On the Speed of Crack Propagation parallel to the Grain in Wood*

Wood Physics, Section III

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Introduction

We have been interested in fracture of wood, specially in tensile rupture, in recent years. When one pulls a wood in parallel to its grain, many cracks to this direction often arise at the first step of rupture, which grow onto larger scale. At sawing across wood or at breaking of wood-construction, one will often observe appearance of the similar cracks. For studies on fracture of wood, it will be one of the most important matter to solve how this crack originates and grows.

In the work herein reported, we measured the speed of propagation of this crack created by the tensile force perpendicular to the grain, analyzed the factors influencing on this speed and roughly considered the mechanism of its growth. The mechanism of its origination must be considered in connection with the molecular construction of wood, its deformation and the force acting on it, but, in the present report, we will not dare to enter into these problem.

The Measurement of the Speed

Two methods have been employed to measure the speed of crack, one the method measuring the distance where a crack goes through at interval by taking photographs with a high speed camera[1] or a special equipment[2], and the other the electronic method[3)4] using an oscillograph that records the time at which a crack goes through a defined distance.

In the present experiments we used the latter method. This was used by G. H. Hudson *et al.*[3] and S. Amijima *et al.*[4] The circuit used in our measurement is shown in Fig. 1.

The first leading wire (No. 0 in Fig. 1) is connected directly with X-axis of the cathode-ray oscillograph (c.r.o.) through a sweep generator—bootstrap circuit that is shown in the left hand of Fig. 2. The breaking of this wire causes to start

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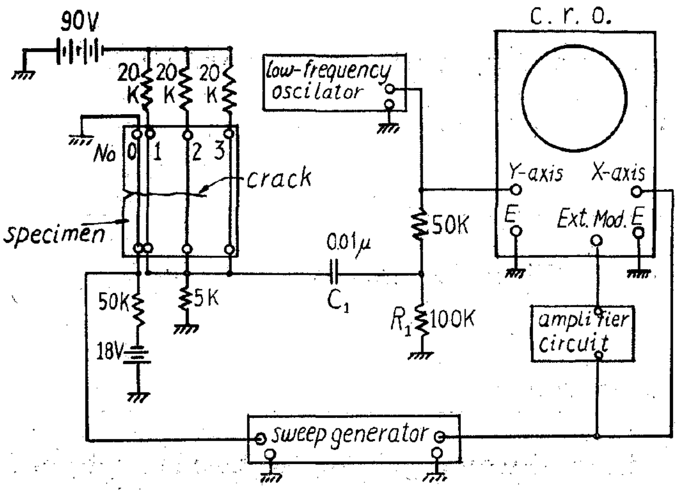


Fig. 1. The circuit of measurement of speed.

a single horizontal sweep of the electron beam on the screen of c.r.o. by the action of a sweep generator. Each of the succeeding wires (No. 1, 2 and 3 in Fig. 1) are connected with Y-axis of c.r.o. through a differentiation circuit that is shown by a condenser C_1 and a resistance R_1, and through a alternating current amplifier circuit in c.r.o.. The breaking

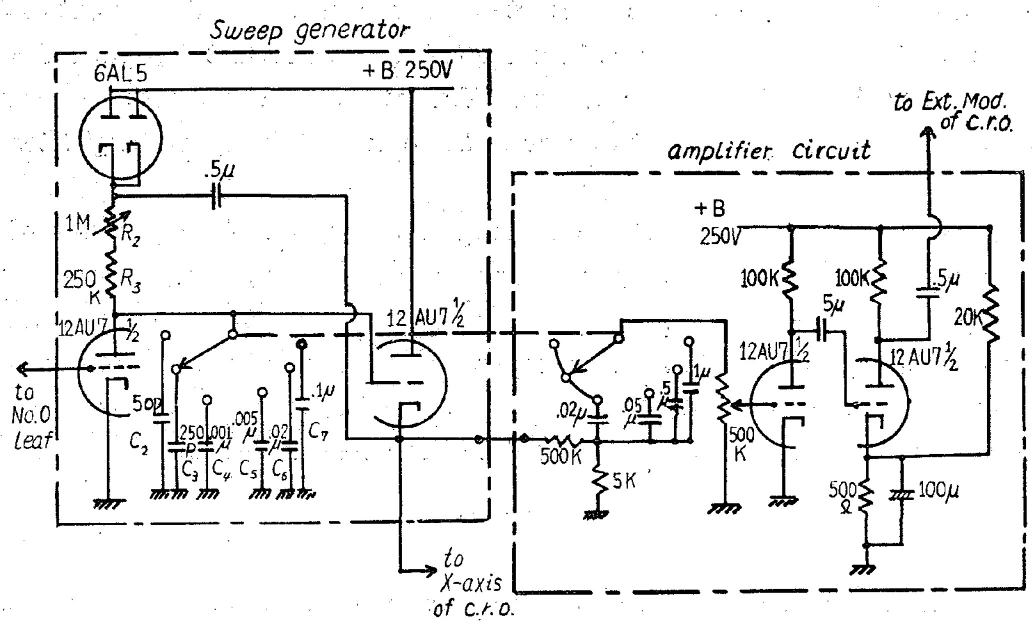


Fig. 2. The sweep generator and the amplifier circuit.

of these wires introduces a vertical jump of the electron beam.

