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Failure in Timber
Part 3: The Effect of Longitudinal Compression on Some Mechanical Properties

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Summary. Experimental data from a series of experiments indicate that the existence of compression damage in timber has a pronounced effect on its toughness, considerably less effect on its tensile strength, and almost no effect on its bending strength. Whereas the toughness of dry timber was reduced by up to 40 per cent at high levels of precompression, toughness of green timber actually increased by up to 37 per cent. The reduction in tensile strength was greater for individual cells and thin sections than for solid timber. The results are discussed in terms of slip plane development and behaviour, and the practical significance of compression damage is emphasised.

Introduction

Previous papers in this series have been concerned with establishing the series of anatomical changes associated with longitudinal compression stressing and with determining the angle of shear or "slip" plane through the cell wall [Dinwoodie 1968, 1975]. Microscopic observations associated with these studies have indicated that the formation of the "slip" plane in the cell wall is irreversible and that such plastic deformation is associated with a re-orientation of the microfibrils within the cell wall.

It could be argued *a priori* that this type of deformation would result in some loss in most mechanical properties if only on the grounds of bond breakage between the microfibrils. The technical significance of such a possible loss in strength is considerable; not only would timber subjected to longitudinal compression in service be affected, but also wood in the growing tree subjected to internal stressing would also be expected to have lower strength properties.

In view of its possible significance, it is surprising that so little attention has been paid to precompression, especially on a quantitative basis. Garland [1939] was one of the first workers to suggest a possible relationship between the occurrence of slip planes and a loss in strength of the wood. This arose from his argument to account

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for the then unexpected reduction in tensile strength of his samples of known fibril angle.

More than two decades were to elapse before the relationship was again examined. The results of a small experiment in which samples were stressed in bending to different percentages of the ultimate load before being reversed and stressed to failure indicated that the normal bending strength was reduced only very slightly whereas the impact strength was lowered by about fifty per cent [Hudson 1961].

Using the results of work by Dinwoodie [1966] and Keith and Côté [1968] which indicated that slip planes could be induced in timber sections during microtomy, Kennedy and Chan [1970] and Biblis [1970] investigated the effect of slip plane development on the tensile strength of wood sections and recorded significant reductions.

The evidence of the effect of compression damage in the cell wall on the mechanical properties of wood is somewhat limited. The purpose of the present paper is to record the results of a comprehensive and quantitative investigation of the effect of compression on the bending, tensile, stiffness and toughness properties of timber of both low and high moisture content.

Methods and results

For each part of the investigation, samples were produced from boards 1 cm in thickness cut from the outer sapwood of a large diameter, slowly-grown Norway spruce tree (*Picea abies*). Samples 18 cm in length (reduced in the later parts of the series to 15 cm) and 1 cm in width were produced having a waisted region 1 cm square.

Tensile strength

The effect of compression damage on tensile strength was assessed at three levels of magnitude–wood blocks, sections and individual cells.

Wood

Four trees were selected and boards prepared as recorded above and conditioned to 12 per cent moisture content. From each tree 210 samples were selected for straightness of grain, evenness of growth rate and absence of defects. For each of the four trees 30 samples, selected at random, were compressed in an Instron testing machine (crosshead movement = 0.5 mm/min) until the reversal in the load/deflection curve indicated that compression failure had occurred. Further batches of thirty samples were subsequently compressed to 20, 35, 50, 65 and 80 per cent of the average ultimate failing load. The compressed blocks, including the 100 per cent set, together with thirty uncompressed control samples were then stressed in tension at a strain rate of 2.5 mm/min.

