MOISTURE CONTENT - STRENGTH RELATIONSHIP FOR LUMBER SUBJECTED TO BENDING *

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Introduction

It is well known that moisture content influences the strength and stiffness of small clear wood specimens subjected to bending. Strength and stiffness increase with a decrease in moisture content.

Kennedy (1965) reported small clear strength values for most Canadian species. The average value for modulus of rupture for Douglas Fir based upon 1057 specimens was reported to be 7540 p. s. i. (52 026 kN/m^2) when tested in the green (wet) condition while the average value for air-dried specimens adjusted to 12% moisture content was found to be 12,850 p. s. i. (88 665 kN/m^2), an increase of 71%. The modulus of elasticity for the same specimens was 1.61×10^6 and 1.96×10^6 p. s. i. (11.1×10^6 and 13.5×10^6 kN/m^2) for wet and dry conditions, respectively, an increase of 22%.

In addition to the changes in strength and stiffness, dimensional changes also occur due to changes in moisture content. Shrinkage takes place with diminishing moisture content. The Timber Design Manual (1972) states that an average shrinkage of 4.6% occurs when the moisture content (M. C.) goes from 24 to 6%. This magnitude of dimensional changes takes place in directions perpendicular to the grain only, while a much smaller change takes place in length.

Allowable Stresses

The CSA-086 Committee on Engineering Design in Timber publishes allowable stress for structural lumber which is to be used for dry conditions (M. C. less than 15%). The cross-sectional dimensions, however, are standardized for a moisture content level of 19%. To convert to wet service conditions, defined as conditions where the average equilibrium moisture content over 1 year will exceed 15%, the designer must reduce the published values by 16% for lumber 4 in. (10.2 cm) or less in thickness while no reduction is required for lumber more than 4 in. (10.2 cm) in thickness.

A publication prepared by the Canadian Wood Council (1972) on behalf of CSA describes in detail how the allowable stresses have been developed. The allowable stresses for bending are based upon testing of

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small clear wet bending specimens. The mean value and the standard deviation are calculated and from these the 5th percentile exclusion limit established. For Douglas Fir 5828 p.s.i. (39,713 kN/m^2) is obtained. This value is now divided by 2.1 to allow for 'duration of load' and 'factor of safety' yielding 2775 p.s.i. (19,147 kN/m^2). To convert from green condition to a condition of 19% M.C. an increase of 25% is applied (3469 p.s.i.) (23,936 kN/m^2); if the strength at 15% is required an increase of 35% is used (3750 p.s.i.) (25,875 kN/m^2).

The above adjustment for moisture content applies only to lumber 4 in. (10.2 cm) or less in thickness. The strength values for material more than 4 in. (10.2 cm) thick is not adjusted for moisture content. If the dressing of the lumber is done at 15% M.C., rather than the normal 19% M.C., a further modification of the allowable stresses can be made because of a difference in the anticipated shrinkage. The process of adjusting the allowable stresses for moisture content is, thus, rather complicated.

The modulus of elasticity is treated somewhat differently but the end result is a decrease of 6% for wet condition.

In an investigation carried out previously for a different purpose (Madsen 1972a, b), it was not possible to observe the difference in strength that the allowable stresses would indicate for wet and dry material. Therefore, it was decided to investigate if the findings obtained from testing of small clear specimens with regard to moisture content also applied to commercial lumber.

Experiment

The matched specimen technique often used with small clear specimens for this type of testing could not be used for commercial lumber since it is impossible to preselect pairs of boards with the same strength.

Instead, five groups containing more than 100 boards each, were formed by randomly selecting the boards from a large sample of material. The assumption was that the five groups would have almost the same distribution of strength because the grouping was done randomly.

One thousand 2 X 6 Douglas Fir joists 12 ft (3.7m) long, 'No. 2 and better' grade were ordered from a local sawmill. When the boards arrived at the laboratory the following operations were performed on each board.

