FOREST ENGINEERING (FWM 518)

Forest engineering is a hybrid of engineering, forestry, and management. Forest engineers are unique people who can combine skills to solve problems in the natural environment, with a focus on the forested landscape. Forest engineers have broad knowledge and solid technical competence.

Forest engineers help design, construct and evaluate the operational systems that make the forest industry 'work'. This can include designing and building new roads and forestry equipment, planning harvest operations, integrating new technologies and optimising transport logistics. It also means looking after the environment. These roles involve the 'hands-on' application of engineering skills.

Forest engineers have a wide skill-set that provides work opportunities both at home and abroad. Graduates can take employment in the forest industry, but because of the multi-disciplinary nature of forest engineering, job opportunities are also available in areas including general engineering consultancy, local and regional councils, government agencies, resource management and research. Scholarships are regularly offered for students to undertake postgraduate forestry and engineering-related study in the USA and Canada.

Forest engineers are adapting at solving problems that arise in the competing environments. In conservation forestry there is tension between ecological and societal needs. In plantation forestry there is tension between economic, societal and environmental requirements. It takes a person with a deep understanding of the situation and strong technical skills to make sensible decisions.

Forests are more than just trees. While it's obviously true that commercial forestry operations must make a profit to be sustainable as businesses, equally the land base must be protected to remain sustainable too. Watersheds, soils, wildlife, and aquatic habitat must be protected.

This is where forest engineers come in. They have the skills to develop and implement harvest plans trucking and roading systems. They use global positioning systems (GPS) and geographic information systems (GIS) routinely. They design and manage equipment. They help develop new wood products, and efficient ways of making them.

Forest engineers deal with people: they work with the public, government agencies, contractors, consultants. They guide their own employees. They solve technical problems in harvesting, access road building, trucking, watershed management, planning, and habitat preservation. They steer projects through the resource consent process. They design and manage machinery.

Current world issues have significant forest engineering opportunities. Woody-based biomass has been identified as a key source of alternative energy for the future. Forests store carbon and are a major part in any governmental carbon plan. With water becoming a serious resource issue in many countries, people are finding that watersheds where commercial forestry is practiced can provide high quality dependable water supplies.

While many graduates of Forestry programme go on to exciting careers in private forestry companies, a number also find a good place to work in the various governmental agencies. Some work for contractors or consultants, some set themselves up in their own consulting or contracting businesses. Some forest engineers find work in positions in overseas development. Forest engineers have rewarding careers with significant responsibility and exciting challenges.

Landscape-Level Forest Management and Sustainable Forestry are great visions guided by sound principles. Everybody wants them to become realities. However, for the past several years all the emphasis has been on biology while technology has been pushed into the background. The forest products industry was often advised never to show timber being harvested in a forest, or processed in a mill, for fear of offending the public. Hiding reality only fuels our urban mass-consumption society's misperception that building materials, furniture and paper products appear out of thin air, as if by magic. Information, engineering and the application of technology make useful things appear in our lives. By reconnecting people to the sources of things they use, we enable them to make informed choices. We must take from life to live, while putting back to provide for future generations.

Technology makes Sustainable Forestry and Forest Ecosystem Management possible. Foresters manage large landscapes over long time horizons. They write silvicultural prescriptions to keep forests healthy, just as physicians prescribe to keep patients healthy. These silvicultural prescriptions often require thinning of overstocked and stagnated stands of trees, to reduce the threat of fire, insects and disease. Since trees compete for sunlight, water and nutrients, proactive forest management is needed to reduce stress, prevent stagnation and maintain forest health. Fortunately a wide variety of sophisticated instruments and machinery are available to carry out the foresters' prescriptions. We can extract commodities from the forest while protecting all the other values including habitat, recreation, aesthetics, soils and water.

Forest Engineering is as important as any discipline in forestry. We depend on forest engineers to design good roads and bridges, and harvesting operations with minimal impact on soils, water quality and habitat. We depend on other engineers to design equipment which is environmentally sensitive while still being able to do the job in a safe, productive and cost effective manner. This machinery must be purpose-built to match a variety of timber, terrain, underfoot and weather conditions. Today’s sophisticated machines require educated operators who understand forestry, mechanics, hydraulics, electronics and computers. It's a new world in the woods, where mechanization has overtaken manual labour. Technology is making both woods and mill operations environmentally compatible, safer and more efficient.

Road Building

We need forest roads to; manage the forest; harvest timber; fight fires, insects and disease; salvage dead and dying timber; and to access forest recreation. Most forest roads were built with the economic incentive of timber harvest. These roads then became multiple-use roads. In fact most of the people using forests for recreation get there on roads initially constructed for timber harvest.

Motor graders maintain more miles of forest roads in the US than exist in the entire Interstate Highway System. The long wheel base helps this machine to take the bumps out of the road for the operator and those of us who travel on them.

Many of the past problems associated with harvesting such as erosion and stream sedimentation were related to road building. Slope and road failures are highly visible, cause stream degradation and create negative public perceptions. Today, roads are being built to very strict standards in compliance with forest practice acts. In many areas, road construction has been minimized by using forwarders, skyline cable logging systems and helicopters to transport the timber over longer distances, and over steep and sensitive terrain.

Harvesting & Processing

The evolution of harvesting and processing techniques has been happening at a lightning fast pace. Trees were once harvested and processed with axes and cross cut saws known as "misery whips." Next came huge chain saws requiring "two men and a boy" to operate. Eventually we got to the modern chain saw which is used to fell, delimb, top, and buck the tree into log lengths, ready for a cable skidder to take to the landing. The next innovation was machines equipped with mechanical shears used to snip the trees off at ground level. The shears were soon surpassed by circular saws which could cut the trees faster and with less fiber damage. These feller-bunchers can fell trees and put them in bunches just the right size for grapple skidders which take them to the landing to be further processed by a delimber or chipper. This completely mechanizes the operation getting the labour off the ground. The feller-bunchers soon got competition from harvesters which can cut the tree and process it into log lengths all in one motion. Forwarders then pick up the processed logs and piggy-back them to the roadside minimizing the need for roads and landings. The Harvesters and Forwarders work as a matched system. Excluding cable logging systems and helicopters, which are really transportation systems, machines used for the mechanized harvesting and processing of trees can be divided into two main ground systems:

Mechanized Logging Systems

The Cut-to-Length systems which have now gained acceptance in North America were developed in Scandinavia. These machines have several advantages. Harvesters process the trees in the woods leaving the tops and limbs on the forest floor where the nutrients can return to the soil. This organic material also protects the soil from compaction and rutting as the machines drive over it. Instead of skidding or dragging "turns" of logs, the self-loading forwarders carry the logs piggy-back style to the road where they load them onto trucks. The need for large landings is eliminated, along with the problem of what to do with the debris (slash) which was the result of processing at the landing. Burning this slash had also become a significant problem because of smoke and soil degradation from intense heat. In general, new woods technology has migrated from Scandinavia to Eastern Canada and then on to the rest of Canada and United States where it has undergone modifications. In Scandinavia, harvest technology was pushed at the same rate as the ecological and silvicultural knowledge base.

Transportation

There are several ways to get trees from where they are harvested to a road or landing where they can be loaded on a truck for transport to the mill. The trees can be skidded (dragged) out of the forest using a Cable Skidder or Grapple Skidder on tracks or wheels. They can be piggy-backed out using a forwarder, after being bucked (cut) to log lengths. They can be pulled (yarded) to a landing by cable yarding systems. They can be relayed or swung to a landing by a log loader in a process known as ‘Shovel Logging.’ They can also be transported by helicopter. There are many options which must be matched to the timber, terrain and underfoot conditions. Depending on the conditions and economics the forest engineer can choose the appropriate mix of ground, cable or aerial systems.

Expensive equipment for harvesting and processing trees must be well selected, well supported and operated properly. It's like racing Indy cars where you have to choose the right body (chassis), the right engine, and the right tires for the track and length of the race. You also have to have an excellent driver (operator), excellent mechanics, and lots of spare parts. It's the same in the woods. A good logger must have an incredible wealth of knowledge and experience. The Forester, Forest Engineer, Wildlife and Fisheries Biologist, Equipment Supplier, and Logger all work together as a team.

Road Layout and Design

Introduction

Forest road layout and design is a process that includes route selection, field Investigation, surveying, and analysis to provide a site-specific road location, and design. Road design provides construction specifications, road prism Geometry, stream crossing site information, and information necessary for construction control. The detail and information required for each phase in this process varies with the type of road required, the complexity of terrain, the size and complexity of stream crossings, and other resource values. This chapter describes the types of projects for which the district manager's approval of road layout and design for construction and modification is mandatory provides information on route selection and layout, and describes the content requirements of a reconnaissance report provides criteria for survey level selection, and explains the types of survey (field traverse and location survey), and the suitability and application of different survey levels

provides procedures for field traverses and location surveys explains general and geometric road design requirement provides example correction factors to convert compacted volume to bank volume for road design purpose discusses slope stability considerations if a proposed road will cross areas with a moderate or high likelihood of landslides provides road design specifications and parameters

Route selection and layout

Decisions made at the route selection stage may have long-term effects on road construction and maintenance costs, user safety, and other resources. Routes must be selected and located to meet the objectives of higher-level plans within the constraints of any approved operational plans or permits. It is essential that adequate time and resources be allocated to route selection. The route selection stage begins with the collecting and analysing of all available information for the development area, focusing on the route corridor. This information may include aerial photos, topographic maps, soil erosion potential maps, land alienation maps, and reconnaissance terrain stability or detailed terrain stability maps and other assessments for the area.

The method of harvesting and constraints of the harvesting system should also be considered if the road will traverse

(1) A harvesting area or

(2) An area that could be harvested in the future. Road drainage flows and drainage structures and road and clearing widths could all be affected by harvesting. Control points (physical features that may influence road location or design) should then be plotted on the aerial photos and/or topographic maps of a suitable scale.

Control points include:

- stream crossings, rock bluffs, benches, passes, saddles, and other dominant terrain features
- road grades and switchback locations
- harvesting system landings
- potential end haul or waste areas
- alienated lands, including power line, gas pipeline, or railway crossings
- current access and junction to existing roads.

Route selection should then be made based on an analysis of all of the available information, and the route should be field verified.

The route selection field phase is an on-the-ground check of the proposed route or potential routes, taking into consideration control points or other constraints. This field traverse is also known as a Level 1 survey (measurements are not usually accurate enough for detailed road design) and is run along a proposed route to confirm that the horizontal and vertical alignment are suitable. Adjustments to the line may be necessary, and often several iterations are needed to establish the alignment and confirm the choice of route. The person carrying out the field traverse should make sufficient notes to prepare a detailed reconnaissance report to assist the location surveyors, road designers, and road builders.

The reconnaissance report should identify and or confirm:

- terrain conditions and road sections that are in unstable or potentially unstable terrain
- road sections with side slopes over 60% or where slope instability is found
- control points and topographic features (e.g., rock bluffs, swamps, avalanche paths, landslides, and debris slides), including those that may be used as photo ties
- the sections of road that encroach on public utilities
- the sections of road that are adjacent to or cross private property, Crown leases, or mineral and placer claims or leases (where possible, alienated lands should be avoided)
- all continuous and intermittent drainage flow channels, springs, seeps, and wet areas
- riparian areas
- stream crossings where channel and bank disturbances can be prevented or mitigated, locations that require site plans, and data required for minor stream crossings
- forest cover (species composition, timber quality, and volume per hectare)
- recommended slash and debris disposal methods and additional clearing widths required for the slash and debris disposal
- soil types based on visual observations of exposed cuts, shallow hand dug test holes and probing, and the location of these soils on maps or aerial photos.
- maximum road grades and minimum curve radii
- location and extent of bedrock, if rippable, and the potential as ballast
- location and extent of gravel sources and the potential for use as subgrade and surfacing materials.
- endhaul sections and potential waste areas
- recommended construction methods and potentially appropriate alternatives
- recommended survey level or levels appropriate for the terrain.

