STRENGTH VALUES FOR WOOD AND LIMIT STATES DESIGN *

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Introduction

The adoption of 'limit states design' in the National Building Code of Canada 1975 presents both a challenge to and an opportunity for the timber industry (Allen 1975).

It is a challenge in the sense that the industry will have to provide more relevant strength information of their products in order to take advantage of this new design concept. It is an opportunity in the sense that it allows the industry to establish a new base for the appropriate strength properties.

This paper reviews the present method of deriving allowable stresses used for structural design of wood and suggests an alternate method of obtaining relevant material information suitable for limit states design.

Present Method

General

The present method used to derive allowable stress for wood seems to have served society adequately in the past. An inordinate amount of structural failures has not been experienced. However, it is not possible to determine purely from practical experience whether some (possibly all) of the structures were overdesigned and hence were not as economical as they possibly could have been.

The present allowable stresses are based upon testing of small, clear, straight grain specimens. The test results are then modified successively by factors which are supposed to convert the test results to represent the conditions for commercial material. Allowable bending stresses are, for example, developed from testing specimens 2 in. X 2 in. X 28 in. (51 mm X 51 mm X 716 mm) in three point bending and the conversion is done according to the following formula:

$$[1]\quad \sigma_{\text{allowable bending}} = (\tilde{X} - 1.645s) \times F_{\text{time}} \times F_{\text{moisture}} \times F_{\text{height}} \times F_{\text{grade}} \times (1/F_{\text{safety}})$$

($\tilde{X}$ - 1.645s) Variability

$\tilde{X}$ is the average of the test results and s is the standard deviation. To subtract 1.645 times s implies a calculation of the 5th percentile level assuming that the distribution of the test results is gaussian or normal. It is quite common that the coefficient of variation will be in the order of 15%.

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F_{time} Duration of Load

It has been observed by testing of small clear specimens at the United States Forest Products Laboratory, Madison, Wisconsin, that a reduction in strength takes place with time. Thus material loaded to, say, 70% of its estimated short term strength will fail on the average after about 2000 h (83 days). A factor of 0.62 is used to convert the short term strength to the predicted strength after 10 years.

This period (10 years) is referred to as the normal load duration for which the allowable stresses are valid, and the designer modifies the allowable stresses further to suit his particular load conditions. For snow load, supposedly lasting for an accumulated period of 2 months, the designer may increase the allowable stresses by 15%.

$F_{moisture}$ Moisture Content

This factor takes care of the change in strength as the wood dries out. The usual testing procedure calls for testing of the small clear specimens in the green condition (wet) and the $F_{moisture}$ factor allows for the conversion to dry condition.

The allowable stresses are published for dry conditions and when necessary the designer will convert back to wet conditions, for instance, if the structure is such that the wood will have an average moisture content in excess of 15%.

F_{height} Height Effect

The standard test for beams of 2 in. depth (51 mm) gives values which are somewhat greater than those observed for beams of clear material but of greater depth. The F_{height} factor converts the 2 in. (51 mm) test results to material 12 in. (304 mm) deep.

F_{grade} Grade Factor

The grade factor takes into account the maximum strength reducing defect allowed within the grade. The maximum knot and the maximum slope of grain are coordinated in the grading rules. A 60% grade indicates that the reduction in strength caused by a knot can be a maximum of 40%. Similarly the maximum slope of grain for that grade should result in strength reduction close to but not more than 40%. Other defects such as shake, split, etc. are restricted in a similar manner. The grades are described in the Standard Grading Rules for Canadian Lumber.

F_{safety} Factor of Safety

The final step is to divide by the factor of safety which is stated to be 1.3 for bending. This may seem low relative to other materials, but each reduction factor for wood has been selected conservatively and each contains an unspecified amount of safety so that the true safety factor is larger than the stated factor of safety.

For all the worst conditions to be operable at the same time, a really weak basic material with the maximum size defect would be loaded for the full duration with an overload of 1.3 in unfavorable moisture conditions, which is very unlikely.