(1) Identification number assigned.
(2) Weakest edge selected based upon knot location and slope of grain.
(3) Grade marked by the mill checked for correctness.
(4) Width, thickness, and length recorded.
(5) Moisture content established at three locations.
(6) Weight measured.
(7) Relationship between the weakest edge and the presence of crown, if any noted.
(8) Deflection at a constant load when the board acted as a joist (weakest edge in tension).
(9) Date of measurements.

After this had been completed, each of the 1000 boards were assigned to one of eight groups by drawing identification numbers at random. Five of the groups were to be used for the strength - moisture content investigation while the remaining three groups were to be used for other purposes.

The five groups were brought to the basement of the laboratory where each board was placed on edge in a rack with a 2 in. (5.1 cm) air space between boards (no controlled environment). Each group was assigned one of the following moisture content levels: 25%, 20%, 15%, 10%, and 7%. The material was left to dry out and when a board reached its desired moisture level it was pulled out and tested. The moisture content was measured with a resistance type moisture meter. Before the board was broken in the testing machine the following data were obtained.(1) dimensions, (2) moisture content at three locations, (3) weight, (4) deflection as before, and (5) date of testing. The board was then loaded in the Olson testing machine, using a rate of loading of 5000 p.s.i./min (35,400 kN/m^2/min) load and the failing load and failure mode recorded.

Test Results

(a) Moisture Content

The failure stresses of the five groups are shown in Fig. 1. Failure stresses are arranged in ascending order plotted as normalized rank along the abscissa while the failing stress is plotted along the ordinate. For material with a strength of more than 8000 p.s.i. (55,200 kN/m^2) the moisture content does influence the strength approximately as data developed for clear material. For material with lower strength caused by knots and other growth chracteristics, this concept does not hold.

It is not possible to observe a consistent difference in strength caused by moisture content for the lower 30% of the sample or a strength below about 4000 p.s.i. (27,600 kN/m^2). It is difficult to read the curves in this region because they are closely intertwined. Table 1 shows the strength at selected percentile levels. Graphs were produced similar to Fig. 1 in which each moisture group was broken into grades of lumber. It was not possible to detect a consistent difference in strength due to the different moisture content in the lower third of the sample for the three grades.

(b) Stiffness

Two moduli of elasticity were calculated for each board, one from the initial deflection readings (green condition) and another at the designated moisture level. The results are shown in Figure 2. The line for wet conditions contains data from all the 620 specimens while the other lines represent about 120 points. It would appear that there is an increase in E values with decreasing moisture content throughout the whole range of the distribution. The results are also shown in Table 2 and it is evident that the increase in E values per percentage change in moisture content becomes greater as the material becomes drier.

The relationship between strength and stiffness is important to establish since several mechanical grading systems are based on such

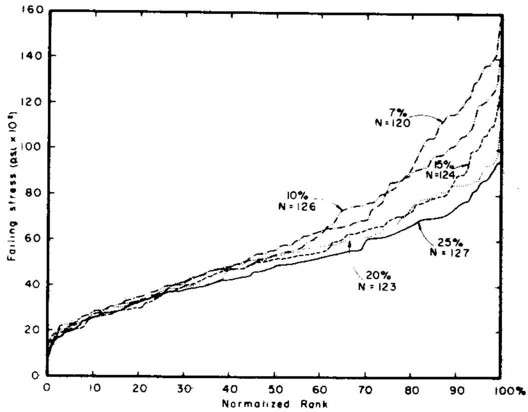

Fig. 1. Strength distributions at different moisture contents.

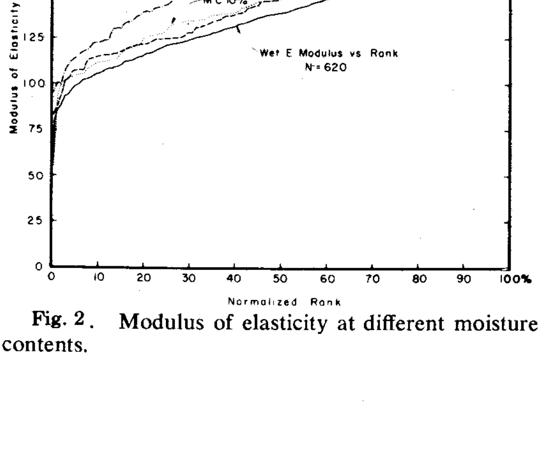

Fig. 2. Modulus of elasticity at different moisture contents.