The field reconnaissance report should also record the characteristics of existing roads in the vicinity of the proposed road location by identifying and recording soil types, stable cut and fill slope angles, and existing sources of road surfacing materials.

Field reconnaissance is an appropriate stage to evaluate the need for any additional information or assessments that may include:

- riparian classification of streams, wetlands, and lakes
- identification of fish streams in community watersheds
- visual impact assessments
- archaeological impact assessments
- soil erosion field assessments.

Road design requirements

The purpose of road design is to produce design specifications for road construction by determining the optimum road geometry that will accommodate the design vehicle configuration for load and alignment, and traffic volume, and provide for user safety, while minimizing the cost of construction, transportation, maintenance, and deactivation. The optimum road design should minimize impacts on other resources by minimizing clearing and road widths, minimizing excavation, using rolling grades, and installing proper drainage structures. Road design software has been developed to replace manual drafting and repetitious design calculations so that various alignment alternatives can be quickly evaluated. Once the location survey data have been entered into the road design program, select and input appropriate design parameters for the specific project. Ensuring this requires direction from a skilled and knowledgeable designer familiar with forest road layout, design, and construction practices. As each phase of road layout and design builds on the previous phase, the quality of the final design depends on the appropriateness of the road location, field data, and survey—and the competence of the designer.

General design requirements

This section provides road design requirements common to all levels of road layout and design. Construction techniques, road width, cut and fill slope angles, and horizontal and vertical control angles are selected according to terrain and soil conditions for the required road standard. Forest road standards are defined primarily in terms of stabilized road width and design speed. Road design specifications consist of alignment elements (e.g., horizontal curvature, vertical curvature, road grade, and sight distance) and cross-section elements (e.g., full or partial bench construction, sidecast construction, road width, angles of repose for stable cut slopes, ditch dimensions, drainage specification, and clearing widths).

Geometric road designs include plans, profiles, cross-sections, and mass haul diagrams showing the optimum balance of waste, borrow, and endhaul volumes.

The designs are generated from the route selection process and the location survey. From the location survey information, a road centreline (L-Line) is designed for vertical and horizontal alignment, earthwork quantities are calculated, and a mass haul diagram is produced to show the optimum placement of excavated material.

Factors to consider in road design

Road design should consider the following factors:

General considerations:

- intended season and use of the road (design vehicle configuration for load and alignment, and traffic volume)
- climate (heavy snowfall areas, heavy rainfall areas, etc.)
- design service life of the road
- user safety, resource impacts, economics
- road alignment (horizontal and vertical geometry)
- junctions with existing roads
- road width (turnouts and widenings).
- the measures to maintain slope stability if the road will cross areas with a moderate or high likelihood of landslides (also see .Geometric road design requirements. below)
- soil types (including the use of appropriate conversion factors to adjust for swell and shrinkage of materials)
- . cut and fill slope angles, clearing widths, slash disposal methods
- planned movement and placement of materials (balancing of design), including waste areas and endhaul areas.

Drainage, construction techniques, sediment prevention, road deactivation:

- culverts (locations, type, size, and skew angles)
- drainage and ditch (including depth) locations
- . rock blasting techniques to optimize usable rock
- anticipated construction problems
- measures to mitigate soil erosion (including vegetative requirements and prescriptions)
- measures to maintain water quality
- future deactivation requirements

Design specifications and parameters

Road alignment

Road design incorporates horizontal and vertical road alignments that provide for user safety. This involves establishing:

- . appropriate travel speeds
- suitable stopping and sight distances
- road widths, turnouts
- truck and trailer configurations
- appropriate traffic control devices.

Designed travel speeds often vary along forest roads due to terrain conditions or changing road standards. The cycle time or distance from the logging area to the dump or processing area may be an important economic factor to consider in establishing an overall design speed, and may be derived from a transportation study and stated in the overall plan for the area. In other cases, topography and terrain will dictate alignment, with little impact from other factors. In general, the safe vehicle speed for a road should be based on:

- horizontal and vertical alignment of the road
- super-elevation on curves
- coefficient of friction between tires and road surface
- type and condition of road surface, road width
- sight distance and traffic volume.

Turnouts should be located in suitable numbers (intervisible and often three or more per kilometre) on single-lane roads to accommodate user safety.

Fill slope and cut slope angles

Stable cut slopes, road fills, borrow pits, quarries, and waste areas should be designed and constructed in a manner that will not contribute directly or indirectly to slope failures or landslides over the expected design life.

Fill slopes

The stability of a fill slope depends on several variables, including the forces that tend to cause instability (gravitational and water pressure forces), and the forces that tend to oppose instability (e.g., shear strength resistance of the soil or rock materials expressed as an internal friction angle or cohesion). The stability of an embankment fill can be increased several ways:

- Construct the side slopes of fill embankments at a gentle angle, and usually not steeper than the .angle of repose.The term .angle of repose should be used in the context of loose, cohesionless soils only (e.g., nonplastic silt, sand, sand and gravel). Constructing flatter side slopes in all types of soil will reduce the gravitational forces that tend to cause slope instability. For a fill slope in cohesionless material, the angle of repose is about the same as the *minimum* value of that material.s angle of internal friction. Steeper fill slopes are more likely to cause a road-induced slope failure or landslide than flatter fill slopes.
- Compact the fill materials to make them more dense and increase the shearing resistance of the soil. The angle of internal friction depends primarily on the relative density (loose versus dense), the particle shape (round versus angular), and the gradation (uniformly graded versus well graded). For relatively loose cohesionless soils. soil grains. For relatively dense cohesionless soils, the maximum value of the angle of internal friction will range from about 35 degrees for rounded uniform soil grains to 45 degrees for angular, well-graded soil grains.

Cut slopes

The design of cut slopes should consider and address factors such as the desired performance of the cut slopes, types of cut slope materials, issues about overall terrain stability, engineering properties of soils, seepage conditions, construction methods, and maintenance. In general, cut slopes will remain stable at slightly steeper angles than fill slopes constructed from like soil materials. The reason for this is the undisturbed soil materials in a cut
(1) Are often in a denser state than similar type materials placed in a fill, and
(2) May contain sources of cohesive strength that further increases the shearing resistance of the soil.

Cut slopes constructed at too flat an angle can be uneconomical in steep ground because of the large volumes of excavation. Steeper cut slopes may be more economical to construct in terms of reduced volumes of excavation. However, they can also be more costly from an operational standpoint because they require more road maintenance. For most forest roads, cut slope angles are generally designed to favour steeper angles to reduce the length of cut slopes, to minimize visible site disturbance, and to reduces excavation costs, provided that a somewhat higher level of road maintenance and likelihood of slope destabilization is acceptable for the site.

In the latter case, prepare and implement a maintenance schedule that addresses the erosional processes acting on the exposed cut slope face (such as splash, sheet, rill, and gully erosion) and reduces the threat to drainage systems (as a result of cut bank slope failure redirecting ditchwater flows onto potentially unstable fill or natural slopes), user safety, and the environment. It may be necessary to construct flatter cut and fill slopes, or to build retaining wall structures to support cut slopes or fill slopes, in cases where slope stability problems are expected to be difficult to manage with maintenance measures alone.

Clearing widths

Clearing widths should be as narrow as possible, to minimize impacts on other resources, but wide enough to accommodate: the road prism, user safety, turnouts, subgrade drainage, subgrade stability waste areas and endhaul areas, pits and quarries, landings, slash disposal equipment operation, snow removal, fencing and other structures standing timber root protection, especially on cut banks. Organic debris, rock, or any other excess material that cannot be placed in the road prism and within the clearing width because of terrain stability or other factors should be moved to waste areas. Such areas should be of suitable size to accommodate the estimated volume of waste material and should be identified in the road design. Clearing widths are calculated on a station-by-station basis as part of a geometric road design.

Design and Construction of Bridges and Stream Culverts

Introduction

This part describes some of the activities and practices that precede and follow the construction of forest road bridges and stream culverts. These include:

- design requirements for bridges and stream culverts
- bridge and major culvert design responsibility

- site data and survey requirements for bridges and major culverts
- construction drawings and specifications for bridges, major culverts, and stream culverts on fish streams
- site data and survey requirements for culverts on non.fish-bearing streams
- estimating design discharge for streams
- statement of construction conformance and documentation.

Bridge means a temporary or permanent structure carrying a road above a stream or other opening

culvert means a transverse drain pipe or log structure covered with soil and lying below the road surface

cross-drain culvert means a culvert used to carry ditchwater from one side of the road to the other

major culvert means a stream culvert having a pipe diameter of 2000 mm or greater, or a maximum design discharge of 6 m3/sec or greater

stream culvert means a culvert used to carry stream flow in an ephemeral or perennial stream channel from one side of the road to the other.

Design requirements for bridges and stream culverts

The design of bridges and stream culverts encompasses more than the design of structural components. A bridge or stream culvert design should consider the composition and interaction of all the components, as well as their relationship and impact to the users, road, and stream. A bridge comprises the superstructure, substructure, connections, vertical and horizontal alignment controls, approach road fills, and scour protection works. Similarly, a stream culvert comprises the culvert materials, compacted backfill, scour protection, and roadway. Bridge or stream culvert designs include, but are not limited to, consideration of:

- user safety
- site selection
- environmental integrity
- fish habitat and passage
- impact of proposed structure on stream during and after construction
- site revegetation requirements
- structure alignment and location (vertical and horizontal) relative to the road and stream channel
- complete structure combination (substructure, superstructure, connections, and scour protection)
- suitability of selected foundations for the specific site
- design flood development
- navigation (*Navigable Waters Act*)
- debris potential and passage, scour protection
- design vehicle configuration for load and alignment
- design service life influence on selection of bridge type and composition

- Construction layout, methodology, and timing, economics.

Road Construction
Road corridor preparation
Establishing clearing widths

Clearing widths are established to facilitate the construction, use, and maintenance of forest roads. The objective is to minimize the width of the clearing, yet accommodate:

- 1.3 m of width between standing timber and any excavation to avoid undercutting roots that may create dangerous trees and destabilize the top of road cut (see Figures 7 and 8)
- the road prism, including widenings for curves and turnouts
- subgrade drainage structures
- landings and slash disposal without piling wood or excavated material against standing trees
- borrow pits, gravel pits, quarries, and waste areas
- safe sight distance for user safety
- snow removal
- fencing and other structures that are ancillary to the road
- other special operational requirements.

  For slopes greater than 60%, or in areas of moderate or high likelihood of landslides, clearing widths should be determined from the geometric road design.

Laying out clearing widths

Clearing limits should be marked in the field with flagging tape. The clearing boundaries should be sufficiently flagged to be clearly visible for machine operators or hand fallers to follow. Flagging should be hung on trees and shrubs that will remain after the clearing operation is completed. Trees that are on the boundary should be left Standing, unless the roots will be undermined by operations within the clearing width. Where slope staking is not required, the flagging can be used as an offset line to establish the top of cut for grade construction.

Establishing pilot trails

Frequently, pilot trails or tote roads are built within the clearing width before falling begins. These trails are to provide easy access for the faller (hand or mechanical), a route for skidding felled timber to a landing or collection point, and temporary access along the road corridor. Terrain and soil conditions will govern the location of the pilot trail within the clearing width. Generally, the trail is constructed below the flagged centreline on side hills, near the lower clearing width limits. This allows for easy access to skid fallen timber, and allows for the toe of the road fill to be keyed into the slope. Where drilling for blasting is required, the trail may be built above the road centreline, just below the upper clearing limit, to permit vertical drilling of the rock cut. Care should be taken during pilot trail construction to minimize damage to any timber and to ensure that unsafe conditions are not created for fallers. Excavators are superior machines for constructing trails because they can push down, remove, and place trees along the trail for easy removal later. Pilot trails are often constructed to allow trucks to remove the merchantable timber within the clearing area. This is desirable where there is insufficient room to construct large landings for timber storage. Drainage structures should be installed concurrently with pilot trail construction. Temporary stream crossings may be required during the road construction phase until the permanent crossing is commissioned. Ideally, to minimize the impact on the stream, the temporary crossing should be situated in the same location as the permanent crossing, but this may be impractical.