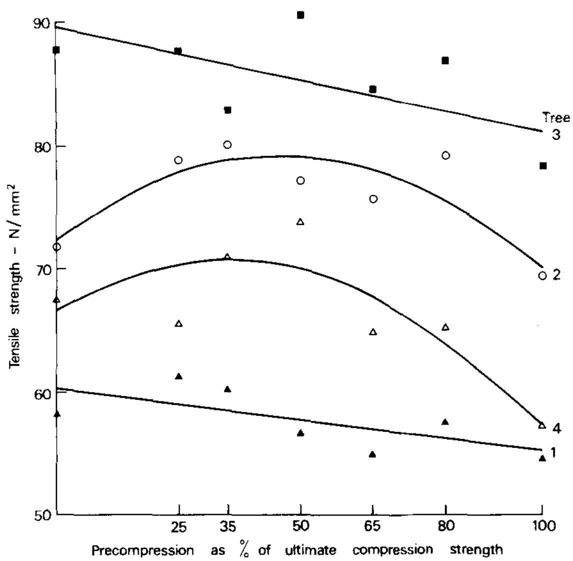

Fig. 1. The effect of degree of precompression on the ultimate tensile strength of samples removed from four Norway spruce trees (*Picea abies*)

The relationship between tensile strength and the degree of precompression, expressed as a percentage of the ultimate strength in compression, for each of the four trees is illustrated in Fig. 1. Statistical analyses of these results comprised initial analyses of variance to test the significance of the mean values of different precompression groups, followed by the derivation and test for significance of a linear regression. Where the deviations from linearity were significant, as in trees 2 and 4, a quadratic regression was fitted and tested for significance. Regression equations, their level of significance, and the degree of variation accounted for (r^2) are presented in Table 1, while plots of the regression lines are shown in Fig. 1.

It will be observed from Fig. 1 that tensile strength decreases with increasing degree of precompression, though in trees 2 and 4, this decrease was preceded by an initial increase in strength. A comparison of recorded strength values at the 100 per cent level with those of control blocks indicates that the overall loss in strength varies between trees from 3 to 15 per cent (Table 1), averaging out at about 9 per cent.

Although curvilinearity is significant only in two of the four trees, there is a suggestion of it in the plotted values of the other two trees (Fig. 1), though it is not strong enough to be statistically significant or, as is more likely, the large variability within precompression levels masks its effect.

In all trees the amount of variation accounted for by the fitted regressions is very small indeed (Table 1); this is due primarily to the very large variation in strength values at each level of precompression. Thus although the analyses of variance indicated significant differences in strength between different precompression levels, and although the various regression lines were either significant or highly significant, the

Table 1. The effect of degree of precompression on the tensile strength of wood blocks

Tree	Regression	Significance level of regression	r^2	Loss in strength at 100 % precompression compared with controls
1	$y = 60.18 - 0.0492\,x$	1 %	0.05	6.0 %
2	$y = 72.36 + 0.2969\,x - 0.00319\,x^2$	5 %	0.08	3.3 %
3	$y = 89.70 - 0.0858\,x$	5 %	0.04	10.8 %
4	$y = 66.71 + 0.2224\,x - 0.00315\,x^2$	1 %	0.20	15.3 %

x = percentage precompression level
y = tensile strength (N/mm^2)

fact that the degree of variation accounted for by these regression lines is so small, especially in terms of the large number of samples used, casts some doubt on the extent of the effect of level of precompression on tensile strength.

The average density of the samples from each of trees 2 and 3 was higher than that for the other two trees. This resulted not only in higher tensile strengths, but