TABLE 1. Failing stress in p.s.i. at different percentiles and moisture contents. The percentages shown are for the wet (25% M.C.) stress equal to 100%

Percentile level	Moisture content				
	25%	20%	15%	10%	7%
5%	2000 100%	2250 112%	2050 102%	2150 107%	2150 107%
10%	2550 100%	2650 104%	2550 100%	2750 108%	2650 104%
15%	2850 100%	3000 105%	2800 98%	3100 109%	3100 109%
20%	3200 100%	3300 103%	3050 95%	3450 108%	3300 103%
25%	3550 100%	3700 104%	3600 102%	3800 107%	3600 101%
30%	3750 100%	3900 104%	4000 107%	4200 112%	4100 109%
40%	4250 100%	4550 107%	4700 111%	4850 114%	4800 113%
50%	4800 100%	5250 109%	5200 108%	5350 111%	5550 116%
75%	6200 100%	6500 105%	6900 111%	8150 131%	8200 132%
90%	7500 100%	8400 112%	8800 117%	10200 136%	11700 156%

TABLE 2. Modulus of elasticity (p.s.i. × 10^6) at different percentile levels and moisture content. Percentages shown are for the wet moisture condition equal to 100%

Percentile level	Moisture content			
	Wet	15%	10%	7%
5%	0.98 100%	1.075 110%	1.04 106%	1.13 115%
10%	1.05 100%	1.15 110%	1.11 106%	1.23 117%
25%	1.225 100%	1.25 102%	1.30 106%	1.38 113%
50%	1.39 100%	1.48 107%	1.46 105%	1.67 120%
75%	1.575 100%	1.70 108%	1.72 110%	1.93 123%
90%	1.755 100%	1.95 111%	1.90 108%	2.17 124%
95%	1.85 100%	2.05 111%	2.05 111%	2.24 121%

a correlation. Scattergrams of strength versus modulus of elasticity are shown in Figs. 3 and 4. Figure 3 shows strength versus the wet modulus of elasticity while in Fig. 4, strength versus the dry modulus of elasticity is shown. It would not appear to be a very efficient relationship to build a mechanical grading system around.

(c) Shrinkage

The averages of cross-sectional dimensions are shown in Table 3 together with their standard deviations and the percentage shrinkage. The calculated shrinkage is somewhat less than indicated by the Timber Design Manual - 4.0% versus 4.6%. The lumber appears to be slightly oversized since it should be 1.50 X 5.50 in. (3.8 X 14.0 cm) at 19% M. C., whereas the estimated average dimensions at that moisture content level are 1.54 X 5.58 in: (3.9 X 14.2 cm). This increase in size results in an area 4.1% larger than the standard. The sectional modulus is 5.6% and the moment of inertia is 7.1% larger than called for.

Accuracy of Grading

A comparison between the mill grading and the grading performed in the laboratory by trained personnel is showed in Table 4. The mill had combined 'Select Structural' and No. 1 grade under one grade mark. The grade specification called for 'No. 2 and better' with no more than 25% No. 2 grade. Thus, according to the mill grading the shipment met this specification while according to the laboratory grading the quantity of No. 2 grade was slightly in excess. A total of 70 boards (11%) had a mill grade mark higher than the laboratory grading would allow while 28 boards (4.5%) had a mill grade mark lower than they deserved. It is interesting to observe that more than 53% of the material was of 'Select Structural grade' and the customer, thus, gets a substantial amount of high strength material.

Strength of Grades

Since it was found that moisture content does not influence the strength of the weaker portion of the sample, it is possible to combine the five groups into one sample and analyze the effect of grading at least for the weaker portion. The testing was done with the weakest edge consistently in tension and one would expect to find results lower than if the placement of the weakest edge was a random occurrence, as would be the case on a construction site.

