage that the other side of the log is then sawn directly against the taper.

2. Resawing

Resawing is the sawing to width or thickness or both of larger pieces produced by the log-sawing machines.

The most common type of resaw consists essentially of a horizontal table in which is arranged either a single circular saw or a single band-saw. The table also incorporates a fence or gauge, which is parallel to the saw line and which enables wanted timber dimensions to be produced by setting the gauge the desired distance from the saw line and causing the timber to be pressed against it while being passed through the saw.

On simpler machines, the feed of the timber is either fully powered or at least power-assisted and the timber being processed is passed backwards and forwards across the bench, only one piece at a time being handled. On higher production machines, the flitches, after passing through the saw, are returned to the in-feed side of the bench by a system of transfers or conveyors; this permits a second piece to be sawn while the first is being returned.

Since cutting is sequential, a high level of production flexibility is achieved, but the production capacity is relatively low. Capacity can be increased by employing two, three or four saws, but some flexibility is sacrificed.

Small carriage and saw combinations are sometimes used as resaws. They offer much the same advantages and disadvantages as the resaw benches just described, except that they can be less labour-intensive.

Reciprocating gang-saws are widely employed as resaws, giving very high production capacities, but, of course, reduced flexibility. However, where flitches for resawing can be prepared to a reasonably high quality, this reduction in grade-sawing ability may not necessarily be a disadvantage.

Multi-saw ripping machines are classified as resaws but are used mainly for cutting timber to desired widths. Such machines carry between two and twenty circular saws, the spacing between saws (or, on the larger machines, between banks of saws) being capable of accurate variation between cuts.

3. Docking or trimming

Docking is the cross-cutting of sawn pieces to produce wanted lengths or to upgrade the product by removing defects. Where the intention is to produce ordered lengths or simply to square uneven ends, the process is sometimes referred to as trimming.

In low-capacity mills, the sawn timber is simply conveyed lengthwise past an operator who, after deciding what cuts are necessary, controls a single cross-cut saw, either manually or by power. Such systems handle two or three pieces per minute.

At the other end of the scale, in large, modern mills the sawn timber is conveyed transversely past graders who, after deciding what cuts, if any, are needed, key this information into a computer. Subsequently the timber is conveyed, also transversely, either under or over a large bank of circular cross-cut saws, which under the command of the computer perform the cross-cutting pattern decided by the grader. These systems can handle up to 60 sawn pieces per minute.

4. Sorting and grading

After having been produced to wanted cross-sectional dimensions, lengths and grades, the sawn timber must then be prepared for marketing. It is sorted either into these classifications or into orders, although in many cases it is also seasoned and/or machine-profiled before sale.

In small mills, the grading and sorting is carried out by the dockerman and is then manually stacked, often by the same operator.

In medium-sized mills, the timber is conveyed past grading and sorting personnel by either a transverse conveyor or a circular table, from which the personnel manually build stacks of the timber they classify. Otherwise, graders place classified timber into a series of channels, along which it is conveyed on edge, each channel leading to a stacking area for one particular sort of product.

The larger, high-capacity mills have computer-controlled sorting systems in which sawn timber is moved transversely past equipment that measures and records its physical dimensions in a computer. A grader then inspects both sides of the piece and keys the appropriate grade into the computer. The piece is then conveyed over a series of storage bins, each holding a particular classification. As the sawn piece passes over the bin appropriate to its classification, the computer causes it to be deposited into that bin. Bins, when full, are emptied automatically and the timber is made up into stacks of sorted and graded wood.

The above descriptions are, by intention, very cursory and are intended to provide users of timber with a general understanding of some of the production philosophies, the problems and the manufacturing systems associated with the conversion of forests into sawn timber.

VI. SEASONING OF STRUCTURAL TIMBER

F. J. Christensen*

Introduction

In general, structural timber should be dried to an extent determined both by its required load-carrying capacity at the time of installation and its subsequent tendency to develop unacceptably high levels of drying degradation that would impair it structurally or aesthetically. Partial drying and possibly some redrying may be required for timber needing preservative treatment to combat high biological attack hazards in service. These guidelines apply to both sawn and round structural timber, which can generally be dried by the same methods and equipment.