The specimen was placed in the grap of the wood-testing machine of Amsler type and pulled to failure. To fix the point of initiation of the rupture, a notch was made into one side of the specimen midway between its ends. A crack initiated at the notch, as indicated in Fig. 1, propagates across the specimen and breaks these wires in succession. Then, the vertical jumps will be made to appear on the horizontal sweep of the electron beam. The time of the horizontal sweep are regulated by six condenseres indicated as $C_2 \sim C_7$ and two resistances indicated as R_2, R_3 in Fig. 2. They must be chosen suitably as the failure are finished in this time. A calibration wave for timing provided by a low-frequency oscillator as shown in Fig. 1 are superposed upon the movements of the beam described above. Then the electron beam on the screen of c.r.o. always moves describing sine waves.

Potographs of these movements of beam can be taken with a X-ray film. But here is a problem : When is the shutter to be opend? It is to be desired that the shutter is opened at the moment when a crack starts. But we cannot previously estimate it. Then, we settled the problem by decreasing initially the brightness of the beam to such an extent that film is not exposed and then increasing it to expose film at the moment when the crack starts, i. e., No. 1 wire breaks. The circuit, shown in Fig. 1, going through the amplifier circuit, that is shown in the right hand of Fig. 2, from the sweep generator to the terminal of the brigtness-change of c.r.o. (Ext. Mod. in Fig. 1) is for this purpose. The shutter is kept opening from the time when we begin to load the specimen. Photo. 1 is an example of our results. The jumps indicated by the symbols of 1, 2 and 3 in this photograph correspond to the breaking of No. 1, 2 and 3 wires on the specimen respectively. The time in which the crack goes through the distance between two wires is known from the numbers of sine waves between two jumps and the frequency of oscillator.

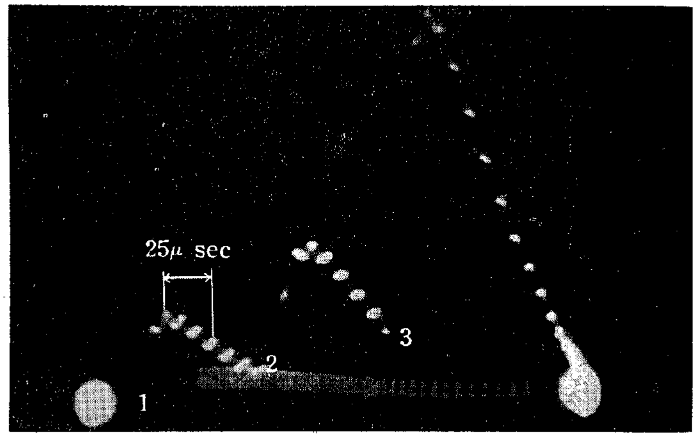


Photo. 1 A typical record obtained from the breaking of a specimen.
The numbers 1, 2 and 3 designate the positions of the electron beam at the instants of breakiug of Al leaves 1, 2 and 3, respectively.

We used aluminium leaves, approximately 30μ thick, as the leading wires. The form of the leaves was like dumb-bells as shown in Fig. 3. The central straight part of these leaves, 30 *mm* long and approximately 0.5 *mm* wide, were arranged to be approximately parallel to each other and perpendicular to the expected path of the crack and were pasted on the specimen by Araldite (epoxy resin) as shown in Fig 1 and Fig. 4. No. 0 leaf and No. 1 was 5 *mm* apart in air-dry test*, and 2 *mm* apart in water-satu-

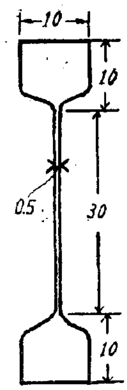


Fig. 3. Schematic figure of aluminium leaf.
The numbers indicate length in *mm*.

* The air-dry test or the water-saturate test means the test in which the moisture condition of specimens is in air dry or in water-saturate, respectively.