The strength distributions of the different grades are shown in Fig. 5. It can be seen that there is not a pronounced difference in strength between No. 1 grade and No. 2 grade even though the code states that No. 1 grade should be 23% stronger than No. 2 grade. Table 5 shows the allowable stresses for the grades as well as estimates for the ultimate stress at the 5th percentile level. From this a calculation of the overload factor can be made and it should be noted that this factor is not consistent for the grades, indicating that the grading rules do not provide the same factor of safety for the different grades.

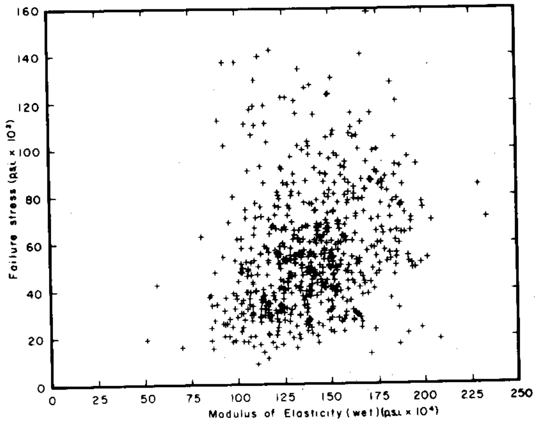

Fig. 3 . Failure stress dry *versus* wet modulus of elasticity.

TABLE 3. Cross-sectional dimensions in inches

M.C.(%)	Initial	Final	Shrinkage (%)	Standard deviation Initial	Standard deviation Final
			Thickness		
25	1.56	1.55	0.64	0.0184	0.0190
20	1.57	1.54	1.94	0.0213	0.0159
15	1.57	1.53	2.61	0.0270	0.0197
10	1.57	1.52	3.28	0.0179	0.0224
7	1.57	1.51	3.97	0.0160	0.0429
			Width		
25	5.68	5.64	0.70	0.0295	0.0469
20	5.67	5.59	1.43	0.0363	0.0475
15	5.67	5.53	2.53	0.0321	0.0516
10	5.67	5.47	3.65	0.0326	0.0596
7	5.66	5.41	4.62	0.0732	0.0676

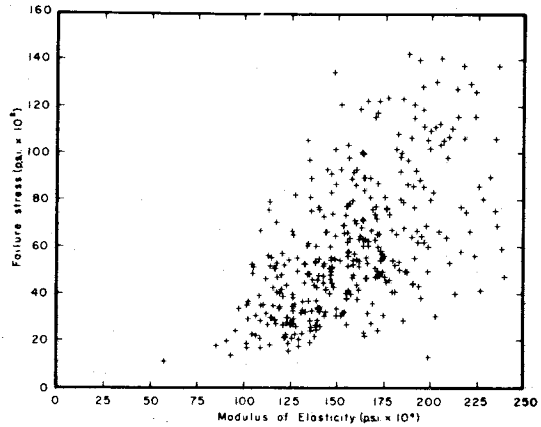

Fig. 4. Failure stress *versus* modulus of elasticity at same moisture content levels.

TABLE 4. Comparison of mill grading and laboratory grading for 620 2 × 6 joists

Grade as marked	Actual grade				
	S*	1	2	3	Total
S*	0	0	0	0	0
1	316	96	57	7	476 76.8%
2	13	15	109	6	143 23.2%
3	0	0	0	1	1 0%
Total	329 53.1%	111 17.9%	166 26.8%	14 2.2%	620 100%

*S = select structural values are number of piecs and percentage of sample

TABLE 5. Ultimate strength at the 5th percentile level compared with allowable stresses

Grade	Present allowable stress (p.s.i.) CSA-086	Ultimate stress at 5th percentile level (p.s.i.)	Overload factor
Select structural	1900	3100	1.63
No. 1 grade	1600	1950	1.23
No. 2 grade	1300	1900	1.46
No. 2 and better	1300	2540	1.95

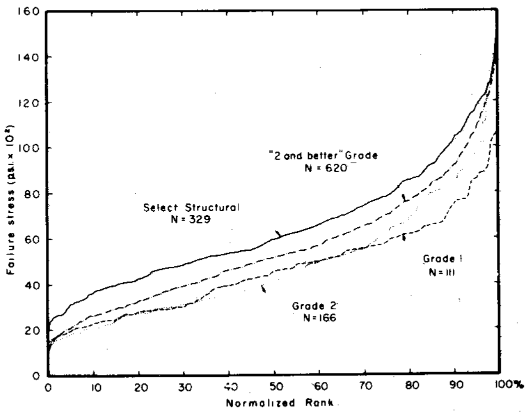

Fig. 5. Strength distribution of four grades.