Felling and yarding within the clearing width

Felling methods

Several methods for falling trees within the clearing width are available, depending on terrain, soil conditions, timber size, and total volume.

Mechanical methods:

- feller-bunchers (tracked, high flotation tired) used for merchantable and non-merchantable timber and on terrain suited to the safe operation of such equipment
- crawler tractors/excavators used for non-merchantable timber or to assist hand fallers where hang-ups or faller safety dictates such action.

Hand methods*:*

- ✓ hand falling to avoid site impacts associated with mechanical falling
- ✓ directional falling of leaning timber, using jacks, excavators, or hydraulic log loaders.

Explosives:

- use is restricted to falling large dangerous trees that cannot be removed safely by other means
- if used adjacent to streams, explosives must first be approved by the appropriate resource agencies
- the person using explosives must have valid Workers.

Grubbing and stripping

After all standing trees and dangerous trees have been felled and removed; the road prism should be grubbed and stripped of all topsoil and unsuitable mineral soils. Grubbing includes the removal of stumps, roots, logging slash, and downed or buried logs. Stripping includes the removal of topsoil, or other organic material, and mineral soils unsuitable for forming the road subgrade. Where grubbing operations have removed all organic soil, no stripping is required unless other unsuitable soils are encountered. Organic material, such as stumps, roots, logging slash, embedded logs, topsoil, and otherwise unsuitable soils may be left within the subgrade width where one-season winter use or snow roads are constructed, or where overlanding.

Disposal of slash and debris

Slash and debris must be disposed of by burning, burying, scattering, or endhauling. The method selected should:

- ✓ meet objectives of higher-level plans (such as those for smoke management, aesthetics, or pest management)
- ✓ be compatible with terrain conditions
- ✓ consider the slash volume, loading, species, and piece sizes
- ✓ not alter natural drainage patterns
- ✓ be compatible with other resource values.

Disposal sites must:

- ✓ be sufficiently stable to support the debris
- ✓ have very low potential for failing into a stream (such as by landslide or snowslide)
- ✓ have little or no impact on other forest resource values.

  Under no circumstances may slash be placed within the high-water mark of a stream, or in a manner likely to cause the material to fall into a stream. Best practice is to remove all organic debris from within the road prism width.
- ✓ stumps, roots, and embedded logs may be left or placed outside the road subgrade width on the downhill side
- ✓ for a 5-year road, stumps, roots, and embedded logs may be left or placed within the road subgrade width.

  For each of these two situations above, the person responsible for constructing the road must provide a statement that indicates that leaving or placing stumps, roots, and embedded logs in the road prism will not significantly increase the risk of a failure of the road subgrade.

  In all cases of road site preparation, topsoil must be removed from within the road prism width.

Piling and burning

Piling and burning may be considered as an alternative to burying in areas with flatter terrain, heavy slash loading, and moderate to high pest or fire hazard, and where smoke management objectives can be met.

Where possible, use natural openings and landings.

- ✓ pile slash and debris at least twice the width of the pile away from standing timber
- ✓ to facilitate efficient burning, ensure that the slash pile contains as little soil as is possible
- ✓ ensure that slash is piled tightly, using a brush blade or excavator
- ✓ excavate a fireguard down to mineral soil around each burn pile to prevent ground fire escape
- ✓ ensure that a Burning Reference Number has been obtained before initiating the burn.

The use of burning racks can be very useful to ensure that a hot clean burn results. This eliminates the need to push in or re-pile debris that does not burn cleanly.

Burying

Burying is usually the preferred practice and there are three methods for burying slash and debris with overburden material: trenching, mounding or windrowing, and creating pushouts. The volume of slash and overburden should first be calculated per lineal metre of road. Generally, for every cubic metre of debris, a metre of clearing is required for disposal. When excessive slash volumes are encountered, other disposal methods should be considered.

Buried material should:

- ✓ be compacted before being covered with soil
- ✓ be covered with a minimum of 300 mm of soil
- ✓ be placed so as not to interfere with roadway or other drainage, utilities, planned road improvements, snow removal, design sight distance, future developments, or standing timber
- ✓ not interfere with any watercourse.

Trenching

This is a type of burying in which slash and debris are placed in a trench rather than being spread over the ground surface. The volume of debris should determine the size of the trench. To minimize the size of the cleared area, a deep, narrow trench is preferable to a shallow, wide trench. To prevent undermining tree roots, 3 m of cleared width should remain between any standing timber and the trench. The trench should lie parallel to the roadway and may be continuous or intermittent, depending on the volume of debris. The woody debris is placed on the bottom of the trench and compacted before being buried with topsoil and other strippings from the road prism. This method works well where usable subgrade material occurs fairly continuously below a veneer of unsuitable soil. The excavated trench material can be used to raise the subgrade above the normal groundline. Trenching should not be used on natural slopes with greater than 20% gradient, as it could undermine the road surface, causing long-term subgrade instability.

Mounding or windrowing

With this technique, all slash and debris are accumulated along one side of the cleared width between the road prism and the standing timber. The woody debris is placed first and compacted by the grubbing equipment. Stripping material from the road prism is used to cover the slash with additional mineral soil, used as required to ensure that a minimum of 300 mm of soil cover is achieved. Because of the difficulty of maintaining an adequate soil cover on the downslope side, the results of this method on natural slopes with greater than 50% gradient are not easy to control.

Pushouts

Pushouts should be located in natural openings along the cleared area and should be appropriate for the volume of material to be disposed of. Debris should not be pushed into standing timber, and the piles should be properly groomed to be stable and visually acceptable. chipping may limit erosion of exposed soils and facilitate revegetation.

Endhauling slash and debris

Endhauling slash and debris from the road corridor is required in steep or unstable terrain where this material must be removed to maintain slope stability. It may also be required in areas with high recreational value where aesthetics may be an issue. The approved waste area should be stable and well drained, isolated from streams or wet sites, and have a minimal adverse impact on other forest resources. Overloading of slopes should be avoided. Once endhauled, the slash and debris should be disposed of by burning, burying, or scattering. Where possible and practical, stockpile organic and fine-textured soils for placement over abandoned borrow and waste areas to facilitate revegetation. All waste areas should be identified before construction.

Timber mechanics

If a beam is loaded too heavily it will break or fail in some characteristic manner. These failures may be classified according to the way in which they develop, as tension, compression, and horizontal shear; and according to the appearance of the broken surface, as brash, and fibrous. A number of forms may develop if the beam is completely ruptured. Since the tensile strength of wood is on the average about three times as great as the compressive strength, a beam should, therefore, be expected to fail by the formation in the first place of a fold on the compression side due to the crushing action, followed by failure on the tension side. This is usually the case in green or moist wood. In dry material the first visible failure is not infrequently on the lower or tension side, and various attempts have been made to explain why such is the case. Within the elastic limit the elongations and shortenings are equal, and the neutral plane lies in the middle of the beam. Later the top layer of fibres on the upper or compression side fail, and on the load increasing, the next layer of fibres fail, and so on, even though this failure may not be visible. As a result the shortenings on the upper side of the beam become considerably greater than the elongations on the lower side. The neutral plane must be presumed to sink gradually toward the tension side, and when the stresses on the outer fibres at the bottom have become sufficiently great, the fibres are pulled in two, the tension area being much smaller than the compression area. The rupture is often irregular, as in direct tension tests. Failure may occur partially in single bundles of fibres some time before the final failure takes place. One reason why the failure of a dry beam is different from one that is moist, is that drying increases the stiffness of the fibres so that they offer more resistance to crushing, while it has much less effect upon the tensile strength.

There is considerable variation in tension failures depending upon the toughness or the brittleness of the wood, the arrangement of the grain, defects, etc., making further classification desirable. The four most common forms are:

(1) Simple tension, in which there is a direct pulling in two of the wood on the under side of the beam due to a tensile stress parallel to the grain, this is common in straight-grained beams, particularly when the wood is seasoned.

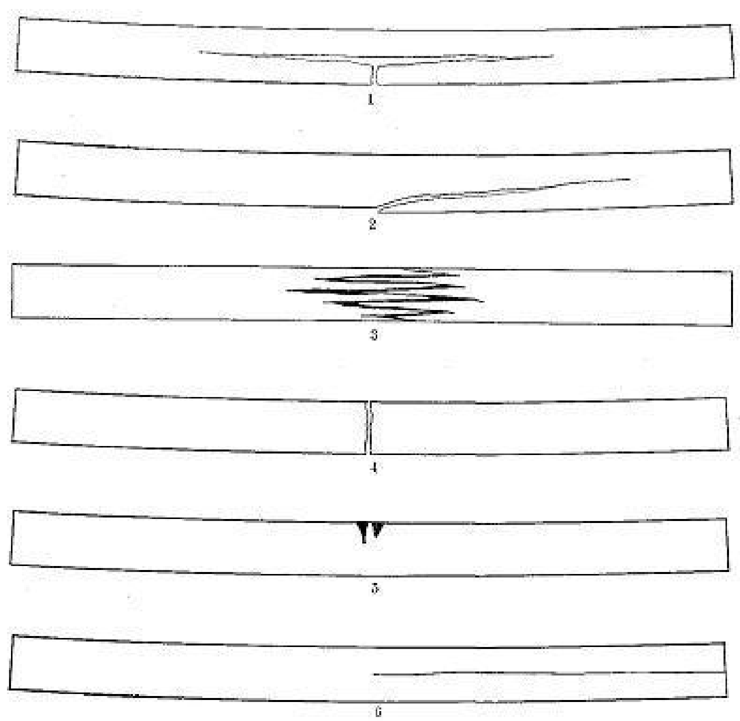
(2) Cross-grained tension, in which the fracture is caused by a tensile force acting oblique to the grain. This is a common form of failure where the beam has diagonal,

spiral or other form of cross grain on its lower side. Since the tensile strength of wood across the grain is only a small fraction of that with the grain it is easy to see why a cross-grained timber would fail in this manner.

(3) Splintering tension, in which the failure consists of a considerable number of slight tension failures, producing a ragged or splintery break on the under surface of the beam. This is common in tough woods. In this case the surface of fracture is fibrous.

(4) Brittle tension, in which the beam fails by a clean break extending entirely through it. It is characteristic of a brittle wood which gives way suddenly without warning, like a piece of chalk. In this case the surface of fracture is described as brash.

Compression failure has few variations except that it appears at various distances from the neutral plane of the beam. It is very common in green timbers. The compressive stress parallel to the fibres causes them to buckle orbend as in an endwise compressive test. This action usually begins on the top side shortly after the elastic limit is reached and extends downward, sometimes almost reaching the neutral plane before complete failure occurs. Frequently two or more failures develop at about the same time



Characteristic failures of simple beams.

Horizontal shear failure, in which the upper and lower portions of the beam slide along each other for a portion of their length either at one or at both ends, is fairly common in air-dry material and in green material when the ratio of the height of the beam to the span is relatively large. It is not common in small clear specimens. It is often due to shake or season checks, common in large timbers, which reduce the actual area resisting the shearing action considerably below the calculated area used in the formulæ for horizontal shear. For this reason it is unsafe, in designing large timber beams, to use shearing stresses higher than those calculated for beams that failed in horizontal shear. The effect of a failure in horizontal shear is to divide the beam into two or more beams the combined strength of which is much less than that of the original beam.

Application of Loads

There are three general methods in which loads may be applied to beams, namely:

(1) Static loading or the gradual imposition of load so that the moving parts acquire no appreciable momentum. Loads are so applied in the ordinary testing machine.