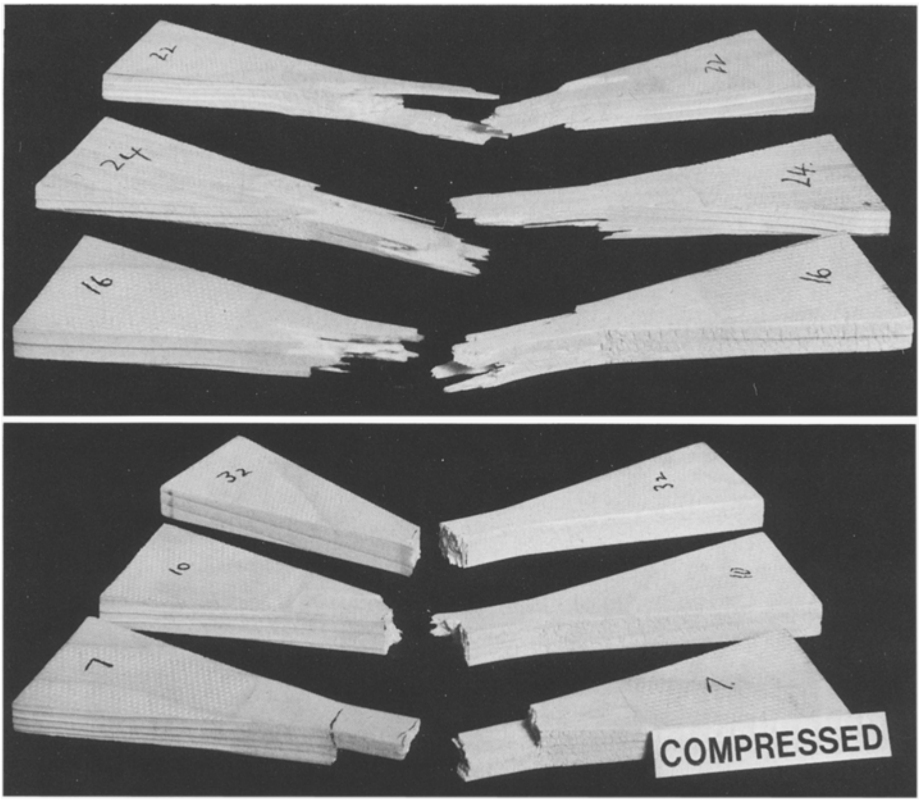

Fig. 2. The influence of precompression on type of fracture. The lower blocks were compressed prior to tensile stressing and failure occurred along compression creases. The upper blocks show interlocked fracture typical of tensile failure in the absence of compression damage

also in the occurrence of a small percentage of samples failing in shear which were omitted from the calculations.

The morphology of the tensile fracture also varied with degree of precompression: when this was low, the fracture was interlocked, but at 65 and 85 per cent precompression many of the fractures were short. In the fully compressed samples, tensile stressing resulted in a very brash fracture, the fracture face corresponding to the occurrence of a compression crease (Fig. 2).

Wood sections

Five waisted blocks similar to those used in the previous section together with blocks 25 mm in length and end matched with the waisted ones were prepared from one of the Norway spruce trees and conditioned to 12 per cent moisture content.

The waisted samples were compressed to failure as previously and twenty 50 μm thick radial sections were cut from the waisted region which now contained a compression crease; a similar set of sections was cut from the control blocks. In the microtomy of these sections extreme care was exercised to prevent the induction of slip planes [Dinwoodie 1968; Keith, Côté 1970]. After trying a range of thicknesses of sections, 50 μm was chosen as this was sufficiently thick to include at least one radial wall and yet thin enough to permit clear microscopic examination of the fracture region.

The sections were conditioned at 65 per cent relative humidity and 20 °C and subsequently stressed in tension under the same conditions with a crosshead speed of 0.1 mm per minute and a jaw gap width of 10 mm. The average values with standard deviations for each set of twenty sections for both failing loads and modulus of elasticity are presented in Table 2. The mean decrease in failing load for the five compressed blocks compared with the controls was 20 per cent; the corresponding reduction in stiffness was 27 per cent.

Table 2. The reduction in failing load and stiffness of sections following precompression

Sample No.	Failing load (N)					Modulus of elasticity (N/mm^2)				
	Control		Compressed		% loss	Control		Compressed		% loss
	load	sd	load	sd		E	sd	E	sd	
1	42.9	5.4	33.2	2.1	22.6	7,750	810	6,160	573	20.5
2	32.0	6.1	23.8	5.0	25.6	7,070	1,184	4,950	1,260	30.0
3	39.0	4.2	31.8	2.5	18.5	10,640	2,037	7,400	809	30.5
4	34.5	3.3	28.2	4.3	18.3	5,990	543	3,500	549	41.6
5	30.0	4.0	25.0	3.6	16.7	4,860	566	4,150	314	14,6
Mean	35.7		28.4		20.3	7,262		5,232		27.4

Considerable differences in the morphology of the fracture occurred in the sections between the compressed and control samples. In the former, failure took place across the wall usually at right angles to the longitudinal axis, the path of the crack following a series of slip planes in adjacent cells. Occasionally, the crack ran along the wall for a short distance before resuming its horizontal progression, but the general impression remained of an exceedingly abrupt or brash fracture (Fig. 3). There was very little difference in morphology between the early and late wood zones with the possible exception of a change from horizontal to an oblique plane of failure at about 45°–60° to the vertical through the last few rows of cells in the late wood.