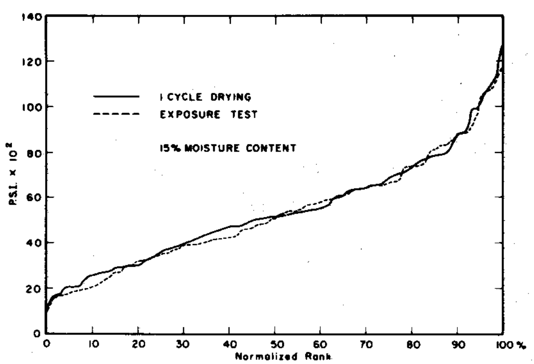

Fig. 6. Comparison of one dry out cycle with exposure test (strength).

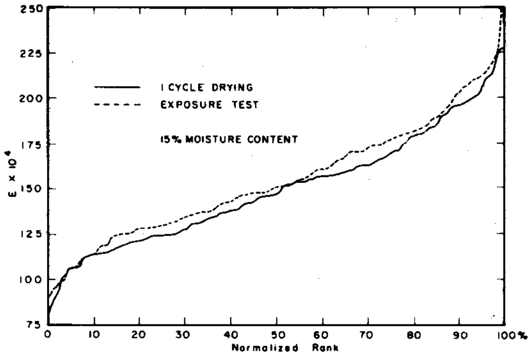

Fig. 7. Comparison of one dry out cycle with exposure test (modulus of elasticity).

Discussion

The main result of this investigation, that strength does not change with moisture content in the weaker material, has some important implications. One is that the designer does not have to be as concerned with the equilibrium moisture content which will result in the finished structure. He should, thus have to work with only one allowable stress as far as strength is concerned.

A second implication is that it should not be necessary to condition lumber to predetermine moisture content levels before testing. This has, in the past, been quite time consuming. Since moisture content does not have the importance previously ascribed to it, as far as bending strength is concerned, one could entertain the idea of obtaining data for determining allowable stresses through field testing. However, when dealing with stiffness it will still be necessary to have knowledge of the moisture content in order to obtain meaningful results.

A possible explanation for the observed difference in behavior between clear wood and commercial lumber with regard to moisture content may well be that the stress concentrations created by knots and grain deviations cause a different mode of failure which over rides the effect of moisture content. The more serious the stress concentration is, the less important will be the effect of moisture content. This same phenomenon has also been observed with regard to the time-strength relationship (Madsen 1972a, b), indicating that observations made from testing of clear wood may not necessarily be applicable to lumber.

Exposure Test

It should be pointed out that the material described above went through only one dry out cycle and that several such cycles could possibly cause a decrease in strength.

To test this, one of the spare samples (120 specimens) mentioned earlier was dried down to 9-12% moisture content and then placed outside the laboratory subjected to the changing climatic conditions. The boards were placed on edge in a rack providing 3 in. (7.6 cm) between the boards so rain and sun could have their full effect upon the strength of the material. The material was moved out during the first week of January and left until the middle of May, a period of about 20 weeks. The Vancouver weather during this period provided rain followed by dry spells and twice snow was encountered even though the temperature did not go below -2°C. At the end of that period the moisture content ranged from 15% to 21%. The boards were brought inside the laboratory and tested at 15% M.C. It was found that the strength distribution had not changed significantly as can be seen in Fig. 6 where the exposed sample is shown together with the original 15% M.C. sample.

The same general observation can be made with regard to modulus of elasticity (Fig. 7). The timing and length of test was chosen to represent somewhat severe construction conditions but the test showed that the strength properties were not adversely affected by the exposure.

The test represents conditions as they occur in Vancouver but similar tests ought to be carried out where the rate of dry out would be faster since the moisture gradient could be expected to be of major importance.