Comments on Present Method

General

The foregoing sections describe in a general way the method of developing allowable stresses for wood. Some minor refinements have, for the sake of brevity, not been dealt with. For other strength properties the philosophy is the same but the magnitude of the factors may be different.

An exception, however, is the modulus of elasticity, where the average value for the species is used. Differentiation according to grade for this property was not made in the National Building Code of Canada until 1970.

At the time when allowable stresses for wood were first required (about 1930), many different species were available commercially, and the above method made sense because it was easy to apply to any species. However, conditions have changed. In present building codes the concept of species groups has been introduced. The 150 species of trees grown in Canada are divided into five groups of similar strength and allowable stresses are published for each species group rather than for the individual species. Species with similar strength properties are grouped together and the most conservative values have been selected to represent the allowable stresses for all the species in the group. The need for a quick method to determine the strength of individual species has thus diminished somewhat.

Allowable stresses are published for two to five grades for each species group. However, it has become increasingly difficult to buy single grades of lumber. The commercial practice of selling, for instance, '#2 and better' has forced the designer to use allowable stresses for #2 grade even though he will receive 25% #2 grade and 75% #1 grade or 'select structural.' He can not take advantage of the strong material in his design without segregating it on the job site. The 5th percentile value and therefore the allowable stress for #2 grade alone is obviously lower than for the mixture #2 and better.

If the commercial practice of marketing mixed grades of lumber cannot be changed, consideration should be given to standarize the grade mixes and publish allowable stresses for those mixes of grades and species which are commercially available.

Format of Formula for Allowable Stresses

Apart from the above general comments a closer look should be taken at the present system from a technical point of view. It can be seen from the format of the formula for deriving allowable stresses that each factor is conceived as an independent phenomenon. However, as will be discussed later this is not so and the method is therefore an oversimplification which may well work to the detriment of the lumber industry.

Variability

As mentioned the statistical treatment of the test results was predicated upon the assumption that the population has a normal distribution. This may be correct for clear specimens. However, it has been found that strength distributions of commercial material, to which the allowable stresses are applied, are not necessarily normally distributed. For instance in a test of two hundred and forty 2 X 6 Douglas Fir joists it was found that the distribution was positively skewed and that a three parameter Weibull distribution, for example, provides a much closer fit as shown in Fig. 1.

Had the assumption of normality and the standard method of estimating the 5th percentile level been applied to this data a 5th percentile value of 732 p. s. i. (5000 kPa) would have been obtained. The normal and Weibull distributions are compared in Fig. 1. It does not appear reasonable to expect that realistic allowable stresses can be derived by a method which has such a great discrepancy in the statistica assumption. The 5th percentile level has been chosen as the characteristic value to be used for materials in limit states design.

Duration of Load

In tests recently carried out at the University of British Columbia (Madsen 1971, 1972a,b) in which the 'duration of load' concept was investigated it was found that the time-strength relationship was highly dependent upon the initial strength of the material. High strength material (almost clear) did lose strength approximately as predicted by the Madison duration of load concept, whereas weak material (containing knots) did not show a significant drop in strength with time. It was thus established that time to failure is not independent of initial strength as assumed in the present method of developing allowable stresses.

Since it is the weakest pieces of the population which determine the allowable stress it would appear that it is erroneous to apply the present duration of load factor. In most cases this has resulted in an error on the safe side. However, where the designer has used the permitted 100% increase for impact, it may have led to unsafe structures.

Moisture Content

As mentioned a factor for moisture content is also applied in deriving allowable stresses. In a test reported by Madsen (1972a, b) it was found that the strong portion of the material did show an increase in strength with decrease in moisture content. However, at the weak end of the population no such difference in strength could be detected. This is further evidence that the factors used in developing allowable stresses are not independent variables as assumed.