(2) Sudden imposition of load without initial velocity. "Thus in the case of placing a load on a beam, if the load be brought into contact with the beam, but its weight sustained by external means, as by a cord, and then this external support be suddenly (instantaneously) removed, as by quickly cutting the cord, then, although the load is already touching the beam (and hence there is no real impact), yet the beam is at first offering no resistance, as it has yet suffered no deformation. Furthermore, as the beam deflects the resistance increases, but does not come to be equal to the load until it has attained its normal deflection. In the meantime there has been an unbalanced force of gravity acting, of a constantly diminishing amount, equal at first to the entire load, at the normal deflection. But at this instant the load and the beam are in motion, the hitherto unbalanced force having produced an accelerated velocity, and this velocity of the weight and beam gives to them an energy, or vis viva, which must now spend itself in overcoming an excess of resistance over and above the imposed load, and the whole mass will not stop until the deflection (as well as the resistance) has come to be equal to twice that corresponding to the static load imposed. Hence we say the effect of a suddenly imposed load is to produce twice the deflection and stress of the same load statically applied. It must be evident; however, that this case has nothing in common with either the ordinary 'static' tests of structural materials in testing-machines, or with impact tests.

(3) Impact, shock, or blow. There are various common uses of wood where the material is subjected to sudden shocks and jars or impact. Such is the action on the felloes and spokes of a wagon wheel passing over a rough road; on a hammer handle when a blow is struck; on a maul when it strikes a wedge.

Resistance to impact is resistance to energy which is measured by the product of the force into the space through which it moves, or by the product of one-half the moving mass which causes the shock into the square of its velocity. The work done upon the piece at the instant the velocity is entirely removed from the striking body is equal to the total energy of that body. It is impossible, however, to get all of the energy of the striking body stored in the specimen, though the greater the mass and the shorter the space through which it moves, or, in other words, the greater the proportion of weight and the smaller the proportion of velocity making up the energy of the striking body, the more energy the specimen will absorb. The rest is lost in friction, vibrations, heat, and motion of the anvil.

In impact the stresses produced become very complex and difficult to measure, especially if the velocity is high, or the mass of the beam itself is large compared to that of the weight.

The difficulties attending the measurement of the stresses beyond the elastic limit are so great that commonly they are not reckoned. Within the elastic limit the formulæ for calculating the stresses are based on the assumption that the deflection is proportional to the stress in this case as in static tests.

A common method of making tests upon the resistance of wood to shock is to support a small beam at the ends and drop a heavy weight upon it in the middle. The height of the weight is increased after each drop and records of the deflection taken until failure. The total work done upon the specimen is equal to the area of the stress-strain diagram plus the effect of local inertia of the molecules at point of contact.

The stresses involved in impact are complicated by the fact that there are various ways in which the energy of the striking body may be spent:

(a) It produces a local deformation of both bodies at the surface of contact, within or beyond the elastic limit. In testing wood the compression of the substance of the steel striking-weight may be neglected, since the steel is very hard in comparison with the wood. In addition to the compression of the fibres at the surface of contact resistance is also offered by the inertia of the particles there, the combined effect of which is a stress at the surface of contact often entirely out of proportion to the compression which would result from the action of a static force of the same magnitude. It frequently exceeds the crushing strength at the extreme surface of contact, as in the case of the swaging action of a hammer on the head of an iron spike, or of a locomotive wheel on the steel rail. This is also the case when a bullet is shot through a board or a pane of glass without breaking it as a whole.

(b) It may move the struck body as a whole with an accelerated velocity, the resistance consisting of the inertia of the body. This effect is seen when a croquet ball is struck with a mallet.

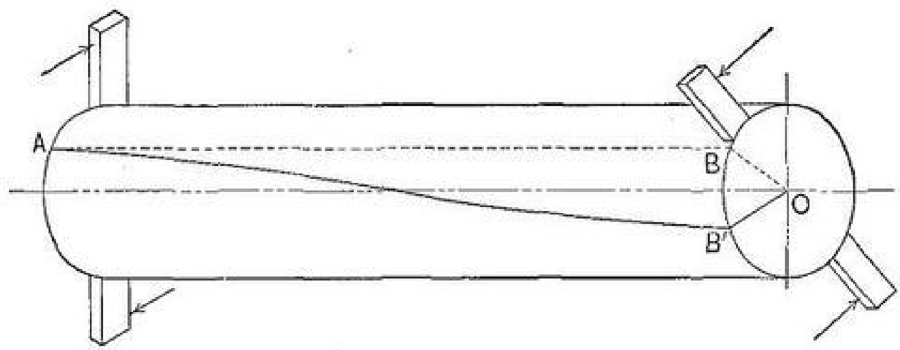
(c) It may deform a fixed body against its external supports and resistances. In making impact tests in the laboratory the test specimen is in reality in the nature of a cushion between two impacting bodies, namely, the striking weight and the base of the machine. It is important that the mass of this base be sufficiently great that its relative velocity to that of the common centre of gravity of itself and the striking weight may be disregarded.

(d) It may deform the struck body as a whole against the resisting stresses developed by its own inertia, as, for example, when a baseball bat is broken by striking the ball.

Impact testing is difficult to conduct satisfactorily and the data obtained are of chief value in a relative sense, that is, for comparing the shock-resisting ability of woods of which like specimens have been subjected to exactly identical treatment. Yet this test is one of the most important made on wood, as it brings out properties not evident from other tests. Defects and brittleness are revealed by impact better than by any other kind of test. In common practice nearly all external stresses are of the nature of impact. In fact, no two moving bodies can come together without impact stress. Impact is therefore the commonest form of applied stress, although the most difficult to measure.

Toughness: Torsion

Toughness is a term applied to more than one property of wood. Thus wood that is difficult to split is said to be tough. Again, a tough wood is one that will not rupture until it has deformed considerably under loads at or near its maximum strength, or one which still hangs together after it has been ruptured and may be bent back and forth without breaking apart. Toughness includes flexibility and is the reverse of brittleness, in that tough woods break gradually and give warning of failure. Tough woods offer great resistance to impact and will permit rougher treatment in manipulations attending manufacture and use. Toughness is dependent upon the strength, cohesion, quality, length, and arrangement of fibre, and the pliability of the wood. Coniferous woods as a rule are not as tough as hardwoods, of which hickory and elm are the best examples.



Torsion of a shaft.

The torsion or twisting test is useful in determining the toughness of wood. If the ends of a shaft are turned in opposite directions, or one end is turned and the other is fixed, all of the fibres except those at the axis tend to assume the form of helices. The strain produced by torsion or twisting is essentially shear transverse and parallel to the fibres, combined with longitudinal tension and transverse compression. Within the elastic limit the strains increase directly as the distance from the axis of the specimen. The outer elements are subjected to tensile stresses, and as they become twisted tend to compress those near the axis. The elongated elements also contract laterally. Cross sections which were originally plane become warped. With increasing strain the lateral adhesion of the outer fibres is destroyed, allowing them to slide past each other, and reducing greatly their power of resistance. In this way the strains on the fibres nearer the axis are progressively increased until finally all of the elements are sheared apart. It is only in the toughest materials that the full effect of this action can be observed. (See Fig. 20.) Brittle woods snap off suddenly with only a small amount of torsion, and their fracture is irregular and oblique to the axis of the piece instead of frayed out and more nearly perpendicular to the axis as is the case with tough woods.

Hardness

The term hardness is used in two senses, namely: (1) resistance to indentation, and (2) resistance to abrasion or scratching. In the latter sense hardness combined with toughness is a measure of the wearing ability of wood and is an important consideration in the use of wood for floors, paving blocks, bearings, and rollers.

Woodworking:

When wood is used as a construction material, whether as a structural support in a building or in woodworking objects, it will absorb moisture until it is in equilibrium with its surroundings. Equilibration (usually drying) causes unequal shrinkage in the wood, and can cause damage to the wood if equilibration occurs too rapidly. The equilibration must be controlled to prevent damage to the wood.

- **Wood burning.** When wood is burned, it is usually best to dry it first. Damage from shrinkage is not a problem here, and the drying may proceed more rapidly than in the case of drying for woodworking purposes. Moisture affects the burning process, with unburnt hydrocarbons going up the chimney. If a 50% wet log is burnt at high temperature, with good heat extraction from the exhaust gas leading to a 100°C exhaust temperature, about 5% of the energy of the log is wasted through evaporating and heating the water vapour. With condensers, the efficiency can be further increased; but, for the normal stove, the key to burning wet wood is to burn it very hot, perhaps starting fire with dry wood.

For some purposes, wood is not dried at all, and is used green. Often, wood must be in equilibrium with the air outside, as for construction wood, or the air indoors, as for wooden furniture.

Wood is air-dried or kiln-dried. Usually, the wood is sawn before drying, but not always, as when the whole log is dried.

Case hardening describes lumber or timber that has been improperly kiln-dried. If dried too quickly, wood shrinks much at the surface, compressing its damp interior. This results in unrelieved stress. Case-hardened wood may warp considerably and dangerously when the stress is released by sawing.

Types of wood

Wood is divided, according to its botanical origin, into two kinds: softwoods, from coniferous trees, and hardwoods, from broad-leaved trees. Softwoods are lighter and generally simple in structure, whereas hardwoods are harder and more complex. However, in Australia, *softwood* generally describes rainforest trees, and *hardwood* describes sclerophyllous species (*Eucalyptus spp*).

Softwood, such as pine, is much lighter and easier to process than hardwood (such as fruit-tree wood, which is heavier. The density of softwoods ranges from 350 kg/m^3 to

700 kg/m³, while hardwoods are 450 kg/m³ to 1250 kg/m³. Both consist of approximately 12% of moisture (*Desch and Dinwoodie, 1996*). Because of hardwood's denser and more complex structure, its permeability is much less than that of softwood, making it more difficult to dry. Although there are about a hundred times more species of hardwood trees than softwood trees, the ability to be dried and processed faster and more easily makes softwood the main supply of commercial wood today.

Wood–water relationships

The timber of living trees and freshly felled logs contains a large amount of water, which often constitutes over 50% of the woods' weight. Water has a significant influence on wood. Wood continually exchanges moisture or water with its surroundings, although the rate of exchange is strongly affected by the degree wood is sealed.

Wood contains water in two forms:

1. Free water: The bulk of water contained in the cell lumina is only held by capillary forces. It is not bound chemically and is called free water. Free water is not in the same thermodynamic state as liquid water: energy is required to overcome the capillary forces. Furthermore, free water may contain chemicals, altering the drying characteristics of wood.
2. Bound or hygroscopic water: Bound water is bound to the wood via hydrogen bonds. The attraction of wood for water arises from the presence of free hydroxyl (OH) groups in the cellulose, hemicelluloses and lignin molecules in the cell wall. The hydroxyl groups are negatively charged electrically. Water is a polar liquid. The free hydroxyl groups in cellulose attract and hold water by hydrogen bonding.

Vapor: Water in cell lumina in the form of water vapour is normally negligible at normal temperature and humidity Moisture content of wood

The moisture content of wood is calculated by the formula (Siau, 1984):

$$\text{moisture content} = \frac{m_g - m_{od}}{m_{od}} \qquad (1.1)$$

Here, m_g is the green mass of the wood, m_{od} is its oven-dry mass (the attainment of constant mass generally after drying in an oven set at 103 +/- 2 °C for 24 hours as mentioned by Walker *et al.*, 1993). The equation can also be expressed as a fraction of the mass of the water and the mass of the oven-dry wood rather than a percentage. For example, 0.59 kg/kg (oven dry basis) expresses the same moisture content as 59% (oven dry basis).

Moisture content could also be present as:

moisture content = $\frac{WeightWhenCut - OvendryWeight}{OvendryWeight}$ x100%

Where the wet weight is the weight of the original 'wet' sample and the dry weight being the weight of the sample after drying in an oven. Moisture contents being expressed as a percentage.