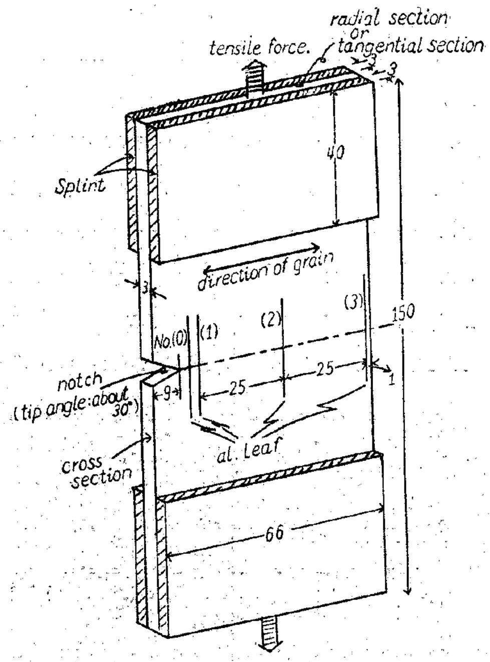


Fig. 4. Form and size of our specimen.
No. (0), (1), (2), and (3) correspond to No. 0, 1, 2 and 3 in Fig. 1 respectively, and other numbers indicate length in *mm*.

rate test*; in the latter there probably existed the region of ductile fracture[5] which run up into 3~4 *mm* from the tip of a notch and then the elapsed time from the breaking of No. 0 leaf to one of No. 1 was too long. Three leaves in succession were 25 *mm* apart from each other. Both unpasted ends of these leaves wrapped copper wires with a diameter of approximately 0.15 *mm*, which were connected with circuit, and then were pasted on the specimen by Scotch tape or vinyl tape.

The reason why we used leaves instead of wires was to adhere leaves on the specimens better. The neccessary condition of these leaves (or wires) is to break as soon as the crack goes through the point where they exist. Perhaps, aluminium leaves have very low elongation even at the breaking because of rolling work, and have low breaking loads because of their thin thickness. It may not be reasonable that they do not break after the crack passages. Consequently, there is a possibility that the leaves elongated on proportion as the elongation of wood break before the crack comes to them. But it is almost sure that such is not the case because of the following facts : In some examples that the crack stopped on this side of leaves, these leaves did not break, and the electron beam did not begin to sweep, that is, No. 0 leaf did not break untill the tensile fracture of specimen happened.

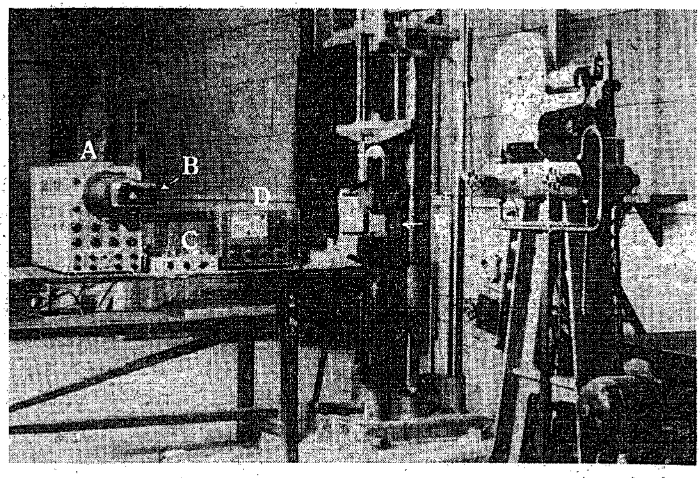


Photo. 2 The panoramic view of our experimental equipments.
A : a cathode-ray oscillograph.
B : a camera for taking a photograph of the movement of beam on the screen of c.r.o.
C : the sweep generator and the amplifier.
D : a low-frequency oscillator for timing.
E : a specimen.

Photo. 2 is the panoramic view of our experimental equipments.

Specimen and other experimental conditions

Buna (*Fagus crenata* Blume) and Hinoki (*Chamaecyparis obtusa* Sieb. et Zucc.) were used in our experiment. The form and size of our specimen are shown in Fig. 4. The planes perpendicular to the tensile force are two—radial and tangential*. The moisture conditions of the specimen are two—air dry and water-saturate. The specimens were made from the same timbers of Buna and Hinoki in air dry state. The water saturating specimens were made by placing in water decreased pressure for about two days. They had not such splints as shown in Fig. 4. The moisture contents of the specimens were measured by the method provided in JIS·A·1002 (1954) directly after the completion of our test. We did not regulate the temperature and humidity during the tensile test, and the temperature was 29～31°*C* in the case of air-dry test, 21～26°*C* in the case of tangential test of Buna in water-saturate test and 11～14°*C* in other cases of water-saturate test. And the rate of increasing the tensile force was about 200 kg/cm^2 per minute. We recorded the breaking loads of every specimen for the data of their tensile strength.

Experimental Results and its Considerations

The speed of the crack, the tensile strength of the specimen, their moisture contents, their annual ring breadths and their specific gravities in oven dry are shown in Table 1.