Another illustration of the same observation is shown in Fig. 2. Two groups of 2 X 10 joist material were tested, one green (wet), the

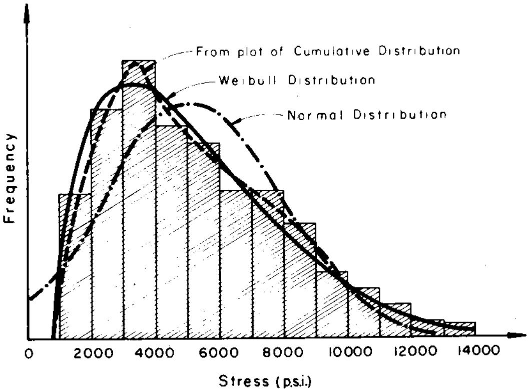

FIG. 1. Histogram and distributions for sample of two hundred and forty 2 × 6 joists (Weibull and normal).

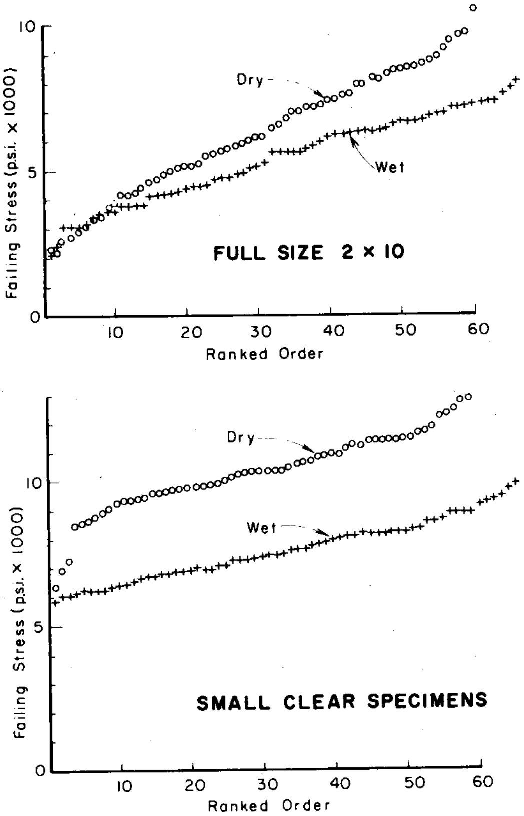

FIG. 2. The effect of moisture content upon strength.

other after it had dried to 12% moisture content. Small clear specimens were cut from each of the joists and also tested in the wet or dry conditions respectively. The test results of the small clear specimens are shown at the bottom of Fig. 2.

The results are ranked from the smallest to the largest on the abscissa. The ordinate shows the failing stress. It can be observed that there is a pronounced difference in strength between the wet and dry testing conditions. In the top half of Fig. 2 the results are plotted in the same manner for the full size 2 X 10's. A strength difference does exist in the strong portion of the population of the full size 2 X 10 but this strength difference disappears at about the 10th percentile level.

This indicates that one cannot reliably transpose results from small clear specimens to full size commercial material.

Height Effect

The height effect observed from testing with clear material may very well be correct but it is questionable if the same reduction would take place with commercial material where knots are the cause of failure. Whether this effect is greater or smaller in commercial material is not easy to predict without testing but undoubtedly it could be tied to the grade of the material and hence height effect and grade effect could not be expected to be independent.

The observed height effect may very well be part of the size effect concept described by Barrett et al. 1975.

Grade Effect

As already pointed out, the grade factor has a pronounced effect upon F_{time} and $F_{moisture}$ and may also be tied into F_{height}.

The present allowable stresses for joists in bending for #1 grade is 84% of the allowable stress for select structural grade, #2 grade is 68% and #3 grade is 40% of the allowable stress for select structural. However, in a test containing a total of eight hundred and fifty 2 X 6 Douglas Fir joists these ratios could not be confirmed. The results of the test are shown in Fig. 3. The normalized rank presentation is used.

It can be observed that the present grading rules do not create the purported differences between #1 grade and #2 grade. It would appear that #2 grade is stronger than #1 grade. The #2 and #3 grade are in approximately correct positions relative to the select structural grade.