Drying improves the physical properties of timber and its general performance in service. The advantages of dried over green (undried) timber are its reduced (a) mass, (b) cost of transporting, (c) tendency to creep under load, (d) susceptibility to biological decay and (e) capacity to develop severe drying degrade with possible loss of strength; and its increased (a) strength, (b) dimensional stability, (c) capacity to absorb preservative liquids during pressure treatment and (d) ease of handling. Within certain limits, the extent of these improvements depends directly on the size of the moisture change: the lower the moisture content, the greater the benefit.

The drying of timber can be complicated by the great diversity of species that are or could be used for construction in countries utilizing tropical forests for timber supplies. Problems also arise from the adverse effects of tropical climates, especially during monsoon periods, when the potential for air-drying is drastically reduced.

A. Timber drying principles

It is assumed that the reader now has an idea of the composition and structure of wood: the basic differences in structure between hardwoods (pored timbers) and softwoods (principally conifers) in terms of such structural elements as tracheids, vessels, fibres, cells, lumens, pits and rays; the major chemical components common to all woods; the distinction between sapwood and heartwood; the existence of growth rings, consisting of earlywood and latewood bands; deposits of various materials in the inactive cells of the heartwood; and the occurrence of growth stresses, reaction wood, spiral grain and corewood (juvenile wood). All of these factors influence the drying of wood and its subsequent appearance in one way or another.

1. Moisture content of wood

Water is a major component of wood, often accounting for more than half of its total mass in the green state. Its removal, either partial or almost complete, is the principal objective of the timber seasoning or drying process. The amount of water in wood, or its moisture content, is expressed as a percentage of the oven-dried mass of the wood substance:

$$\text{Moisture content} = \frac{\text{Mass of water in wood}}{\text{Mass of oven-dried wood}} \times 100\%$$

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There is a great deal of variation in green moisture content both within and between different species of timber and even in different parts of individual trees, but most values range from 50 to 150 per cent.

2. Optimum drying of structural timber

The amount of drying needed by timber before it is used in a structure can vary greatly, from virtually no drying at all in some cases to partial or complete drying in others.

During drying, all timber shrinks to a greater or lesser extent. It may also develop degradation in the form of splitting, checking and distortion (cupping across its width, and twist, spring and bow along its length). Provided strength requirements are met, the amount of drying required depends on how much shrinkage and degradation occur and how much can be tolerated in the end use. It may, for example, be used in an exposed position where appearance is important. Even if it were in a concealed position, subsequent distortion due to (further) drying out *in situ* could create additional work at a later stage of building or make some aspect of the structure unsightly.

All timber mouldings (flooring, architraves, skirtings etc.), joinery timbers (principally door and window frames, and window sashes), doors and cupboards should be thoroughly dried before being installed in a building.

3. Equilibrium moisture content

If wood is left for sufficient time, its moisture content will reach equilibrium with the conditions (dry bulb temperature and relative humidity) of the air to which it is exposed. This value is called the equilibrium moisture content (EMC) of the wood. If wetter than the corresponding EMC, the wood will dry out to that value; if drier, it will absorb moisture from its surroundings to increase to the EMC value.

Values for EMC range from 5 to 25 per cent, depending mainly on the country and its climate but also, occasionally, on extraneous factors such as plumbing leaks and inadequate ventilation under buildings on wet soils. The lower end of the EMC range occurs in very cold and/or very dry climates such as prevail in polar, desert or dry inland regions. The upper end occurs in very wet climates where the relative humidity remains high for prolonged periods. In most countries, the EMC is not a static value but one that varies to a limited extent throughout the year in accordance with the prevailing atmospheric conditions.

In most tropical regions, the EMC can be as high as 18-20 per cent near the coast during the monsoon and can then fall perhaps to 14-16 per cent in the drier seasons. In temperate regions, a yearly variation of 9-15 per cent is common. In dry desert regions, values are likely to be as low as 5-6 per cent. For air-conditioned buildings, the EMC is commonly about 8 per cent when both dry bulb temperature and relative humidity are strictly controlled with refrigeration units and is unpredictable when they are not controlled.