Fibre saturation point

When green wood dries, free water from the cell lumina, held by the capillary forces only, is the first to go. Physical properties, such as strength and shrinkage, are generally not affected by the removal of free water. The fibre saturation point (FSP) is defined as the moisture content at which free water should be completely gone, while the cell walls are saturated with bound water. In most types of woods, the fibre saturation point is at 25 to 30% moisture content. Siau (1984) reported that the fibre saturation point X_{fsp} (kg/kg) is dependent on the temperature T (°C) according to the following equation:

$$X_{fsp} = 0.30 - 0.001(T - 20) \quad (1.2)$$

Keey *et al.* (2000) use a different definition of the fibre saturation point (equilibrium moisture content of wood in an environment of 99% relative humidity).

Many properties of wood show considerable change as the wood is dried below the fibre saturation point, including:

1. volume (ideally no shrinkage occurs until some bound water is lost, that is, until wood is dried below FSP);
2. strength (strengths generally increase consistently as the wood is dried below the FSP (Desch and Dinwoodie, 1996), except for impact-bending strength and, in some cases, toughness);
3. electrical resistivity, which increases very rapidly with the loss of bound water when the wood dries below the FSP.

Equilibrium moisture content

Wood is a hygroscopic substance. It has the ability to take in or give off moisture in the form of vapour. Water contained in wood exerts vapour pressure of its own, which is determined by the maximum size of the capillaries filled with water at any time. If water vapour pressure in the ambient space is lower than vapour pressure within wood, desorption takes place. The largest-sized capillaries, which are full of water at the time, empty first. Vapour pressure within the wood falls as water is successively contained in smaller capillaries. A stage is eventually reached when vapour pressure within the wood equals vapour pressure in the ambient space above the wood, and further desorption ceases. The amount of moisture that remains in the wood at this stage is in equilibrium with water vapour pressure in the ambient space, and is termed the equilibrium moisture content or EMC (Siau, 1984). Because of its hygroscopicity, wood tends to reach a moisture content that is in equilibrium with the relative humidity and temperature of the surrounding air. The EMC of wood varies with the ambient relative humidity (a function of temperature) significantly, to a lesser degree with the temperature. Siau (1984) reported that the EMC also varies very slightly with species, mechanical stress, drying history of wood, density, extractives content and the direction of sorption in which the moisture change takes place (i.e. adsorption or desorption).

Shrinkage and swelling

Shrinkage and swelling may occur in wood when the moisture content is changed (Stamm, 1964). Shrinkage occurs as moisture content decreases, while swelling takes place when it increases. Volume change is not equal in all directions. The greatest dimensional change occurs in a direction tangential to the growth rings. Shrinkage from the pith outwards, or radially, is usually considerably less than tangential shrinkage, while longitudinal (along the grain) shrinkage is so slight as to be usually neglected. The longitudinal shrinkage is 0.1% to 0.3%, in contrast to transverse shrinkages, which is 2% to 10%. Tangential shrinkage is often about twice as great as in the radial direction, although in some species it is as much as five times as great. The shrinkage is about 5% to 10% in the tangential direction and about 2% to 6% in the radial direction (Walker *et al.*, 1993).

Differential transverse shrinkage of wood is related to:

1. the alternation of late wood and early wood increments within the annual ring;
2. the influence of wood rays on the radial direction (Kollmann and Cote, 1968);
3. the features of the cell wall structure such as microfibril angle modifications and pits;
4. The chemical composition of the middle lamella.

Wood drying

Wood drying may be described as the art of ensuring that gross dimensional changes through shrinkage are confined to the drying process. Ideally, wood is dried to that equilibrium moisture content as will later (in service) be attained by the wood. Thus, further dimensional change will be kept to a minimum.

It is probably impossible to completely eliminate dimensional change in wood, but elimination of change in size may be approximated by chemical modification. For example, wood can be treated with chemicals to replace the hydroxyl groups with other hydrophobic functional groups of modifying agents (Stamm, 1964). Among all the existing processes, wood modification with acetic anhydride has been noted for the high anti-shrink or anti-swell efficiency (ASE) attainable without damage to wood. However, acetylation of wood has been slow to be commercialised due to the cost, corrosion and the entrapment of the acetic acid in wood. There is an extensive volume of literature relating to the chemical modification of wood (Rowell, 1983, 1991; Kumar, 1994; Haque, 1997).

Drying, if carried out promptly after felling of trees, also protects timber against primary decay, fungal stain and attack by certain kinds of insects. Organisms, which cause decay and stain, generally cannot thrive in timber with a moisture content below 20%. Several, though not all, insect pests can live only in green timber. Dried wood is less susceptible to decay than green wood is above 20% moisture.

In addition to the above advantages of drying timber, the following points are also significant (Walker *et al.*, 1993; Desch and Dinwoodie, 1996):

1. Dried timber is lighter, and the transportation and handling costs are reduced.
2. Dried timber is stronger than green timber in most strength properties.
3. Timbers for impregnation with preservatives have to be properly dried if proper penetration is to be accomplished, particularly in the case of oil-type preservatives.
4. In the field of chemical modification of wood and wood products, the material should be dried to a certain moisture content for the appropriate reactions to occur.
5. Dry wood works, machines, finishes and glues better than green timber. Paints and finishes last longer on dry timber.
6. The electrical and thermal insulation properties of wood are improved by drying.

Prompt drying of wood immediately after felling therefore significantly upgrades and adds value to raw timber. Drying enables substantial long-term economy by rationalizing the use of timber resources. The drying of wood is thus an area for research and development, which concern many researchers and timber companies around the world.

How wood dries: the mechanisms of moisture movement

Water in wood normally moves from zones of higher to zones of lower moisture content (Walker *et al*., 1993). Drying starts from the exterior of the wood and moves towards the centre, and drying at the outside is also necessary to expel moisture from the inner zones of the wood. Wood subsequently attains equilibrium with the surrounding air in moisture content.

Mechanisms for moisture movement

Moisture passageways

The driving force of moisture movement is chemical potential. However, it is not always easy to relate chemical potential in wood to commonly observable variables, such as temperature and moisture content (Keey *et al.,* 2000). Moisture in wood moves within the wood as liquid or vapour through several types of passageways, based on the nature of the driving force, (e.g. pressure or moisture gradient), and variations in wood structure (Langrish and Walker, 1993), as explained in the next section on driving forces for moisture movement. These pathways consist of cavities of the vessels, fibres, ray cells, pit chambers and their pit membrane openings, intercellular spaces and transitory cell wall passageways.

Movement of water takes place in these passageways in any direction, longitudinally in the cells, as well as laterally from cell to cell until it reaches the lateral drying surfaces of the wood. The higher longitudinal permeability of sapwood of hardwood is generally caused by the presence of vessels. The lateral permeability and transverse flow is often very low in hardwoods. The vessels in hardwoods are sometimes blocked by the presence of tyloses and/or by secreting gums and resins in some other species, as mentioned earlier. The presence of gum veins, the formation of which is often a result of natural protective response of trees to injury, is commonly observed on the surface of sawn boards of most eucalypts. Despite the generally higher volume fraction of rays in hardwoods (typically 15% of wood volume), the rays are not particularly effective in radial flow, nor are the pits on the radial surfaces of fibres effective in tangential flow (Langrish and Walker, 1993).

Moisture movement space

The available space for air and moisture in wood depends on the density and porosity of wood. Porosity is the volume fraction of void space in a solid. The porosity is reported to be 1.2 to 4.6% of dry volume of wood cell wall (Siau, 1984). On the other hand, permeability is a measure of the ease with which fluids are transported through a porous solid under the influence of some driving forces, e.g. capillary pressure gradient or moisture gradient. It is clear that solids must be porous to be permeable, but it does not necessarily follow that all porous bodies are permeable. Permeability can only exist if the void spaces are interconnected by openings. For example, a hardwood may be permeable because there is inter-vessel pitting with openings in the membranes (Keey *et al.*, 2000). If these membranes are occluded or encrusted, or if the pits are aspirated, the wood assumes a closed-cell structure and may be virtually impermeable. The density is also important for impermeable hardwoods because more cell-wall material is traversed per unit distance, which offers increased resistance to diffusion (Keey *et al.*, 2000). Hence lighter woods, in general, dry more rapidly than do the heavier woods. The transport of fluids is often bulk flow (momentum transfer) for permeable softwoods at high temperature while diffusion occurs for impermeable hardwoods (Siau, 1984). These mechanisms are discussed below.

Driving forces for moisture movement

Three main driving forces used in different version of diffusion models are moisture content, the partial pressure of water vapour, and the chemical potential (Skaar, 1988; Keey *et al.*, 2000). These are discussed here, including capillary action, which is a mechanism for free water transport in permeable softwoods. Total pressure difference is the driving force during wood vacuum drying.

Capillary action

Capillary forces determine the movements (or absence of movement) of free water. It is due to both adhesion and cohesion. Adhesion is the attraction between water to other substances and cohesion is the attraction of the molecules in water to each other.

As wood dries, evaporation of water from the surface sets up capillary forces that exert a pull on the free water in the zones of wood beneath the surfaces. When there is no longer any free water in the wood capillary forces are no longer of importance.

Moisture content differences

The chemical potential is explained here since it is the true driving force for the transport of water in both liquid and vapour phases in wood (Siau, 1984). The Gibbs free energy per mole of substance is usually expressed as the chemical potential (Skaar, 1933). The chemical potential of unsaturated air or wood below the fibre saturation point influences the drying of wood. Equilibrium will occur at the equilibrium moisture content (as defined earlier) of wood when the chemical potential of the wood becomes equal to that of the surrounding air. The chemical potential of sorbed water is a function of wood moisture content. Therefore, a gradient of wood moisture content (between surface and centre), or more specifically of activity, is accompanied by a gradient of chemical potential under isothermal conditions. Moisture will redistribute itself throughout the wood until the chemical potential is uniform throughout, resulting in a zero potential gradient at equilibrium (Skaar, 1988). The flux of moisture attempting to achieve the equilibrium state is assumed to be proportional to the difference in chemical potential, and inversely proportional to the path length over which the potential difference acts (Keey *et al.*, 2000).

The gradient in chemical potential is related to the moisture content gradient as explained in above equations (Keey *et al.*, 2000). The diffusion model using moisture content gradient as a driving force was applied successfully by Wu (1989) and Doe *et al.* (1994). Though the agreement between the moisture-content profiles predicted by the diffusion model based on moisture-content gradients is better at lower moisture contents than at higher ones, there is no evidence to suggest that there are significantly different moisture-transport mechanisms operating at higher moisture contents for this timber. Their observations are consistent with a transport process that is driven by the total concentration of water. The diffusion model is used for this thesis based on this empirical evidence that the moisture-content gradient is a driving force for drying this type of impermeable timber.

Differences in moisture content between the surface and the centre (gradient, the chemical potential difference between interface and bulk) move the bound water through the small passageways in the cell wall by diffusion. In comparison with capillary movement, diffusion is a slow process. Diffusion is the generally suggested mechanism for the drying of impermeable hardwoods (Keey *et al.*, 2000). Furthermore, moisture migrates slowly due to the fact that extractives plug the small cell wall openings in the heartwood. This is why sapwood generally dries faster than heartwood under the same drying conditions.

Moisture movement directions for diffusion

It is reported that the ratio of the longitudinal to the transverse (radial and tangential) diffusion rates for wood ranges from about 100 at a moisture content of 5% to 2 to 4 at a moisture content of 25% (Langrish and Walker, 1993). Radial diffusion is somewhat faster than tangential diffusion. Although longitudinal diffusion is most rapid, it is of practical importance only when short pieces are dried. Generally the timber boards are much longer than in width or thickness. For example, a typical size of a green board used for this research was 6 m long, 250 mm in width and 43 mm in thickness. If the boards are quartersawn (sawing around the pith), then the width will be in the radial direction whereas the thickness will be in tangential direction, and vice versa for back-sawn (sawing through and through) boards. Most of the moisture is removed from wood by lateral movement during drying.