The large spread in strength should also be noted. More than half of the select structural grade material has a strength of more than twice the strength at the 5th percentile level, indicating a poor performance from the present visual grading system.

Factor of Safety

The actual factor of safety at a specified percentile level is not well established since as mentioned, the factors (F_{times} $F_{moisture}$,

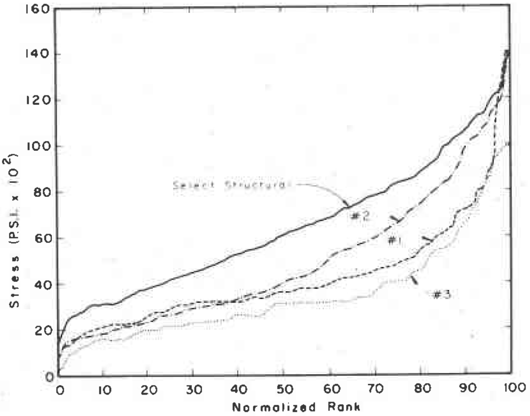

FIG. 3. Strength distributions of four commercial grades based upon eight hundred and fifty 2 × 6 Douglas Fir joists tested in bending.

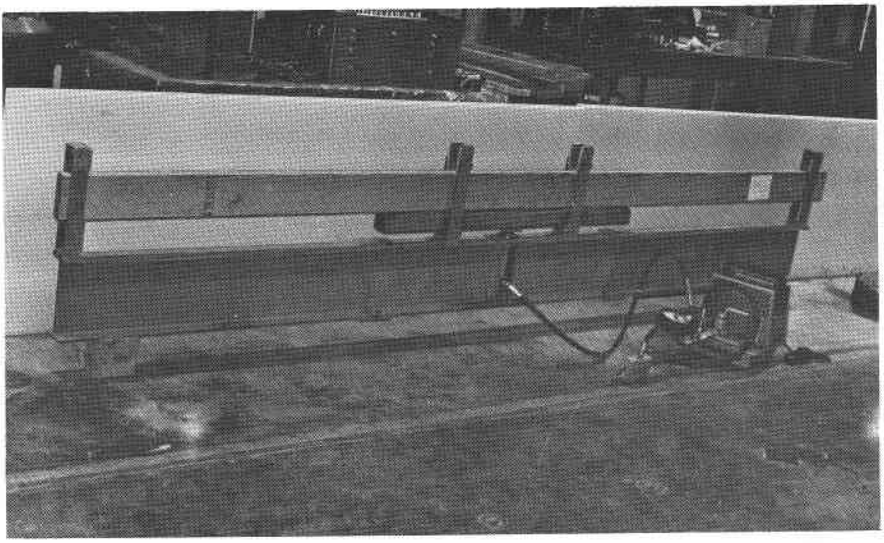

Fig. 4. Testing beam with hydraulic pumping unit.

etc.) have been selected conservatively. The present method cannot be expected to result in consistent factors of safety and thus does not result in the optimum, economical, and safe use of wood.

It would be desirable to have a constant factor of safety and it should be about the same as for other materials. For example, a basic nominal safety factor on tensile yield of 1.67 is used for hot rolled steel, and 1.6 for aluminum and cold formed steel.

Alternative Method: In-grade Testing

General

In light of the above, it seems highly desirable to review the basis for our allowable stresses for wood or, looking to the future, the basis upon which we are to develop characteristic values to be used in conjunction with limit states design. It would appear that the small clear specimen approach has outlived its usefulness, since it does not manage to correctly reflect the strength of commercial material. A logical first step is to change from tests of small specimens to 'in-grade testing' (testing of the material as it is produced in the sawmill).

Such an approach may at first appear to be quite expensive but if one keeps in mind that we are mainly interested in the strength at the 5th percentile level, it is possible to use a proof loading technique and, thereby, reduce the amount of material which will be destroyed during the testing. A proof load which would break, say about 10% of the material, could be estimated or measured roughly through preliminary testing, and a large quantity of material could then be subjected to this load.