It is important to stress that it takes a finite time for wood to reach EMC. This time depends principally on its moisture content and thickness and on the magnitude and duration of the change in atmospheric conditions to which it is exposed. This can vary from a few days for thin timber subjected to a small change in EMC conditions to years for large sections of dense timbers at high moisture contents.

The practical result of changes in EMC on dry timber used in structures is their influence on its dimensional stability, i.e. the amount of shrinkage and swelling that occurs, mainly in the width and thickness of components. Although relatively slight in most cases, these periodic changes in EMC can cause doors and windows to expand and stick during the wetter parts of the year or cause unsightly gaps to develop in a variety of timber objects during the drier periods.

4. Fibre saturation point of wood

The fibre saturation point (FSP) is a useful concept in drying. It is the hypothetical moisture content at which all of the free water in the cell lumen or cavity has been removed while the cell wall is still saturated with water. The value of FSP varies from species to species from a low of about 22 per cent to a high of about 33 per cent. At FSP, certain wood properties begin to change: for example, normal shrinkage commences and most strength properties start to increase, two factors of interest to the structural engineer.

5. Shrinkage of wood

Green wood starts to dry from the outside inwards, since moisture flows from a region of high to low concentration. Therefore, at all stages of drying there is a gradation of moisture content varying from the current EMC value at the surface to the maximum moisture content in the interior of the wood. In the early stages of drying, the establishment of such a moisture gradient indicates that part of the wood is already below FSP and has started to shrink and that part is still well above FSP and has not started to shrink. Thus, changes in the external dimensions of the wood start when its average moisture content is still above FSP.

Normal shrinkage is usually expressed as the percentage change in green dimension of the wood from green to 12 per cent moisture content. From about FSP, shrinkage increases linearly with decreasing moisture content until the wood is almost oven dry. Individual values are given for tangential and radial shrinkages, which are roughly in the ratio 2:1. Values are sometimes given for unit shrinkage, i.e. the percentage change in shrinkage per 1 per cent change in moisture content. Unit shrinkage is used for estimating changes in dimensions between 5 and 25 per cent moisture content.

Wood does not shrink evenly in the longitudinal, tangential and radial directions. Mostly, the longitudinal shrinkage is negligible (<0.1%) and can be ignored, but it cannot be ignored when spiral grain is present. Normal shrinkage values for most species, from green to 12 per cent moisture content, are 2-8 per cent tangentially and 1-4 per cent radially. Thus, the way in which a piece of timber is sawn determines how much it shrinks in width and thickness. It also influences the type of drying degradation that occurs. The shrinkage in width of backsawn (flatsawn) timber is greater than that of quartersawn (edgesawn) timber of the same width, though the reverse is true in respect of shrinkage for equal thicknesses.

With some species, notably many species of the genus Eucalyptus, an abnormal form of shrinkage known as collapse occurs in the green wood down to FSP. Collapse has certain characteristics that make it easily recognizable, such as drying checks that pinch in at their edges, a general concavity of the faces or edges of a piece of timber or "washboarding" of its faces, and the occurrence of end checks in the earlywood. Shrinkage due to collapse can be of the same order of magnitude as normal shrinkage but is usually somewhat less. Much of it can be recovered by a steaming treatment known as reconditioning. This is most effective when given at an average moisture content of 20 per cent or less, a value which generally ensures that all parts of the wood have dried below the FSP and all collapse shrinkage has taken place.

6. Drying degrade, stresses and distortion

The occurrence of drying defects and the worsening of inherent defects in wood can usually be traced to the influence of shrinkage and its effect on the development of drying stresses. The strength property that determines the susceptibility of wood to checking and splitting during drying is its tensile strength perpendicular to the grain.

In the early stages of drying, wood at or relatively near the surface (the case) falls below FSP and wants to start shrinking but this tendency is resisted by the wetter, unshrunken wood in the interior region (the core). As a result, the case goes into tension and the core into compression. If the drying from the surface is too rapid and produces a steep moisture gradient, the shrinkage stress produced in the case may exceed the transverse strength of the wood and produce a fissure in the form of a split or check. This usually continues to worsen with further drying of the case until the core moisture content starts to fall below the FSP and the established stress condition starts to reverse.