In the control blocks, the general impression of the fracture was that it was interlocked. The situation, however, changed from early to late wood: in the former the fracture was short, with cross-wall breakages occurring usually obliquely; in the late wood, large tongues of fibre were pulled out completely with interwall shear failure predominating (Fig. 3).

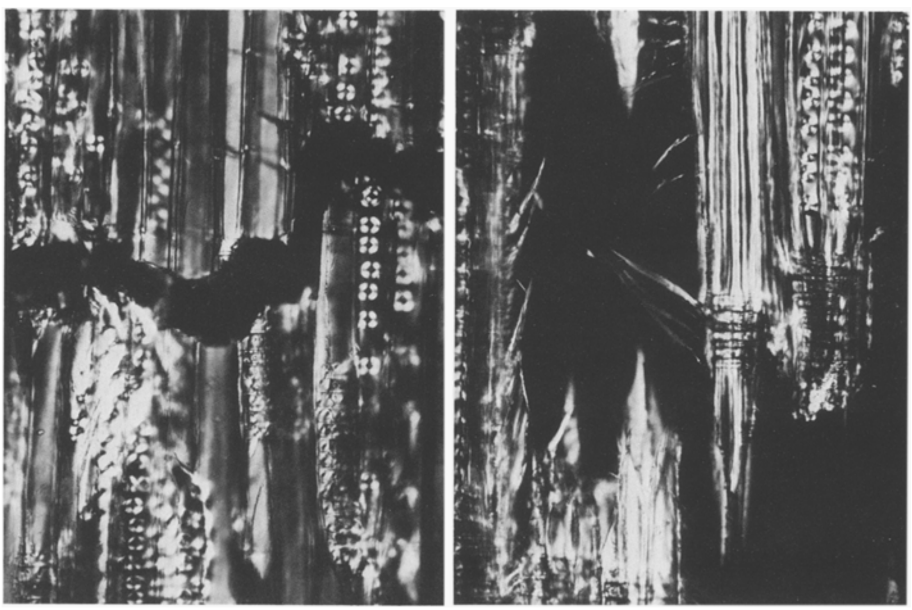

Fig. 3. Tensile failure of wood sections, prepared from precompressed samples (left) and matching control blocks (right)

Individual fibres

Following the same procedure as that recorded in the previous section, a control block and a compressed waisted block were produced from four samples removed from the sapwood of an old, slowly-grown Norway spruce tree. From the latter block a sample about 6 mm in length and containing the compression crease was removed using a fine fret saw; a corresponding sample was cut from the control block and both were macerated using a mixture of 100 volume hydrogen peroxide and glacial acetic acid. To prevent the induction of fibre damage the agitation necessary to separate the fibres was applied sparingly and gently. After careful washing the fibres were stained with congo red.

Following the recommendations of Duncker and Nordman [1965] that at least 80 fibres per sample should be tested, 100 whole, straight and undamaged fibres were carefully selected from each of the eight suspensions and mounted on paper tags using ethylhydroxyethyl cellulose [Hartler, Kull, Stockman 1963; Dinwoodie 1965; Packman, Laidlaw 1967]. The fibres were first conditioned and subsequently stressed in tension in a controlled environment of 20 °C and 65 per cent relative humidity; the strain rate was 0.1 mm per minute.

The mean values and standard deviations for each sample of 100 tracheids for both failing load and the deflection at constant load are presented in Table 3. The mean of the failing loads for the four trees showed a reduction of 46.5 per cent, while the mean deflection to constant load increased by nearly 22 per cent (i. e. stiffnes decreased).