The breaking stress of any piece of material which fails before the full proof load has been applied will be recorded. Material which does not break will be returned to mill output, but the number of pieces that were stronger than the proof load stress will be recorded also. The failure stresses for the material which failed can be ranked and, since large samples can be tested inexpensively in this manner, the 5th percentile level can be obtained with the desired degree of accuracy.

Pilot Test

In order to obtain an assessment of the magnitude of work involved in this approach to deriving suitable characteristic values for wood, it was decided to carry out an experiment with 2 X 6 lumber in bending.

It is almost inherent in the method that the testing should be carried out in the sawmill rather than in the laboratory. The cost of bringing the material to the laboratory and a portion of it back to the mill again would be much higher than bringing a testing machine to the mill.

A small testing machine, as shown in Fig. 4, was therefore built. It consists of a steel I-beam, a hydraulic cylinder, a spreader bar, and a hydraulic pumping unit with appropriate valving. The rate of travel of the cylinder can be adjusted by a flow control valve and the maximum load can be preset on a pressure release valve.

The unit was made easily portable by cutting the beam into three sections and providing bolted connections. The whole unit could then fit into the trunk of an automobile (Fig. 5). The unit was calibrated on the laboratory equipment. Two technicians were sent to several sawmills and after having explained the purpose of the test, excellent cooperation was received from the mill personnel.

It was first established what species and grade mixtures were produced in the plant and the technicians would then request randomly selected packages of lumber to be brought to the testing machine. Each board in the package would be placed in the testing machine and the selected proof load applied. Initially, twice the present allowable stress was generated but it was found that only 3-5% of the boards would fail at that stress level and the proof load was subsequently increased to three times the design stress. The load was applied in about 5 s and held for an additional 15 s. If the board broke the failing load would be recorded as well as the moisture content and grade stamp on the board. A note of failure mode was also made. The boards which did not fail would be reformed into packages but the technicians would keep track of the grade marked on the board and also of the number of boards they found to be off grade. The two technicians were able to test an average of 600 boards per day. An example of the test results is shown plotted in Fig. 6. The abcissa is the rank and the equivalent percentile is also shown. The ordinate represents the failure stress.

Test Results

One mill located on the coast and three mills in the interior of British Columbia were visited during this pilot test and the results are shown in Table 1. The results are, of course, not conclusive and can at best only show some trends.

One would expect variations in strength from location to location due to differences in growth conditions for the trees and many more mills would have to be investigated before conclusions could be established. A few of the mills should also be tested at different times to see by how much the strength would vary due to changes in log supply and grading practice.

It would appear from the table that the present allowable stresses do not result in a uniform factor of safety at the 5th percentile level. The 'Spruce-Pine'Fir' group seems underrated relative to the Douglas Fir. The #3 grade also seems underrated even though this grade should have been proof loaded at a higher stress level.

The absolute level of safety, or the characteristic values, cannot be derived from this kind of testing alone. The duration of load factor for commercial lumber is presently being investigated and before that test is completed it is not possible to establish the proper characteristic value. Similarly, the effect of moisture content should be further assessed for commercial material.