At this stage of drying, the case has largely dried to EMC and most of its shrinkage has occurred. From then on, the core progressively dries and wants to shrink but is restrained by the already shrunken case. This places the core into tension and the case into compression. If the shrinkage stress in the core becomes too high, internal checking will occur. At the same time, the compressive forces exerted on the outer part of the wood may partly or fully close the surface checks and even narrow any splits near the surface. This is the normal condition after drying and is commonly known as case-hardening (not a good term, being dissimilar to case-hardening in metals). It can be relieved by a mild steaming treatment or a high humidity treatment that puts some moisture back into the case and relieves the drying stresses.

Moisture gradients in timber can lead to distortion if the timber is deep sawn or unevenly dressed after drying. For this reason, timber should be converted as nearly as possible to the final cross-section required before drying is commenced.

7. Factors affecting the drying rate

The three principal factors that affect the drying rate are the dry bulb temperature, the relative humidity and the velocity of the air passing over the timber in stickered stacks. These are commonly called the drying conditions. Increasing the dry bulb temperature increases the rate at which moisture diffuses from the interior to the surface of the timber. Decreasing the relative humidity and increasing the air velocity both increase the rate of evaporation of moisture from the surface of the timber. These principles apply irrespective of whether timber is air-dried under natural conditions or is dried under accelerated conditions in some type of drier.

With all other factors equal, the drying rate is also affected by the following: (a) the moisture content of the timber (the higher the moisture content, the easier it is to remove the moisture); (b) the permeability of the timber (the higher the permeability, the higher the rate of diffusion); (c) the structure of the timber (non-pored timbers have higher permeabilities than pored ones); (d) the thickness of the timber (the thicker the timber, the longer it takes to dry); (e) the density of the timber (the higher the density, the slower the drying); (f) the width of the stack (the wider the stack, the greater the lag in drying at its centre); (g) the sticker thickness (the thinner the sticker, the slower the drying within limits); and (h) the method of sawing (backsawn timber generally dries faster than quartersawn timber).

8. Drying schedules

A drying schedule consists either of one fixed set of drying conditions or a series of progressively more severe drying conditions determined by the declining moisture content of the timber.

It is usual to give schedules in terms of dry bulb temperature (DBT) and wet bulb temperature (WBT) or wet bulb depression (WBD): WBD = DBT - WBT. Measurement of WBT in preference to relative humidity, which can be obtained from DBT and WBT readings is based on (a) the better accuracy and reproducibility attainable with wet bulb temperature measurements, which are also not subject to the upper DBT limitations of relative humidity measurement, and (b) the unique relationship between WBD and EMC over the normal range of kiln temperatures, which gives a ready indication of the severity of the drying conditions being applied.

B. Timber drying practices

1. Stacking and handling

Stacking

Good drying results depend to a large extent on good stacking practices, irrespective of the method of drying used. The main purposes of stacking are (a) to provide uniform air circulation over the timber with the aim of promoting uniform drying conditions and (b) to minimize drying degradation due to distortion and checking. Different thicknesses of timber should not be dried in the one stack, but this can be done with groups of species having similar drying characteristics.

One of the first questions to be decided before setting up drying operations is the optimum stack size(s) to use, particularly if the use of driers is contemplated. Stack size must also be considered in relation to the lifting capacity of any mechanical handling equipment used for moving stacks about the seasoning yard.

Experience has shown that stack widths and heights between 1.6 and 1.8 m are optimum at most drying plants not employing mechanical stackers. Optimum stack lengths are more difficult to determine but are obviously related to the lengths of timber produced and the length of any driers used. The best decision is to use only one stack length or, failing that, a minimum number of stack lengths. Different lengths of timber can be accommodated in the one stack in several ways depending on their length. Alternate pieces that are longer than half the length of the stack are end-for-ended across each layer to give two square ends to the stack. Suitable spaces can be filled with shorter lengths. Timber should not be allowed to overhang the ends of stacks. The volume of timber in stacks commonly ranges from 70 to 100 per cent of the theoretical holding capacity.

Separating stickers placed between each row of timber are usually 40 x 20 mm in cross-section. They are spaced along the length of the stack at 400-900 mm centres, depending on the thickness of the timber. Stack bearers

100 x 75 mm in cross-section are placed under each row of stickers. Any variations in the thickness of stickers or timber can introduce distortion in the timber from lack of adequate restraint. Stickers must be kept aligned vertically to properly support the timber. The use of simple stacking guides can facilitate and improve stacking practices.