Reasons for splits and cracks during timber drying and their control

The chief difficulty experienced in the drying of timber is the tendency of its outer layers to dry out more rapidly than the interior ones. If these layers are allowed to dry much below the fibre saturation point while the interior is still saturated, stresses (called drying stresses) are set up because the shrinkage of the outer layers is restricted by the wet interior (Keey *et al.*, 2000). Rupture in the wood tissues occurs, and consequently splits and cracks occur if these stresses across the grain exceed the strength across the grain (fibre to fibre bonding).

The successful control of drying defects in a drying process consists in maintaining a balance between the rate of evaporation of moisture from the surface and the rate of outward movement of moisture from the interior of the wood. The way in which drying can be controlled will now be explained. One of the most successful ways of wood drying or seasoning would be kiln drying, where the wood is placed into a kiln compartment in stacks and dried by steaming, and releasing the steam slowly.

Influence of temperature, relative humidity and rate of air circulation

The external drying conditions (temperature, relative humidity and air velocity) control the external boundary conditions for drying, and hence the drying rate, as well as affecting the rate of internal moisture movement. The drying rate is affected by external drying conditions (Walker *et al.*, 1993; Keey *et al.*, 2000), as will now be described.

Temperature: If the relative humidity is kept constant, the higher the temperature, the higher the drying rate. Temperature influences the drying rate by increasing the moisture holding capacity of the air, as well as by accelerating the diffusion rate of moisture through the wood. The actual temperature in a drying kiln is the dry-bulb temperature (usually denoted by Tg), which is the temperature of a vapour-gas mixture determined by inserting a thermometer with a dry bulb. On the other hand, the wet-bulb temperature (TW) is defined as the temperature reached by a small amount of liquid evaporating in a large amount of an unsaturated air-vapour mixture. The temperature sensing element of this thermometer is kept moist with a porous fabric sleeve (cloth) usually put in a reservoir of clean water. A minimum air flow of 2 m/s is needed to prevent a zone of stagnant damp air formation around the sleeve (Walker *et al.*, 1993). Since air passes over the wet sleeve, water is evaporated and cools the wet-bulb thermometer. The difference between the dry-bulb and wet-bulb temperatures, the wet-bulb depression, is used to determine the relative humidity from a standard hygrometric chart (Walker *et al.*, 1993). A higher difference between the dry-bulb and wet-bulb temperatures indicates a lower relative humidity. For example, if the dry-bulb temperature is 100 °C and wet-bulb temperature 60 °C, then the relative humidity is read as 17% from a hygrometric chart.

Relative humidity:

The relative humidity of air is defined as the partial pressure of water vapour divided by the saturated vapour pressure at the same temperature and total pressure (Siau, 1984). If the temperature is kept constant, lower relative humidities result in higher drying rates due to the increased moisture gradient in wood, resulting from the reduction of the moisture content in the surface layers when the relative humidity of air is reduced. The relative humidity is usually expressed on a percentage basis. For drying, the other essential parameter related to relative humidity is the absolute humidity, which is the mass of water vapour per unit mass of dry air (kg of water per kg of dry air). The following equation can be used to calculate the absolute humidity from the relative humidity (Strumillo and Kudra, 1986):

Air circulation rate: Drying time and timber quality depend on the air velocity and its uniform circulation. At a constant temperature and relative humidity, the highest possible drying rate is obtained by rapid circulation of air across the surface of wood, giving rapid removal of moisture evaporating from the wood. However, a higher drying rate is not always desirable, particularly for impermeable hardwoods, because higher drying rates develop greater stresses that may cause the timber to crack or distort. At very low fan speeds, less than 1 m s-1, the air flow through the stack is often laminar flow, and the heat transfer between the timber surface and the moving air stream is not particularly effective (Walker *et al.*, 1993). The low effectiveness (externally) of heat transfer is not necessarily a problem if internal moisture movement is the key limitation to the movement of moisture, as it is for most hardwoods (Pordage and Langrish, 1999).

Classification of timbers for drying

The timbers are classified as follows according to their ease of drying and their proneness to drying degrades:

1. Highly refractory woods: These woods are slow and difficult to dry if the final product is to be free from defects, particularly cracks and splits. Examples are heavy structural timbers with high density such as ironbark (*Eucalyptus paniculata*), blackbutt (*E. pilularis*), southern blue gum (*E. globulus*) and brush box (*Lophostemon cofertus*). They require considerable protection and care against rapid drying conditions for the best results (Bootle, 1994).
2. Moderately refractory woods: These timbers show a moderate tendency to crack and split during seasoning. They can be seasoned free from defects with moderately rapid drying conditions (i.e. a maximum dry-bulb temperature of 85 °C can be used). Examples are Sydney blue gum (*E. saligna*) and other timbers of medium density (Bootle, 1994), which are potentially suitable for furniture.
3. Non-refractory woods: These woods can be rapidly seasoned to be free from defects even by applying high temperatures (dry-bulb temperatures of more than 100 °C) in industrial kilns. If not dried rapidly, they may develop

discolouration (blue stain) and mould on the surface. Examples are softwoods and low density timbers such as *Pinus radiata*.

Methods of drying timber

Broadly, there are two methods by which timber can be dried: (i) natural drying or air drying, and (ii) artificial drying.

Air drying

Air drying is the drying of timber by exposing it to the air. The technique of air drying consists mainly of making a stack of sawn timber (with the layers of boards separated by stickers) on raised foundations, in a clean, cool, dry and shady place. Rate of drying largely depends on climatic conditions, and on the air movement (exposure to the wind). For successful air drying, a continuous and uniform flow of air throughout the pile of the timber needs to be arranged (Desch and Dinwoodie, 1996). The rate of loss of moisture can be controlled by coating the planks with any substance that is relatively impermeable to moisture; ordinary mineral oil is usually quite effective. Coating the ends of logs with oil or thick paint, improves their quality upon drying. Wrapping planks or logs in materials which will allow some movement of moisture, generally works very well provided the wood is first treated against fungal infection by coating in petrol/gasoline or oil. Mineral oil will generally not soak in more than 1–2 mm below the surface and is easily removed by planning when the timber is suitably dry. Benefits- It can be less expensive to use this drying method (there are still costs associated with storing the wood, and with the slower process of getting the wood to market), and air drying often produces a higher quality, more easily workable wood than with kiln drying. Drawbacks- Depending on the climate, it takes several months to a number of years to air-dry the wood.

Kiln drying

The process of kiln drying consists basically of introducing heat. This may be directly, using natural gas and/or electricity or indirectly, through steam-heated heat exchangers, although solar energy is also possible. In the process, deliberate control of temperature, relative humidity and air circulation is provided to give conditions at various stages (moisture contents or times) of drying the timber to achieve effective drying. For this purpose, the timber is stacked in chambers, called wood drying kilns, which are fitted with equipment for manipulation and control of the temperature and the relative humidity of the drying air and its circulation rate through the timber stack (Walker *et al.*, 1993; Desch and Dinwoodie, 1996).

Kiln drying provides a means of overcoming the limitations imposed by erratic weather conditions. In kiln drying as in air drying, unsaturated air is used as the drying medium. Almost all commercial timbers of the world are dried in industrial kilns. A comparison of air drying, conventional kiln and solar drying is given below:

1. Timber can be dried to any desired low moisture content by conventional or solar kiln drying, but in air drying, moisture contents of less than 18% are difficult to attain for most locations.

2. The drying times are considerably less in conventional kiln drying than in solar kiln drying, followed by air drying.
    1. This means that if capital outlay is involved, this capital is just sitting there for a longer time when air drying is used. On the other hand, installing an industrial kiln, to say nothing of maintenance and operation, is expensive.
    2. In addition, wood that is being air dried takes up space, which could also cost money.
3. In air drying, there is little control over the drying elements, so drying degrade cannot be controlled.
4. The temperatures employed in kiln drying typically kill all the fungi and insects in the wood if a maximum dry-bulb temperature of above 60 °C is used for the drying schedule. This is not guaranteed in air drying.
5. If air drying is done improperly (exposed to the sun), the rate of drying may be overly rapid in the dry summer months, causing cracking and splitting, and too slow during the cold winter months.

The significant advantages of conventional kiln drying include higher throughput and better control of the final moisture content. Conventional kiln and solar drying both enable wood to be dried to any moisture content regardless of weather conditions. For most large-scale drying operations solar and conventional kiln drying are more efficient than air drying.

Compartment-type kilns are most commonly used in timber companies. A compartment kiln is filled with a static batch of timber through which air is circulated. In these types of kiln, the timber remains stationary. The drying conditions are successively varied from time to time in such a way that the kilns provide control over the entire charge of timber being dried. This drying method is well suited to the needs of timber companies, which have to dry timbers of varied species and thickness, including refractory hardwoods that are more liable than other species to check and split.

The main elements of kiln drying are described below:

a) Construction materials: The kiln chambers are generally built of brick masonry, or hollow cement-concrete slabs. Sheet metal or prefabricated aluminium in a double-walled construction with sandwiched thermal insulation, such as glass wool or polyurethane foams, are materials that are also used in some modern kilns. Some of the elements used in kiln construction. However, brick masonry chambers, with lime and (mortar) plaster on the inside and painted with impermeable coatings, are used widely and have been found to be satisfactory for many applications.

b) Heating: Heating is usually carried out by steam heat exchangers and pipes of various configurations (e.g. plain, or finned (transverse or longitudinal) tubes) or by large flue pipes through which hot gases from a wood burning furnace are passed. Only occasionally is electricity or gas employed for heating.

c) Humidification: Humidification is commonly accomplished by introducing live steam into the kiln through a steam spray pipe. In order to limit and control the humidity of the air when large quantities of moisture are being rapidly evaporated from the timber, there is normally a provision for ventilation of the chamber in all types of kilns. d) Air circulation: Air circulation is the means for carrying the heat to and the moisture away from all parts of a load. Forced circulation kilns are most common, where the air is circulated by means of fans or blowers, which may be installed outside the kiln chamber (external fan kiln) or inside it (internal fan kiln). Throughout the process, it is necessary to keep close control of the moisture content using a moisture meter system in order to reduce over-drying and allow operators to know when to pull the charge. Preferably, this in-kiln moisture meter will have an auto-shutoff feature.

Kiln drying schedules

Satisfactory kiln drying can usually be accomplished by regulating the temperature and humidity of the circulating air to suit the state of the timber at any given time. This condition is achieved by applying kiln-drying schedules. The desired objective of an appropriate schedule is to ensure drying timber at the fastest possible rate without causing objectionable degrade. The following factors have a considerable bearing on the schedules.

1. The species; because of the variations in physical, mechanical and transport properties between species.
2. The thickness of the timber; because the drying time is approximately inversely related to thickness and, to some extent, is also influenced by the width of the timber.
3. Whether the timber boards are quarter-sawn, back-sawn or mixed-sawn; because sawing pattern influences the distortion due to shrinkage anisotropy.
4. Permissible drying degrade; because aggressive drying schedules can cause timber to crack and distort.
5. Intended use of timber; because the required appearance of the timber surface and the target final moisture contents are different depending on the uses of timber.

Considering each of the factors, no one schedule is necessarily appropriate, even for similar loads of the same species. This is why there is so much timber drying research, including this work, focused on the development of effective drying schedules.

Drying defects

Drying defects are the most common form of degrade in timber, next to natural problems such as knots (Desch and Dinwoodie, 1996). There are two types of drying defects, although some defects involve both causes:

1. Defects from shrinkage anisotropy, resulting in to warping: cupping, bowing, twisting, crooking, spring and diamonding.
2. Defects from uneven drying, resulting in the rupture of the wood tissue, such as checks (surface, end and internal), end splits, honey-combing and case hardening. Collapse, often shown as corrugation, or "washboarding" of the wood surface, may also occur (Innes, 1996). Collapse is a defect that results from the physical flattening of fibres to above the fibre saturation point and is thus not a form of shrinkage anisotropy.