Table 3. Reduction in failing load and deflection at constant load of individual cells following compression to failure

Sample No.	Failing load (N)					Deflection at 10 g (mm)				
	Control		Compressed		% loss	Control		Compressed		% gain
	load	sd	load	sd		deflection	sd	deflection	sd	
1	.188	.067	.084	.032	55.3	.039	.012	.049	.023	25.6
2	.230	.085	.098	.052	57.4	.035	.009	.047	.021	34.3
3	.191	.064	.127	.043	33.5	.035	.007	.038	.008	8.6
4	.192	.063	.116	.048	39.6	.038	.010	.045	.013	18.4
Mean					46.5					21.7

Bending strength

About 450 waisted samples were produced from each of two trees as described previously; following selection 300 remained from the first tree and 360 from the second. In each batch, half the samples was tested green while the remainder was conditioned to 12 per cent moisture content.

From the green and conditioned samples from both trees, 30 were selected at random and compressed longitudinally to failure. Subsequently, batches of 30 samples were compressed to 80, 65 and 50 per cent of the ultimate load: a further 30 were left unstressed to act as controls. For tree 2, the greater number of samples available permitted additional stressing at 35 per cent of the ultimate.

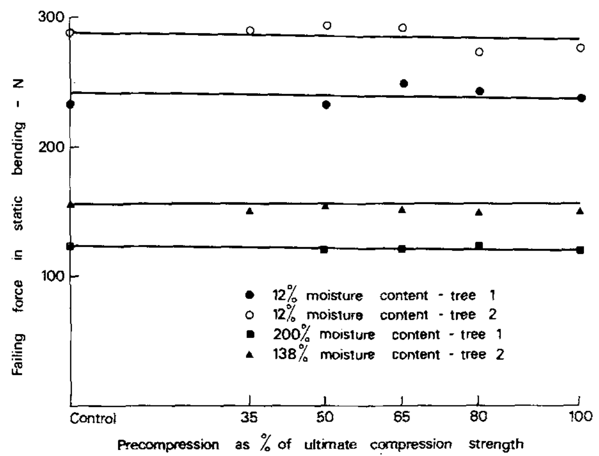

Fig. 4. The relation of static bending strength to degree of precompression in samples of different moisture contents from two Norway spruce trees (*Picea abies*)

Following compression the "wings" were removed from the waisted samples to produce beams 1 cm square in cross-section and 18 cm in length. These were stressed in three-point loading using a crosshead speed of 0.5 mm/min. The failing loads and modulus of elasticity for both green and dry samples from each tree are illustrated in Figs. 4 and 5 from which it will be noted that the degree of precompression has no effect on both the bending strength and modulus of elasticity in timber both above and below the fibre saturation point.

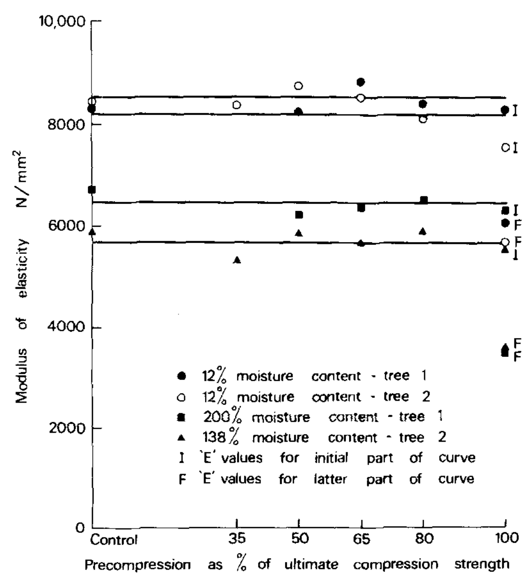

Fig. 5. The relation of stiffness in bending to degree of precompression in samples of different moisture contents from two Norway spruce trees (*Picea abies*)

Two values of E were computed at the 100 per cent level, one for the initial part of the curve which was similar to that for other levels of stressing, and a second for the latter part of the load/deflection curve, which was considerably lower and is obviously related to the prior development of large compression creases during compression stressing to high levels.

Toughness

In order to obtain some preliminary information on the effect of precompression on the impact resistance or toughness of wood, the area under the load/deflection curves for the samples tested in static bending and recorded in the previous section was integrated to provide an estimate of the work done to maximum load.