Handling

There are a number of mechanical handling systems in use in seasoning yards. Any system has to fulfil two functions: (a) handle stacks in the yard and (b) transfer stacks in and out of driers and steaming chambers. For yard handling, the choices of system are as follows: (a) forklift truck, (b) straddle truck, (c) overhead or gantry crane and (d) mobile jib crane. For drier handling, there are two choices: (a) lift and transfer truck system and (b) drier or bogey truck system. The use and selection of handling systems cannot be treated in detail here.

2. Methods of drying structural timber

There are many ways of drying structural timber, ranging from simple air-drying to sophisticated kiln-drying methods. Where a choice of drying method does exist, the determining factors are almost always (a) the cost of drying (including wastage from excessive degrade), (b) the final moisture content required, (c) the period of time available for drying and (d) the appropriateness of the drying technology in relation to the state of development of the country's timber processing industry.

The most appropriate methods of drying structural timber are considered to be air-drying, forced-air drying, pre-drying, and kiln-drying in screen, solar, progressive and conventional kilns. Each of these methods, together with an outline of the equipment needed, will now be considered.

Air-drying

This is the simplest method of drying, requiring the least infrastructure. However, capital investment in timber stocks can be high, particularly for slow-drying structual-size timber. For 40-50 mm thick hardwoods, drying from green to 15-20 per cent moisture content can take from 3 to 24 months or more, depending on the species and atmospheric conditions.

Good air-drying rates can be achieved during the drier months of the year in well-designed and maintained drying yards exposed to favourable winds. The basic requirements are an open, flat and well-drained site with roadways traversable throughout the year if mechanical handling equipment is to be used. For fastest and most uniform drying it is recommended that stacks be oriented lengthwise to the prevailing wind direction, not across it.

Good stack foundations are needed to provide adequate structural support for the stack. Otherwise, irregularities in foundation levels will be reflected in every piece of dried timber from the stack. Foundations are commonly of pier-and-beam construction, with a recommended clearance of 400-500 mm from the ground to the bottom layer of the stack. Piers should be of durable or treated timber, and beams should be stiff enough to carry the stack-supporting cross-bearers without undue deflection.

Side and end gaps must be allowed between all stacks in air-drying yards to provide for adequate air circulation through the stacks. For short, low stacks up to about 5 m long and 1.6-1.8 m high, side and end gaps of at least 600 mm are recommended. For long stacks of the same height, the side spacing should be at least 1 m and the end spacing, 1.5-2.0 m. A much wider space is needed every second or fourth row of stacks if handling is by forklift truck or mobile crane. In this situation, two or more stacks may be piled on top of one another to minimize infrastructural requirements. For such stacking, the side spacing should be 1.5-2.0 m and the end spacing 2.0-2.5 m. Spaces between and under stacks should be kept clear of weeds, scrap timber and other debris to ensure that free circulation of air is not impeded in the lower part of the stacks.

As mentioned earlier, air-drying rates are markedly reduced by unfavourable weather conditions, e.g. during the monsoon when the relative humidity is high and timber in unprotected stacks is subjected to repeated rain wetting. Stack covers may help to alleviate the latter problem and decrease the otherwise required drying time to some extent.

The minimum moisture content attainable with air-drying is determined by the EMC of the atmosphere, which can vary considerably throughout the year. Also, the rate of drying becomes slower as the wood approaches the EMC value. These factors may not present difficulties for timber that does not have to be dried to a relatively low moisture to stabilize it sufficiently for satisfactory use. But they do mean that some additional drying, at least at a slightly elevated temperature, will be needed by timber whose moisture content must be lower than the EMC value. Another disadvantage of air-drying is the potential economic loss from drying degradation, predominately in the top layers of uncovered stacks and in the outermost boards along both sides of the stacks.

In spite of the problems, air-drying is widely practised in many countries and gives a generally acceptable result some, if not all, of the time.