The standard organizations in Australia and New Zealand (AS/NZS 4787, 2001) have developed a standard for timber quality. The five measures of drying quality include:

1. moisture content gradient and presence of residual drying stress (case-hardening);
2. surface, internal and end checks;
3. collapse;
4. distortions;
5. discolouration caused by drying.

Wood-drying kiln

A variety of wood drying kiln technologies exist today: conventional, dehumidification, solar, vacuum and radio frequency.

Conventional wood dry kilns (Rasmussen, 1988) are either package-type (sideloader) or track-type (tram) construction. Most hardwood lumber kilns are sideloader kilns in which fork trucks are used to load lumber packages into the kiln. Most softwood lumber kilns are track types in which lumber packages are loaded on kiln/track cars for loading the kiln.

Modern high-temperature, high-air-velocity conventional kilns can typically dry 1-inch-thick (25 mm) green lumber in 10 hours down to a moisture content of 18%. However, 1-inch-thick green Red Oak requires about 28 days drying down to a moisture content of 8%.

Heat is typically introduced via steam running through fin/tube heat exchangers controlled by on/off pneumatic valves. Less common are proportional pneumatic valves or even various electrical actuators. Humidity is removed via a system of vents, the specific layout of which are usually particular to a given manufacturer. In general, cool dry air is introduced at one end of the kiln while warm moist air is expelled at the other. Hardwood conventional kilns also require the introduction of humidity via either steam spray or cold water misting systems to keep the relative humidity inside the kiln from dropping too low during the drying cycle. Fan directions are typically reversed periodically to ensure even drying of larger kiln charges.

Most softwood lumber kilns operate below 240 °F (116 °C) temperature. Hardwood lumber kiln drying schedules typically keep the dry bulb temperature below 180 °F (82 °C). Difficult-to-dry species might not exceed 140 degrees F.

Dehumidification kilns are very similar to conventional kilns in basic construction. Drying times are usually comparable. Heat is primarily supplied by an integral dehumidification unit which also serves to remove humidity. Auxiliary heat is often provided early in the schedule where the heat required may exceed the heat generated by the DH unit.

Solar kilns are conventional kilns, typically built by hobbyists to keep initial investment costs low. Heat is provided via solar radiation, while internal air circulation is typically passive.

The total (harmful) air emissions produced by wood kilns, including their heat source, can be significant. Typically, the higher the temperature the kiln operates at, the larger amount of emissions are produced (per pound of water removed). This is especially true in the drying of thin veneers and high-temperature drying of softwoods.

DRYING DEFECTS

The success of a company and the livelihood of the dry kiln operator may depend on knowing the causes of defects in lumber and methods to prevent their occurrence. Since some defects are not observed in green lumber and are first noted after the drying operation, they are often called drying defects even though the defects may have started in the tree, log, or green lumber. Defects that develop in dry wood products during machining, gluing, and finishing operations may also be blamed on poor drying practices. A drying defect is any characteristic or blemish in a wood product that occurs during the drying process and reduces the product's intended value. Drying degrade is a more specific term that implies a drying defect that lowers the grade of lumber. Every year, drying degrade and other drying defects cost the softwood and hardwood lumber industries millions of dollars in lost value and lost volume caused by poor product performance. When unexpected defects appear in dried wood products, their cause is often blamed on the drying operation. The purpose of this chapter is to describe the various types of defects that can occur in dried wood products and to show how these defects are related to the kiln-drying operation.

Many features of wood affect its utility when it is processed into lumber and special products. These includes knots, ring shake, bark, mineral streaks, pitch pockets, compression and tension wood, juvenile wood, and spiral or interlocked grain, all of which form in the tree and directly influence the grade and value of each individual board. Ordinary processing of lumber may remove some of these natural features through trimming and thus improve the quality and value of the remaining piece. Defects that reduce the grade and value of lumber often develop during logging, sawmilling, drying, finishing, and mechanical handling. A principal objective is to dry the wood economically with as little development of defects as possible. The degree of care to exercise in controlling the development of defects depends on the final use of the lumbar. It is important for the kiln operator to be familiar with the various defects that reduce the grade and value of dry wood products, to know when the defects can be reduced or eliminated with proper drying practices, and to recognize when corrective measures other than drying are required. When drying is used to control defects, it should be done in a manner consistent with the economy of the overall manufacturing system. Before adopting a drying procedure to control specific drying defects, the kiln operator should determine whether the procedure will induce other defects that may lower the value of the lumber.

Effect of Drying Temperatures

High temperatures reduce the strength of wood in two ways:
First, there is an immediate and reversible effect. For example, wood is weakened when heated from 75 to 240 °F but regains strength if immediately cooled to 75 °F. The second effect occurs over time and is permanent. When wood is heated for long times at high temperatures, 'it is permanently weakened; the loss of strength remains after the wood is cooled.

Roth effects are greater at high moisture content than at low moisture content. The permanent effect is caused by a combination of time, temperature, and moisture content. Strength loss increases as any one of these factors increases. The immediate,-reversible effect of high-temperature drying is important in the development of drying defects that result from breakage or crushing of wood cells. When the drying stresses become greater than the strength of the wood, this type of drying defect develops. This is why high temperatures early in drying are dangerous. The weakening effect of high temperatures coupled with high moisture content can cause the wood to fracture or be crushed.

High-temperature drying for long periods, particularly early in drying when the moisture content is high, may not result in breakage or crushing-type drying defects, but it can cause a permanent loss in strength or other mechanical properties that affect product performance in end use. In general, stiffness is not greatly reduced by high-temperature drying; hut bending strength may be reduced by as much as 20 percent. For many uses of wood, some reduction in strength is not important. In some uses, it is quite important. Wood for ladders, aircraft, and sporting goods requires high strength and toughness retention. There is evidence that lumber treated with waterborne preservatives and fire retardants is particularly sensitive to strength reduction if drying temperatures are too high. Temperatures ranging from 140 to 160 °F have little effect on mechanical properties.
Defect Categories

Most defects or problems that develop in wood products during and after drying can be classified under one of the following categories:

1. Rupture of wood tissue
2. Warp
3. Uneven moisture content
4. Discoloration

Defects in any one of these categories are caused by an interaction of wood properties with processing factors. Wood shrinkage is mainly responsible for wood ruptures and distortion of shape. Cell structure and chemical extractives in wood contribute to defects associated with uneven moisture content, undesirable colour, and undesirable surface texture. Drying temperature is the most important processing factor because it can be responsible for defects in each category.

Rupture of Wood Tissue

Many defects that occur during drying result. from the shrinkage of wood as it dries. In particular, the defects result from uneven shrinkage in the different directions of a board (radial, tangential, or longitudinal) or between different parts of a board, such as the shell and core. Rupture of wood tissue is one category of drying defects associated with shrinkage. Knowing where, when, and why ruptures occur will enable an operator to take action to keep these defects at a minimum. Kiln drying is frequently blamed for defects that have occurred during air drying, but most defects can occur during either process. In kiln drying, defects can be kept to a minimum by modifying drying conditions, and in air drying, by altering piling procedures.

Surface Checks

Surface checks are failures that usually occur in the wood rays on the flatsawn faces of boards. They occur because drying stresses exceed the tensile strength of the wood perpendicular to the grain, and they are caused by tension stresses that develop in the outer part, or shell, of boards as they dry. Surface checks can also occur in resin ducts and mineral streaks. They rarely appear on the edges of flatsawn boards 6/4 or lees in thickness but do appear on the edges of thicker flatsawn or quartersawn boards. Surface checks usually occur early in drying, but in some softwood the danger persists beyond the initial stages of drying. They develop because the lumber surfaces get too dry too quickly as .a result of relative humidity that is too low. Surface checks can also develop during air drying. Thick, wide, flatsawn lumber is more susceptible to surface checking than thin, narrow lumber.

Many surface checks, particularly those in hardwoods, close in the later stages of drying This occurs when the stresses reverse and the shell changes from tension to compression. Closed surface checks are undesirable in products requiring high-quality finished surfaces, such as interior trim and moulding, cabinets, and furniture. The checks will quite likely open to some extent during use because of fluctuations in relative humidity that alternately shrink and swell the surface. Superficial surface checks that will be removed during machining are not a problem. In products such as tool handles, athletic equipment, and some structural members, either closed or open surface checks can increase the tendency of the wood to split during use. In some products, such, as interior parts of furniture, wall studs, and some flooring applications, mild surface checking will not cause any problems in use. Lumber that has surface checked during air drying should not be wetted or exposed to high relative humidity before or during kiln drying. Such treatments frequently lengthen, widen, and deepen surface checks. Lumber that has open surface checks after kiln drying should also not be wetted because subsequent exposure to plant conditions will dry out the wetted surface and enlarge the checks.

End Checks and Splits

End checks, like surface checks, usually occur in the wood rays, but on end-grain surfaces. They also occur in the early stages of drying and can be minimized by using high relative humidity or by end coating. End checks occur because moisture moves much faster in the longitudinal direction than in either transverse direction. Therefore, the ends of boards dry faster than the middle and stresses develop at the ends. End-checked lumber should not be wetted or exposed to high relative humidity before any further drying, or the checks may be driven further into the board. The tendency to end check becomes greater in all species as thickness and width increase. Therefore, the end-grain surfaces of thick and wide lumber squares, and gunstocks should be end coated with one of the end coatings available from kiln manufacturers and other sources. To be most effective, end coatings should be applied to freshly cut, unchecked ends of green wood. End splits often result from the extension of end checks further into a board. One way to reduce the extension of end checks into longer splits is to place stickers at the extreme ends of the boards. End splits are also often caused by growth stresses and are therefore not a drying defect. End splits can be present in the log or sometimes develop in boards immediately after sawing.

Collapse

Collapse is a distortion, flattening, or crushing of wood cells. Collapse usually shows up as grooves or corrugations, a wash boarding effect, at thin places in the board. Slight amounts of collapse are usually difficult or impossible to detect at the board level and are not a particular problem. Sometimes collapse shows up as excessive shrinkage rather than distinct grooves or corrugations. Collapse may be caused by (1) compressive drying stresses in the interior parts of boards that exceed the compressive strength of the wood or (2) liquid tension in cell cavities that are completely filled with water. Both of these conditions occur early in drying, but collapse is not usually visible on the wood surface until later in the process. Collapse is generally associated with excessively high dry-bulb temperatures early in kiln drying, and thus low initial dry-bulb temperatures should be used in species susceptible to collapse and flatsawn (lower) red oak boards showing honeycomb and slight collapse; (b) cross section of flatsawn Wetwood in particular is susceptible to collapse. Although rare, collapse has been known to occur during air drying.

Collapse is a serious defect and should be avoided if possible. The use of special drying schedules planned to minimize this defect is recommended. Some species susceptible to collapse are generally air dried before being kiln dried. In many cases, much excessive shrinkage or wash boarding caused by collapse can be removed from the lumber by reconditioning or steaming, Reconditioning is most effective when the average moisture content is about 15 percent, and 4 to 8 h are usually required. Steaming is corrosive to kilns, and unless collapse is a serious problem that cannot be solved by lowering initial drying temperatures, steaming may not be practical.

Honeycomb

Honeycomb is an internal crack caused by a tensile failure across the grain of the wood and usually occurs in the wood rays. This defect develops because of the internal tension stresses that develop in the core of boards during drying. It occurs when the core is still at relatively high moisture content and when drying temperatures are too high for too long during this critical period. Therefore, honeycomb can be minimized by avoiding high temperatures until all the free water has been evaporated from the entire board. This means that the core moisture content of boards should be below the fiber saturation point before raising temperature because that is where honeycomb develops. When the average moisture content of entire sample boards is monitored for schedule control, there is no direct estimate of core moisture content. Depending on the steepness of the moisture gradient, which is often unknown in most kiln-control schemes, the core moisture content can be quite high even when the average moisture content of the whole sample is low. The danger is that schedule changes based on average moisture content that call for an increase in dry-bulb temperature can be made too soon while moisture content in the core is still high, thus predisposing the wood to honeycomb. Measurements of shell and core moisture content should be taken before these dangerous schedule changes are made. Deep surface and end checks that have closed tightly on the surface of lumber but remain open below the surface often called honeycomb, but they are also known as bottleneck checks. Honeycomb can result in heavy volume losses of lumber. Unfortunately, in many cases the defect is not apparent on the surface, and it is not found until the lumber is in the machine. Severely honeycombed lumber frequently has a corrugated appearance on the surface, and the defect is often associated with severe collapse.