At high moisture content, increasing the amount of precompression damage in the wood results in an increase in the work done to maximum load; at 100 per cent precompression, the increase in work done for both trees is about 10 per cent (Fig. 6). However, for samples conditioned to 12 per cent moisture content, increasing precompression reduces the work done to maximum load and at 100 per cent precompression the reduction for the two trees is 10 and 13 per cent.

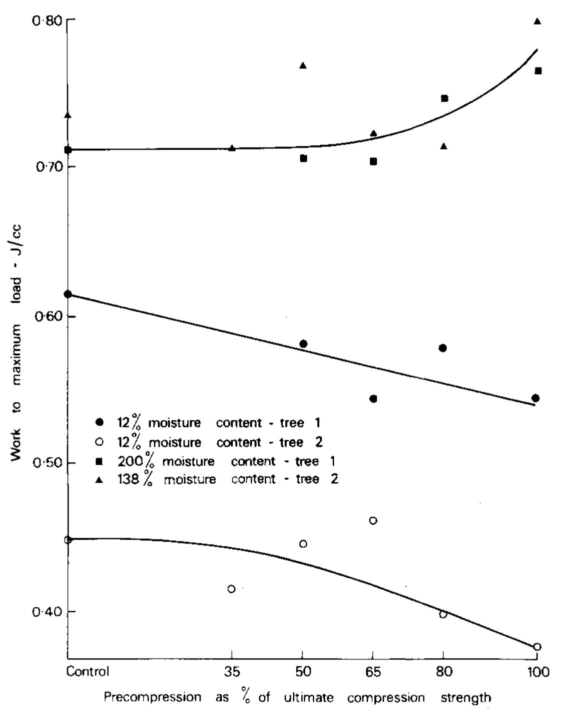

Fig. 6. The effect of degree of precompression on the work done to maximum load in static bending

It is generally agreed that work done to maximum load is not a very sensitive index of toughness, and to obtain a more sensitive measurement of the effect of precompression on toughness separate samples were prepared for testing in a Hatt-Turner impact testing machine. As in previous tests, a large number of waisted samples 18 cm in length were prepared from one tree and 504 were selected for the test. Half the samples were tested green while the others were conditioned to 12 per cent moisture content prior to testing. For each batch, 36 samples were compressed to failure and, subsequently, batches of 36 were compressed to 25, 35, 50, 65 and 80 per cent of the ultimate failing load. Following compression, the "wings" were removed from these together with a further 36 unstressed control samples to produce beams 18 cm long by 1 cm square in cross-section with the bulk of the compression damage located in the middle of the beam. The beams were tested over a span of 15 cm; since the cross-sectional area was only one-quarter that of the standard size of samples used in this test, the mass of the falling head was reduced from 1.5 kg to 375 g: height increments of 2.5 cm were used.

The mean values for each set of 36 samples are presented in Fig. 7 from which it will be noted that for the samples above fibre saturation point an increase in the amount of precompression results in an increase in impact resistance or toughness: in the case of timber at 12 per cent moisture content, impact resistance increased slightly with the lowest amount of precompression and subsequently decreased appreciably as the degree of precompression increased. A comparison of recorded values at the 100 per cent level of precompression with those of the control blocks reveals an increase of 37 per cent in the case of green timber and a decrease of 40 per cent for timber at 12 per cent moisture content (Table 4).