Forced-air drying

This method employs either mobile fan units placed between two or more covered stacks in an air-drying yard (yard driers) or fixed fans installed in one wall of an enclosed shed holding stacks of timber. In both cases, the fans draw ambient or heated air over the timber. The air velocity through the stack is generally 0.5-1.0 m/sec. For the shed units, more even circulation is obtained by sucking the air through the stack. If the timber is susceptible to checking, the fans can be automatically stopped by a hygrostat control when the relative humidity rises above about 90 per cent or falls below about 40 per cent.

Forced-air drying is probably no faster than conventional air-drying when natural drying conditions are good. It can be much faster, however, when natural drying conditions are poor. Therefore, forced-air drying minimizes variations in drying rates caused by seasonal fluctuations in climate. This can reduce both timber stock holdings and the amount of drying degradation produced by conventional air-drying. Capital equipment costs are comparatively low, and direct operating costs depend on the consumption and cost of energy. With forced-air driers, mixed species and different thicknesses of timber can be dried in separate stacks at the same time.

Pre-drying

A pre-drier is a large, multi-line unit having a single air circulation and humidification system. Heating of the air may be provided from a single source or supplemented by reheating at one or more lines in the drying chamber. For hardwoods susceptible to checking and collapse, drying conditions are usually mild and kept constant at all times (40° C dry bulb temperature, 2-3° C wet bulb depression). More severe conditions can be used for less sensitive timbers. An air velocity of 1.5 m/sec through the stack is optimum for hardwoods. Pre-driers with timber-holding capacities of up to 500 m^3 have been built.

Pre-driers are frequently used ahead of kilns to reduce the moisture content of timber to 20-30 per cent, particularly where natural air-drying conditions are poor for all or part of the year. They can also be used as driers in their own right, either for green or partly air-dried timber. The mild drying conditions enable different species and thicknesses of timber in different stacks to be dried at the same time. The main problem with this practice is a logistical one: it is difficult to keep track of the progress of drying of individual stacks.

The capital cost is considerably less than for kilns and so is the operating cost for drying timber from green to about 30 per cent moisture content. Below that figure, the cost position reverses because of the much slower drying rates attainable with pre-driers. As there is no need for steam for heating and humidification, the high capital and operating costs of a steam plant can be avoided. Heating can be effected indirectly by filtered exhaust gases from wood residue burners and humidification can be effected by atomized water sprays.

Pre-driers are of greatest interest to a larger producer of structural timber that wants to maintain constant production rates throughout the year and to be able to dry to comparatively low moisture contents as required.

Kiln-drying

The distinctions between screen, solar, progressive and conventional kilns are distinctions in degree rather than in kind. They do differ considerably in capital cost, but this is probably little more than a reflection of their different drying capacities.

Screen kilns

The main aims of this CSIRO design are to keep capital costs low and to simplify the manufacture and packaging of the components for ease of assembly in the field. Mounting all heavy equipment at ground level, including the single air-circulating fan, enables lightweight and well-insulated wall and roof panels to be used, if desired.

The reversible fan is mounted at the back of the drier adjacent to the heater and humidifying spray. The air is discharged into plenum chambers on each side of the stack, entry to which is through screens extending from floor to ceiling and from end to end of the kiln. The function of the screen is to give uniform air velocity through the stack by providing constant resistance to air flow out of the plenum. Maximum internal lengths are limited to about 13 m by air flow considerations.

Screen kilns have performed well with both hardwoods and conifers. They can be operated over a wide range of dry bulb temperatures and can be heated either directly or indirectly. Holding capacities range up to about 20 m^3 of timber.

Solar kilns

Solar kilns can take a variety of forms, but all share the common feature of deriving much or all of the heat needed for drying from the collection of solar radiation. They have great potential in tropical and even subtropical regions where insolation rates are high throughout the year and not unduly diminished by cloud.

The two main types of solar kilns are based on heat provided by the greenhouse effect or by external solar collectors. The latter type may also incorporate a rockpile or other thermal storage unit to store extra heat collected during the day for use at night. Without stored heat, solar kilns are limited to running during daylight hours only or, at best, until the relative humidity of the air inside builds up to 90 per cent or so. For both types, it is important to minimize heat losses with adequate insulation.