Conclusions

(1) The effect of moisture content upon strength of lumber subjected to bending is different from that observed with clear specimens.

(2) It was not possible to detect a consistent strength difference between wet and dry material at stress levels below 4000 p. s. i. (27,600 kN/m^2).

(3) An increase in stiffness was observed with decreasing moisture content. This applies throughout the whole range of stiffness.

(4) The increase in stiffness per percentage point decrease in moisture content increases at the lower moisture content levels.

(5) The observed percentage shrinkage confirms the values stated in the 'Timber Design Manual.'

(6) The specification for 'grade mix' was exceeded slightly, but 11% of the boards were found to be of a grade below the grade stamped on the board.

(7) A recommendation as to appropriate allowable stresses for the different grades could not be made based upon this investigation but it can be concluded that the present grading rules do not provide overload factors consistent with the published allowable stresses.

(8) An exposure test did not show a decrease in strength when compared to the dry out test.

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Q. If you consider all your variation factors, don't you think it would reduce your optimism?

A. Well the point is we are testing the material the customer receives and the purpose of this testing is to find out what is the strength with all the variations we are talking about. We are not doing anything artificial, we are testing the end product and we are assigning a value to that. What we have done in the past is not dissimilar if you want to know the strength of a concrete beam and then you went and got your bag of cement and you tested the hell out of the cement and you know everything about that but you didn't give a hoot about sand, aggregate, water and the rest of it. Then you say you have a strong beam because I have strong cement. That's what we have been doing and I would like to test the whole kit-and-kaboodle, the end product including variability, and it really indicates that in spite of variability we are still a lot better off than with our present methods.

Q. You haven't done any testing yet on the effect of this machine on the lumber?

A. We have to be quite sure that the strength distribution of that material that has been proof-loaded is no worse than it was initially and there is possibility for damage but we don't know how much, but hopefully we will find out.

Q. In regards to moisture content, is there a skin effect?

A. Now we haven't looked into that. The question is related to the drying. Again we took a very simple practical approach and say what the heck is the end result. Never mind whether there is gradient or not. We are prepared to do sufficient testing that we will take care of those things eventually. I am not suggesting that's the only way to do, we have to go both ways, but there are strong indications that for the lower percent of the material that governs strength values, moisture content is not a serious factor. But let's not forget the fact that in clear material and the strong material there is a difference but we are not using those values anyway, so let's get back to basics and practical things rather than too high falooting conclusions based on small tests.

Q. Can you identify the reason that the No. 2 was stronger than the No. 1?

A. Yes, I think so. I would think that you would have to realize that the grading rule is not just for strength and that maybe perfectly clear pieces may have wane or some other non-stress reducing characteristics throws it into No. 2 and this is my explanation for why we have stronger values in No. 2.

Q. Would it be better to limit your samples to the pieces that are in the grade for structural reasons?

A. I'd say again what is it the customer receives and this is what I am interested in. If I start culling out something because of various reasons the sampling procedure becomes very difficult, you have to ascertain very accurately what the portion you have culled out because of that.

Q. On the other hand, it would be an education problem, educating the customer.

A. True, now this is like worm holes, for example. Aren't you better off if you go to the customers and say yes, I tested the wood worm holes and here are the results and that must be a more convincing argument than saying we tested small pieces of clear and applied some factors to them.

Q. Do you think that the governing factor in this, particularly in the floor joists factor, where the tension factor is governed by the knots on the edges; the grading rule could be changed to allow a bigger knot in the centre of the floor joists than on the edge. It appears there is your breaking point that a little knot will break this particular floor joist much easier than a big knot will in the centre?

A. That's right, you're perfectly right. Tom Littleford was mentioning this where they put greater emphasis on the knots on the edges, but the point here is we can use this method to write better grading rules. You really have to realize that grading rules have been written on a flat desk top without too much consideration to what the wood thought of it. There is very little testing that has been done and it's more or less an academic exercise in knot area ratios with a minimum amount of testing, but I am suggesting let's change that ratio around to one heck of a lot of testing and then write the grading rules.