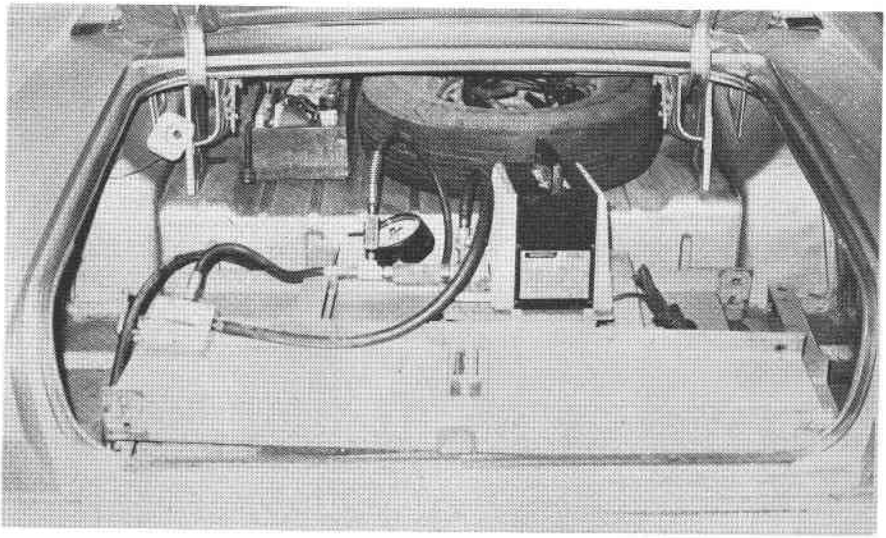

Fig. 5. Testing unit fitting into an automobile trunk.

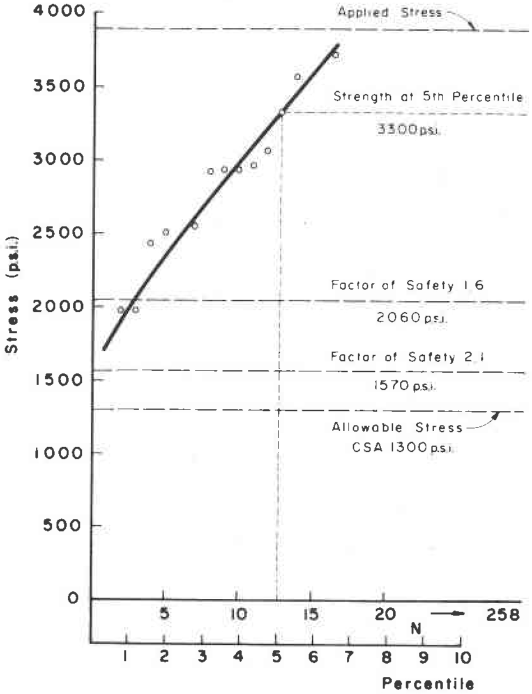

FIG. 6. Results of in-grade testing 258 Douglas Fir 2 × 6 joists of '2 and better' grade.

TABLE 1. In-grade test results

SPECIES	GRADE	MILL	LOCATION	MOISTURE	SAMPLE SIZE	FAILURES	PROOF LOAD	ESTIMATED 5th PERCENT STRENGTH	CSA ALLOWABLE STRESS	APPARENT SAFETY FACTOR	GRADE COMPOSITION	PERCENT	CFF GRADE	PERCENT
DOUG. FIR	2 & Better	F	Coast	Wet	154	13	3900	2800	1300	2.16	178#1+76#2 +	70%#1	16	5.3%
DOUG. FIR	2 & Better	P	Int.	Dry	258	15	3900	3300	1300	2.54	172#1+86#2	67%#1	4	1.6%
FIR	2 & Better	L	Int.	Dry	320	17	3900	3700	1300	2.85	282#1+38#2	88%#1	28	10.0%
DOUG. FIR	#3	F	Coast	Green	250	6	1500	1750	750	2.30				
DOUG. FIR	#3	P	Int.	Dry	258	14	2250	1900	750	2.54				
HEM-FIR	2 & Better	F	Coast	Green	125	4	2850	3000	950	3.16	155#1+73#2 +	68%#1	16	7.0%
HEM FIR	#3	F	Coast	Green	256	0	1100	-	550	-				
SPRUCE,FP	2 & Better	P	Int.	Dry	256	1	2700	2700*	900	3.00+	172#1+84#2	67%#1	4	1.6%
SPRUCE,FP	2 & Better	L	Int.	Dry	320	11	2700	3100	900	3.44	166#1+154#2	52%#1	8	2.5%
SPRUCE,FP	#3	P	Int.	Dry	128	2	1800	1800*	600	3.60				
SPRUCE,FP	ECC.	P	Int.	Dry	143	4	1500	1800*	-	-				

* Estimate Too Low Due to Low Testing Level.

\+ Extra Boards Tested at Twice Design: No Failures.