The timber roof and wall framing of a greenhouse-type unit may be covered on the exterior with sheets of glass or fibreglass-reinforced polyester, either flat or corrugated. Clear polyvinyl chloride film can be fitted to the inside of the framing to provide an insulating gap. Slightly raised wooden floors above a well-drained base covered with an impermeable membrane minimize the loss of heat through the ground. Flat black paint applied to all surfaces exposed to sunlight within the kiln helps to maximize the absorption of solar heat by the structure. Drying in a solar kiln is much more effective if (a) there is positive, not just natural, air circulation through the stacks of timber (a screen kiln system is very suitable for this purpose) and (b) provision is made for venting small amounts of moisture-laden air from the kiln.

Solar kilns employing external collectors have tended to be designed like conventional kilns in respect of both the structure and the mechanical components. Thus, the capital cost will be comparatively high, particularly when a heat storage unit is included. This will be reflected as a major indirect operating cost (interest and depreciation charges) on account of the relatively small throughput of such a kiln. At the same time, direct operating costs will be relatively low.

Compared with air-drying, solar kilns can (a) provide reasonably good drying conditions and relatively constant output throughout the year, (b) reduce drying times by up to half, (c) reduce drying degradation and (d) dry below the prevailing EMC. They are most useful for drying from FSP to EMC or below, since the dry bulb temperature inside the kiln can rise by as much as 25° C above ambient temperature. The times for drying from 30 per cent to 15 per cent moisture content vary from six weeks for 50 mm thick, medium-density hardwoods to 8 weeks for 40 mm thick, dense hardwoods. Solar kilns have been built with holding capacities of up to 40 m^3.

Progressive kiln

In the CSIRO version of the progressive kiln, the stacks of timber are loaded end-to-end and are moved progressively through the drying zone on a stack-by-stack basis from the "cold" (or wet) end to the "hot" (or dry) end of a tunnel-like shed that is up to 60 m long. Stacks are usually mounted on kiln trucks or bogies but can be moved through the kiln by other means. Heated air is sucked in at the hot end by a fan installed to one side of the kiln at the cold end. Hinged baffles placed at regular intervals along both sides of the stacks direct the heated air through each stack in turn, from the hot to the dry end. An air velocity through the stack of 0.5-1.0 m/sec is ideal.

This kiln is intended to operate at a constant heat input from an oil or gas burner, although suitable filtered exhaust gases from a wood residue burner could be used as well. The hot gases mix with the incoming air and heat it by more or less a fixed amount above the ambient temperature. To recover as much heat as possible for drying, the air should exit from the kiln below ambient temperature, preferably close to saturation. For difficult-to-dry hardwoods, the ambient air should be heated by only 10-15° C. This ensures that drying conditions at the wet end are mild and unlikely to cause checking or other degradation in the greenest and most sensitive timber. If drying degradation is unlikely to be a problem, then larger increases in the temperature of the air entering the drier could be used to accelerate the drying, but this may be wasteful if energy has to be bought.

Apart from routine moisture measurements, very little skill or supervision is needed to operate this kiln satisfactorily. Its simplicity ensures that construction is straightforward, and little maintenance is required. Drying times of 5-8 weeks to about 15 per cent moisture content are normal for green and moderately dense hardwoods 40-50 mm thick. A kiln designed to hold six or so stacks of such timber could produce one stack of dried timber per week. Higher outputs would best be achieved by building additional kilns rather than by increasing the length of a kiln. This avoids complications with drying and gives greater flexibility in the drying operations.

Conventional kilns

Several basic designs for compartment kilns have evolved over the years, but experience shows that a well-designed cross-circulation kiln is most capable of providing consistently good drying results. Such kilns may be purchased as pre-fabricated units or constructed on site to specifications. Aluminium-covered panels are commonly used on pre-fabricated kilns and are generally satisfactory if treated with proper care. Steel-sheeted panels are not suitable for hardwood drying because of the possible risk of corrosion. A wide range of materials are satisfactory for on-site construction: reinforced concrete, clay bricks, hollow concrete blocks, or timber or metal frames lined with various materials. Good insulation is essential to prevent heat losses at the higher operating temperatures used in these kilns.