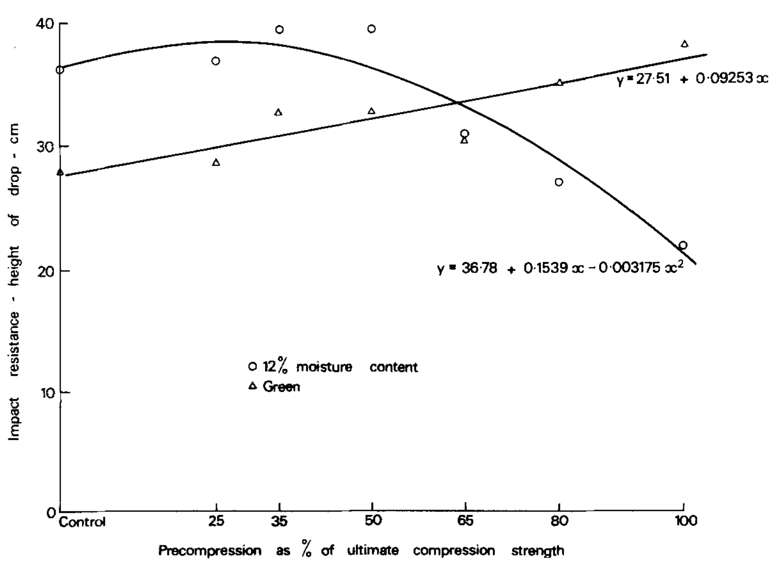

Fig. 7. The effect of degree of precompression on impact resistance (Hatt-Turner) of dry and green samples of Norway spruce (*Picea abies*)

Table 4. The effect of degree of precompression on the impact resistance of green and dry timber

Moisture state	Regression	Significance level of regression	r^2	Change in resistance at 100 % precompression compared with controls
green	$y = 27.51 + 0.09253x$	0.1 %	0.16	+ 37 %
12 %	$y = 36.78 + 0.1539x - 0.003175x^2$	0.1 %	0.34	−40 %

x = percentage precompression level
y = impact resistance : height of drop (cm)

Analyses of variance comparing values of impact resistance or toughness between and within different levels of precompression indicated that for both the green and dry states the differences between the precompression levels were significant at the 0.1 per cent level. Linear regressions were fitted to both sets of data and, as the deviations were significant, a quadratic regression was calculated and tested for significance. In the case of the dry timber strong evidence for curvilinearity was obtained, while for green timber the test for curvilinearity showed it to be non-significant; regressions and their levels of significance are presented in Table 4.

Both regressions account for a relatively low percentage of the total variation in toughness (Table 4) though the levels are appreciably higher than in the case for tensile stressing of wood blocks; once again, this is a reflection of the very high degree of variation in values that occurs at each level of precompression.

Discussion

Tensile strength

The sensitivity of tensile strength in timber and fibres to physical, chemical, or biological deterioration of the cellulosic chains is well documented in literature and there are analogous examples in the field of man-made fibre composites. It may be safely postulated, therefore, that the overall decrease in tensile strength with increasing levels of precompression (Fig. 1) is primarily a manifestation of mechanical damage to the cellulose molecule.

Results of electron microscopical studies, both those of Keith and Côté [1968] and our own (which will be published in a subsequent paper in this series), indicate that the microfibrils are not sheared in the crystallographic sense, but sharply bent in the form of a 'Z' or kink. This results in a loosening of the structure, certainly severance of cross-bonds within the unit cell, and possibly a limited amount of breakage of the longitudinal covalent bonds. In view of this, loss in tensile strength with precompression is to be expected; its restriction to less than 10 per cent can be attributed to the general continuity in microfibrillar structure across the kink.

The influence of precompression on tensile strength was significantly curvilinear in two of the four trees, while the results of the remaining trees showed a curvilinear trend though this was not statistically significant. This increase in tensile strength with increasing degree of precompression at the lower levels of precompression followed by a subsequent decrease would tend to indicate the presence of two interacting variables. The origin of the first is open to some speculation, but one hypothesis is that compression stressing increases the degree of hydrogen bonding within the matrix constituents: the second, namely the reduction in strength of the cellulose through formation of kinks, has already been discussed. At low levels of compression, the effect of the former is more significant and strength increases, while at higher levels of compression, the microfibrils in the 'slip plane' are more severely kinked and this effect outweighs the benefits of increased hydrogen bonding and hence strength decreases.

The sensitivity of tensile strength to degree of precompression increases as the sample size is reduced. Thus with 100 per cent precompression the loss in tensile strength of 1 cm^2 samples compared with controls was about 9 per cent, that of 50 μm sections was 20 per cent, and that of individual fibres was 46 per cent. A size effect of this type is common among materials where the significance of defects plays a disproportionately greater role the smaller the unit containing them, but it is possible that part of the high loss in strength of the individual fibres may be due to the actual process of specimen preparation.