Other Tests for Lumber

The pilot investigation showed that it is practical to undertake in-grade testing of lumber in bending. However, other properties will also have to be included. Information on the modulus of elasticity was not collected in the pilot study but it would be very easy to obtain that data either as part of the proof loading or in a separate test. Since such a test need not be destructive, the whole sample could be measured and the full distribution of E-values obtained. This could be important information for design of structures where load sharing takes place.

In-grade testing for compression and tension values would require a different test setup but a portable apparatus could, no doubt, be designed to take care of both these properties. It may not be possible to transport such a heavy piece of equipment in a car; a light truck may have to be used.

Values for shear could possibly be obtained on the bending machine by use of a spreader bar which would place the load closer to the supports and thus create a loading more prone to failure in shear.

Testing of Glued-laminated Beams

The testing philosophy may have to be changed somewhat for glulam beams. The much greater cost of material would, no doubt, prohibit the use of as large samples as is envisaged for lumber. It will be necessary to develop a more refined statistical approach but it would be possible to use the proof loading approach even for testing of glulam beams in the plants. A few portable cylinders and an assortment of brackets would enable the technicians to make suitable test setups in which one glulam beam is tested against another. Obviously, the time required for each test would be much longer than for lumber but over a period of time very valuable information could be gathered. Fortunately, only a few stress grades of glulam are used.

Tension and compression tests for glulam could best be carried out in the laboratory since very heavy equipment is needed.

Other Testing

Characteristic values for connectors are already based upon full scale tests and any additional information required would best be obtained from laboratory testing. Plywood is now being tested in grade and should not present any additional problems.

Other Benefits

Using the proposed method it would be possible to collect data which could result in improvements of the grading rules. The personnel involved in the testing should be capable of grading according to the NLGA Standard Grading Rules of Canadian Lumbers. They should keep detailed records of what kind of defect appears to be the cause of failure. Through such records it may be possible to recommend improvements to the grading rules by identifying requirements which may now be unnecessarily restrictive. It may also be possible to identify defects which cause an unreasonable lowering of the strength for the grade. Such defects could possibly be prohibited for the grade under consideration.

Since the equipment involved in the testing (at least for bending) is rather inexpensive, it may be possible for the mills to obtain such equipment which would enable them to run periodic quality control checks. Alternatively, the grading supervisors should be equipped with portable testing units and they could run strength checks during their inspections. As it is today, very few graders have ever witnessed a bending test of a board and they would have very little knowledge of what kind of defect is liable to cause the most severe strength reductions.

Evaluation of the Proposed Method

The proposed method for obtaining characteristic values for wood has some very important advantages relative to the present method.

1. Large sample size can be obtained relatively easily, which will diminish the problem of statistical interpretation.
2. It deals with the end product and removes the uncertainties with regard to grade effect.
3. It deals with full size material and the size effect or height effect is included in the measurement.
4. The method can be used to interact with the grading rules and thus lead to improvements of them, which would result in better economical usage of our timber resources.
5. It would be possible to use the method to monitor the production and it could, thus, increase the reliability of the product.

The method does require that better knowledge and understanding of the duration of load phenomenon be obtained, but this would apply to the old method as well. It is also assumed that better information on the effect of moisture content should be obtained.

An apparent disadvantage is the cost involved in the testing. However, if one considers the possible savings which can be achieved through more economical use of timber, the cost of testing will be very small indeed.

Conclusions

1. In light of the upcoming change in the National Building Code of Canada to 'limit states design' it would appear that small clear specimens have outlived their usefulness as the basis for developing allowable stresses or characteristic values for wood properties.
2. In-grade testing using a proof loading approach seems to be a suitable alternate method for determining characteristic strength properties for wood to be used in conjunction with limit states design.
3. A more accurate time-strength relationship for commercial wood needs to be established and the effect of moisture content upon strength should also be clarified.
4. The proposed method affords direct opportunities for improving both the grading rules and the quality of the wood products.
5. Consideration should be given to establishing the strength

properties in accordance with the commercial practice of selling mixed grades of lumber rather than for the grades by themselves.

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