As compartment kilns generally cost much more than the other driers already discussed, it is important to use them to best advantage. For most hardwoods, particularly in structural sizes, it is plainly uneconomic to use an expensive kiln for drying from the green condition when the job can be done just as well and as quickly by a cheaper machine such as a pre-drier or a progressive kiln. One of the main functions of conventional compartment kilns is the final drying of hardwood already at FSP or below but needed for use at a somewhat lower moisture content. They are sometimes used for the fast drying of permeable timbers from the green condition.

Compartment kilns should have cross-shaft fans, mounted above or below the stack, or other fanning designs of proven, comparable performance. This is to ensure uniform air circulation throughout the kiln, a basic requirement for the even drying of timber. Longitudinal shaft kilns are not recommended because they often fail to satisfy this criterion. The air velocity through the stack should be 1.5-2 m/sec. This velocity cannot be achieved unless baffles are provided to restrict or prevent by-passing of air around the stacks. Uniform drying also depends on an even distribution of temperature and relative humidity in the kiln.

Although it is generally impracticable to dry different thicknesses of timber in a kiln at the same time, different species with similar drying characteristics can be dried in the one kiln charge. Residence time in the kiln depends entirely on the drying rate of the slowest drying piece(s) of timber. Periodic reversals of air circulation help to reduce the lag in drying across the kiln, which will tend to be greatest at the centre of the stack in this case. If it is impracticable to identify different species with different drying characteristics, then the drying schedule for stacks of such timber must be such that the most sensitive timber does not degrade. The main penalty is reduced kiln throughput.

Compartment-type kilns are relatively expensive to buy and to operate, particularly when the purchase and operating costs of an ancillary heat plant are considered. The competent running of such kilns largely depends on having kiln operators who are well trained and experienced in the art of drying timber. Such people are often difficult to find unless special training programmes have been developed. Therefore, it is essential to carefully consider whether drying in compartment kilns is the best method or whether one of the less sophisticated methods would be more appropriate for a particular application.

3. Steaming chamber

Reference has already been made to the practice of briefly steaming timber to relieve drying stresses or to recondition collapsed timber. As such a treatment should not be given in any type of drier, mainly because the metal fittings could corrode, steaming chambers are used for this purpose.

A steaming chamber is a box-like structure about 600 mm wider and 400 mm higher internally than the timber charge it is required to hold. It is best constructed from reinforced concrete. The only internal fitting required is a 38 mm diameter steam pipe with 6 mm diameter holes at 300 mm centres running centrally along the length of the floor. Steam pressures can be as low as 50 kPa but should not exceed 200 kPa.

4. Heating of kilns

Steam is the traditional medium for the heating and humidification of kilns. It is commonly generated by burning green or dry wood residues in boilers operated at 300-600 kPa or higher. The steam is fed to heating coils, usually of plain or finned piping, running from one end of the kiln to the other and back again to minimize any differences in temperature along the length of the kiln. Humidification is usually provided by discharging steam through holes drilled at fixed intervals in a pipe running the length of the kiln.

When oil and gas were much cheaper, automatic steam generators were sometimes used instead of wood-fired boilers, but high fuel costs now make them uneconomic in most countries. Steam generators have been replaced to some extent by various types of wood-fired furnaces. These are mostly automatic and fairly expensive to buy. They may also have special requirements in respect of the size and moisture content of the wood residue fuel. Some units are suitable for the direct firing of kilns with furnace gases; others need to be used with heat-exchangers to guard against the starting of fires inside the kilns.

Apart from the heat sources just discussed and the possibility of utilizing solar heat to a limited extent, there are few other options for the heating of kilns. One of the most promising is direct-coupled wood gasifiers for retrofitting into oil- or gas-fired steam generators or for direct firing of progressive kilns and the like. Another is the use of filtered exhaust gases from wood-residue burners, preferably fed with fuel from a hopper big enough to let it run overnight without attention.

5. Moisture content measurement

Two methods are widely used by the timber industry to measure moisture content: oven-drying and electrical moisture metres. The oven-drying method is accurate at all moisture contents but it takes 12-48 hr to get a result unless microwave ovens are used (in a particular way), in which case the time can be reduced to an hour or so. Moisture metres are portable, give instant readings and are fairly accurate from 5 to 25 per cent if used properly and if corrections are applied for species and temperature. The hardware for the two methods would cost roughly the same.

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