The loss in tensile strength of radial sections prepared from precompressed blocks in the present experiment is only about half that of the mean of a series of tangential sections of uncompressed wood microtomed in such a way as to contain induced slip planes [Kennedy, Chan 1970]; this would imply that the degree of kinking of the microfibrils and the amount of interfibrillar bond rupture is greater in those kinks induced in section cutting than in those produced in compressing a block of timber, probably as a result of lower stress concentration in the latter. The present results also support the findings of Biblis [1970] and Page *et al.* [1972] on the marked reduction in tensile strength of wood sections and fibres respectively following the induction of compression damage.

The slip-plane constitutes a weak link during stressing and it will be observed from Figs. 1 and 4 how the line of crack propagation during tensile stressing has been strongly influenced by the presence of slip-planes and creases. A brittle-type fracture occurs, though it must be appreciated that there are many reasons in addition to compression damage to account for the occurrence of brittle failure in timber [Dinwoodie 1976].

Bending

Since the tensile strength of solid timber decreases by up to 10 per cent at high levels of stressing it may appear surprising that precompression has little or no effect on the bending strength and stiffness. However, it should be recalled that compressive strength of timber is only about one-third the tensile strength; consequently under a bending stress the compressive strength of clear timber is probably more critical than the tensile strength. Since compressive strength and degree of precompression are synonymous, it is to be expected that bending strength will be little affected by degree of precompression.

Toughness

Both the work done to maximum load (Fig. 6) and the results of tests using the Hatt-Turner impact testing machine (Fig. 7) provide similar evidence of the effect of precompression on the impact resistance or toughness of timber, though the latter technique appears to be more sensitive than the former.

In timber at 12 per cent moisture content, low levels of precompression result in slight increase in toughness and no doubt this increase in energy consumed prior to rupture can be accounted for in the process of straightening out the kinked microfibrils in the region of the slip-plane. At higher levels of precompression, however, toughness decreases appreciably with increasing degree of precompression, due to the higher degree of microfibrillar kinking and the severance of intermicrofibrillar bonding. The fracture surface is again brittle, the crack having propagated along horizontal lines of slip-planes as is the case with tensile failure. The relationship between toughness and precompression is therefore similar in qualitative terms to that between tensile strength and precompression but, quantitatively, toughness is much more sensitive to the presence of compression damage than is tensile strength. Present results support those of Hudson [1961].

In green timber, impact resistance was shown to increase progressively with increasing precompression, an occurrence which is obviously related to the increased flexibility (decreased stiffness) of wood which is both wet and contains compression damage. Thus it has been shown that ash for spade-handle manufacture can be rendered more flexible by steaming and compressing longitudinally [Stevens, Dean 1967]. Much of the energy absorbed in impact stressing of wet timber appears to be absorbed in deforming the material rather than in the initiation and propagation of cracks, a conclusion which is supported by the diffuse nature of the distribution of slip planes in wet timber [Dinwoodie 1968].

Conclusions

The effect of precompression in both green and dry timber on the tensile strength and toughness at levels as low as 35 per cent of the ultimate short term stress supports views expressed in Part I of this series [Dinwoodie 1968] that the first stages of slip plane development leading eventually to compression failure could be detected microscopically at stress levels equivalent to 25 per cent of the ultimate short term stress. The effect of precompression, however, was disproportionately greater at stresses above about 65 per cent where, as noted in Part I, there was a significant increase in the number of slip planes and creases.

Although the existence of precompression damage has no effect on bending strength and only a minor effect on the tensile strength of solid timber as distinct from sections or individual fibres, it does have a very pronounced effect on the impact resistance or toughness of the material. Unfortunately there are countless practical examples where serious injury has been inflicted on workmen who in their movements have applied loads suddenly to such highly stressed items as ladders and scaffold boards which contained previously induced compression damage. This could have originated in the standing tree either as a result of the high longitudinal compressive growth stresses which result in the formation of what is commonly known as brittleheart, or the occurrence of natural compression failures resulting from severe gales. Compression damage can also occur during felling of the tree if it lands across some obstacle on the ground, or in the overstressing or cyclic loading of timber in practice. Examples of these have been published [Dinwoodie 1976] and the necessity for the utmost care in visual inspection has already been emphasised.

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