Ring Failure

Ring failure occurs parallel to annual rings either within a growth ring or at the interface between two rings. It is similar in appearance and often related to shake, which is the same kind of failure that takes place in the standing tree or when the tree is felled; wood weakened by shake fails because of drying stresses. In wood with ring failure, internal tension stresses, especially in high-temperature drying, develop after stress reversal. The failure frequently involves several growth rings, starting in one and breaking along wood rays to other rings. It can occur as a failure in the end grain in the initial stages of drying and extend in depth and length as drying progresses. Ring failure can be kept to a minimum by end coating and by using high initial relative humidity and low dry-bulb temperature schedules.

Boxed-Heart Splits

These splits start in the initial stages of drying and become increasingly worse as the wood dries. The difference between tangential and radial shrinkage of the wood surrounding the pith causes such severe stresses in the faces of the piece that the wood is split. It is virtually impossible to prevent this defect.

Checked Knots

Checked knots are often considered defects. The checks appear on the end grain of knots in the wood rays. They are the result of differences in shrinkage parallel to and across the annual rings within knots. Checked knots occur in the initial stages of drying and are aggravated by using too low a relative humidity. These defects can be controlled by using higher relative humidity and by drying to higher final moisture content, but it is almost impossible to prevent them.

Loose Knots

Encased knots invariably loosen during drying because they are not grown into the surrounding wood but are held in place by bark and pitch. These knots shrink considerably in both directions of the lumber face (across the width and along the length), whereas the board shrinks considerably in width but very little in length. Consequently, the dried knot is smaller than the knothole and frequently falls out during handling or machining. Nothing can be done to prevent the loosening of dead knots during drying. Fewer dead knots will fall out during machining, however, if the final moisture content of the lumber can be kept as high as possible before machining.

Warp

Warp in lumber is any deviation of the face or edge of a board from flatness or any edge that is not at right angles to the adjacent face or edge (squares). It can cause significant volume and grade loss. All warp can be traced to two causes; differences between radial, tangential, and longitudinal shrinkage in the piece as it dries, or growth stresses. Warp is also aggravated by irregular or distorted grain and the presence of abnormal types of wood such as juvenile and reaction wood, Most warp that is caused by shrinkage difference can be minimized by proper stacking procedures. The five major types of warp are cup, bow, crook, twist, and diamonding.

Cup

Cup is a distortion of a board in which there is a deviation flatwise from a straight line across the width of a board. It begins to appear fairly early in drying and becomes progressively worse as drying continues. Cup is caused by greater shrinkage parallel to than across the growth rings. In general, the greater the difference between tangential and radial shrinkage, the greater the degree of cup. Thinner boards cup less than thicker ones. Because tangential shrinkage is greater than radial shrinkage, flatsawn boards cup toward the face that was closest to the bark. A flatsawn board cut near the bark tends to cup less than a similar board cut near the pith because the growth ring curvature is less near the bark. Similarly, flatsawn boards from small-diameter trees are more likely to cup than those from large-diameter trees. Due quartersawn boards do not cup. Cup can cause excessive losses of lumber in machining. The pressure of planer rollers often splits cupped boards. Cup can be reduced by avoiding overdrying. Good stacking is the best way to minimize cup.

Bow

Bow is a deviation flatwise from a straight line drawn from end to end of a board. It is associated with longitudinal shrinkage in juvenile wood near the pith of a tree, compression or tension wood that occurs in leaning trees, and crossgrain. The cause is the difference in longitudinal shrinkage on opposite faces of a board. Assuming that there are no major forms of grain distortion on board faces; bow will not occur if the longitudinal shrinkage is the same on opposite faces.

Crook

Crook is similar to bow except that the deviation is edgewise rather than flatwise. While good stacking practices also help reduce crook, they are not as effective against this type of warp as they are against cup and bow.

Twist

Twist is the turning of the four corners of any face of a board so that they are no longer in the same plane. It occurs in wood containing spiral, wavy, diagonal, distorted, or interlocked grain. Lumber containing these grain characteristics can sometimes be dried reasonably flat by wing proper stacking procedures. Twist, bow, and crook have definite allowable limits in the grading rules for softwood dimension lumber, so it is desirable to minimize these defects.

Diamonding

Diamonding is a form of warp found in squares or thick lumber. In a square, the cross section assumes a diamond shape during drying. Diamonding is caused by the difference between radial and tangential shrinkage in squares in which the growth rings run diagonally from corner to corner. It can be controlled somewhat by sawing patterns and by air drying or pre-drying before kiln drying.

Glossary

Skid: The bunch of logs pulled behind a track or wheel skidder. Also known as a pull, turn, drag, or twitch among other names.

Skidder: A machine on tracks or wheels used to drag logs from the forest to a landing where they can be further processed and loaded on a truck. Skidders are equipped with cables or grapples.

Forwarder: A machine with a crane which can load logs onto its chassis and piggy-back them to a road where it can sort and pile them or load them directly onto a truck.

Harvester: A purpose-built machine with a head (attachment) for felling and processing trees into log lengths. Sometimes the processing head itself is referred to as a Harvester.

Delimber: An excavator based machine with an attachment which removes a tree's limbs and bucks the top off the tree at the landing. A log loader then places the processed logs on a truck.

Mechanized: Harvesting and processing timber with machines, reducing manual labor on the ground.

Roads: Generally classified as skid trails, spur roads, and main haul roads.

Shovel Logging: Relaying logs from a harvest area to roadside using a hydraulic log loader.

Side: A group of people and machines working together as a unit. A contractor might have a "skidder side" and a "cable side" working on the same "show."

Feller-Buncher: A machine which fells trees using a mechanical shear or a disc saw as an attachment. A Feller-Buncher may accumulate several trees before creating just the right size bunch for a grapple skidder to take to the landing. A mechanical delimber or a whole tree chipper might be waiting at the landing to further process the tree.

References

Simpson, William; John Tschernitz (1979). *Importance of Thickness Variation in Kiln Drying Red Oak Lumber*. Corvallis, Oregon: Western Dry Kiln Clubs. http://ir.library.oregonstate.edu/dspace/bitstream/1957/5722/1/Importance_Thick_ocr.pdf. Retrieved 2008-11-15.

"Infrared Oven Dries Wood" *Popular Mechanics*, July 1949

ABARE (2000). National Plantation Inventory, March, 2000. 4p.

Anon. (1997). Timber markets, home and away: Australian growers capitalising on international demand. Pie, Newsletter of Australia's International and National

Primary Industries and Energy (PIE) R&D Organisations. Volume 7 (Summer Issue): p14.

Bootle, K.R. (1994). Wood in Australia: Types, Properties and Uses. McGraw-Hill Book Company, Sydney. 443p.

Desch, H.E. and Dinwoodie, J.M. (1996). Timber: Structure, Properties, Conversion and Use. 7th ed. Macmillan Press Ltd., London. 306p.

Doe, P.D., Oliver, A.R. and Booker, J.D. (1994). A Non-Linear Strain and Moisture Content Model of Variable Hardwood Drying Schedules. Proc. 4th IUFRO International Wood Drying Conference, Rotorua, New Zealand. 203-210pp.

Haque, M.N. (1997). The Chemical Modification of Wood with Acetic Anhydride. MSc Dissertation. The University of Wales, Bangor, UK. 99p.

Hoadley, R. Bruce (2000). *Understanding Wood: A Craftsman's Guide to Wood Technology* (2nd. ed.). Taunton Press. ISBN 1-56158-358-8.

Innes, T. (1996). Improving Seasoned Hardwood Timber Quality with Particular Reference to Collapse. PhD Thesis. University of Tasmania, Australia. 172p.

Keey, R.B., Langrish, T.A.G. and Walker, J.C.F. (2000). Kiln-Drying of Lumber. Springer, Berlin. 326p.

Kollmann, F.F.P. and Cote, W.A.J. (1968). Principles of Wood Science and Technology. I. Solid Wood. Springer-Verlag, NewYork. 592p.

Kumar, S. (1994). Chemical modification of wood. Wood and Fiber Sci., 26(2):270-280.

Langrish, T.A.G. and Walker, J.C.F. (1993). Transport Processes in Wood. In: Walker, J.C.F. Primary Wood Processing. Chapman and Hall, London. pp121–152.

Panshin, A.J. and de Zeeuw, C. (1970). Textbook of Wood Technology. Volume 1, Third Edition. McGraw-Hill, New York, 705 p.

Pordage, L.J. and Langrish, T.A.G. (1999). Simulation of the effect of air velocity in the drying of hardwood timber. Drying Technology - An International Journal, 17(1&2):237-256.

Rasmussen, E.F. (1988). Forest Products Laboratory, U.S. Deptartment of Agriculture.. ed. *Dry Kiln Operators Manual*. Hardwood Research Council.

Rowell, R.M. (1983). Chemical modification of wood. Forest Product Abstract, 6(12):363-382.

Rowell, R.M. (1991). Chemical Modification of Wood. In: Hon, D.N.-S and Shiraishi, N. (eds), Wood and Cellulosic Chemistry. pp. 703-756. Marcel Dekker, Inc., New York.

Siau, J.F. (1984). Transport processes in wood. Springer-Verlag, NewYork. 245p.

Sjostrom, E. (1993). Wood Chemistry: Fundamentals and Applications. Academic Press Limited, London. 293p.

Skaar, C. (1988). Wood Water Relations. Springer-Verlag, NewYork. 283p.

Stamm, A. J. (1964). Wood and Cellulose Science. Ronald Press, New York. 509p.

Standard Australia (2000). Timber - Classification into Strength Groups. Australian/New Zealand Standard (AS/NZS) 2878. Sydney. 36p.

Standard Australia (2001). Timber - Assessment of Drying Quality. Australian/New Zealand Standard (AS/NZS) 4787. Sydney. 24p.

Strumillo, C. and Kudra, T. (1986). Drying: Principles, Applications and Design. Gordon and Breach Science Publishers, New York. 448p.

Walker, J.C.F., Butterfield, B.G., Langrish, T.A.G., Harris, J.M. and Uprichard, J.M. (1993). Primary Wood Processing. Chapman and Hall, London. 595p.

Wise, L.E. and Jahn, E.C. (1952). Wood Chemistry. Vol 2. Reinhold Publishing Corp., New York. 1343p.

Wu, Q. (1989). An Investigation of Some Problems in Drying of Tasmanian Eucalypt Timbers. M.Eng. Sc. Thesis, University of Tasmania. 237p.

Chatwin, S.C., D.E. Howes, J.W. Schwab, and D.N. Swanston. 1994. A guide for management of landslide-prone terrain in the Pacific Northwest. Land Management Handbook No. 18. 2nd ed. B.C. Ministry of Forests, Victoria, B.C. 220 p.

Fannin, R.J. 2000. Basic Geosynthetics: A Guide to Best Practices. BiTech Publishers Ltd., Richmond, B.C.

British Columbia Ministry of Forests. 2002. *Fish-stream Crossing Guidebook.* Victsoria, B.C.

1999. *Forest Service Bridge Design and Construction Manual.* Victoria, B.C.

Wellburn, G.V., M.M. Nagy, and J.T. Trebett. 1980. *Log Bridge Construction Handbook*. Forest Engineering Research Institute of Canada, Vancouver, B.C.