The values of speed of the crack propagation parallel to the grain of Buna and Hinoki caused by the tensile force perpendicular to the grain are very widely variant, from minimum value about 70～80 *m/sec* to maximum value about 3,000 *m/sec* in air-dry test and from about 4～5 *m/sec* to about 3,000 *m/sec* in water-saturate test as shown in Table 1. The maximum value, about 3,000 *m/sec*, is near the value of the sonic speed parallel to the grain in wood[6]. The variance of these values are shown in Fig. 5 which are histogramms drawn in 500 *m/sec* interval. The maximum frequency of speed values in Fig. 5 exists in near 1,000 *m/sec* in air-dry test and below 500 *m/sec* in water-saturate test except some cases as in the tangential test of Hinoki.

Now, the analysis of variance[7] was carried out to know what factors influenced upon the speed. We analyzed the factors in regard to the species, the planes in which the crack propagated, the moisture contents of specimens, the positions

* We will call them radial test and tangential test respectively in the following.

Table 1. The result of our experiment and some characteristics of our speccimens.

a) air-dry test

		speed of crack propagation (*km/sec*)						tensile strength** (*kg/mm*²)			moisture content %	annual ring breadth *mm*	apecific gravity in oven dry
		V_{1-2}*			V_{2-3}*								
		Min.~Mean~Max.	number of specimen	standard deviation	Min.~Mean~Max.	number of specimen	standard deviation	Min.~Mean~Max.	number of specimen	standard deviation	Min.~Mean~Max.	Min.~Mean~Max.	Min.~Mean~Max.
Buna	radial test	0.25~1.33~3.1	12	0.78	0.75~1.19~2.3	15	0.38	0.19~0.40~0.61	23	0.12	13.0~14.6~15.5	2.0~2.8~3.6	0.56~0.615~0.66
	tangential test	0.25~1.38~3.2	17	0.70	1.0~1.47~3.1	17	0.42	0.31~0.72~1.02	22	0.16	14.4~15.4~16.0	1.5~2.5~3.0	0.57~0.616~0.66
Hinoki	radial test	0.42~1.15~2.3	15	0.59	0.28~1.33~3.6	14	0.97	0.16~0.28~0.48	17	0.10	13.8~14.5~15.7	0.6~1.0~1.4	0.37~0.420~0.46
	tangential test	0.084~1.29~3.1	22	0.97	0.073~0.905~2.3	21	0.64	0.16~0.33~0.53	26	0.09	13.4~15.8~17.7	0.7~0.9~1.6	0.36~0.385~0.70

b) water-saturate test

		speed of crack propagation (*km/sec*)						tensile strength** (*kg/mm*²)			moisture content %	annual ring breadth *mm*	specific gravity in oven dry
		V_{1-2}*			V_{2-3}*								
		Min.~Mean~Max.	number of specimen	standard deviation	Min.~Mean~Max.	number of specimen	standard deviation	Min.~Mean~Max.	number of specimen	standard deviation	Min.~Mean~Max.	Min.~Mean~Max.	Min.~Mean~Max.
Buna	radial test	0.007~0.528~1.3	18	0.360	0.005~0.417~1.2	21	0.294	0.10~0.29~0.47	24	0.10	96~112~128	1.9~3.1~4.5	0.55~0.598~0.64
	tangential test	0.47~0.850~1.1	13	0.360	0.53~0.729~0.97	11	0.147	0.41~0.56~0.79	15	0.10	97~111~123	2.6~3.0~3.4	0.57~0.606~0.64
Hinoki	radial test	0.039~0.743~3.1	22	0.751	0.004~0.530~2.5	15	0.625	0.09~0.18~0.29	22	0.06	70~131~175	0.5~1.0~1.6	0.34~0.379~0.41
	tangential test	0.021~0.875~2.5	19	0.707	0.036~0.760~2.1	22	0.515	0.12~0.28~0.48	24	0.09	64~124~201	0.6~0.9~1.2	0.35~0.375~0.43

* V_{1-2} and V_{2-3} indicate the speeds between No. 1 leaf and No. 2, and between No. 2 and No.3 respectively.

** Strength is expressed by the value obtained by dividing the breaking load by the area of section exempting the notch.

where the speeds were measured and the strength of specimens.

At the time when we did it, we used the method of successive modification as follows :

1) The analysis of three factors—the species, the directions of tensile force (i. e., the plances in which the crack propagated) and the moisture contents—for the strength of the specimens,

2) The analysis of four factors, described above, except the strength for speed,

3) The adjustment of the data of the speed such as to remove the effect of factors that were significant in 2) for speed and the analysis of the strength for these data of speed,

4) The analysis of factors decribed in 2) for the data of the speed which were removed the effect of the strength from its original data,

5) The adjustment of original data of the speed such as to remove the effect of factors that were significant in 4) and the analysis of the strength for these data of speed.

The reason why we used the method of successive modification is that the strength

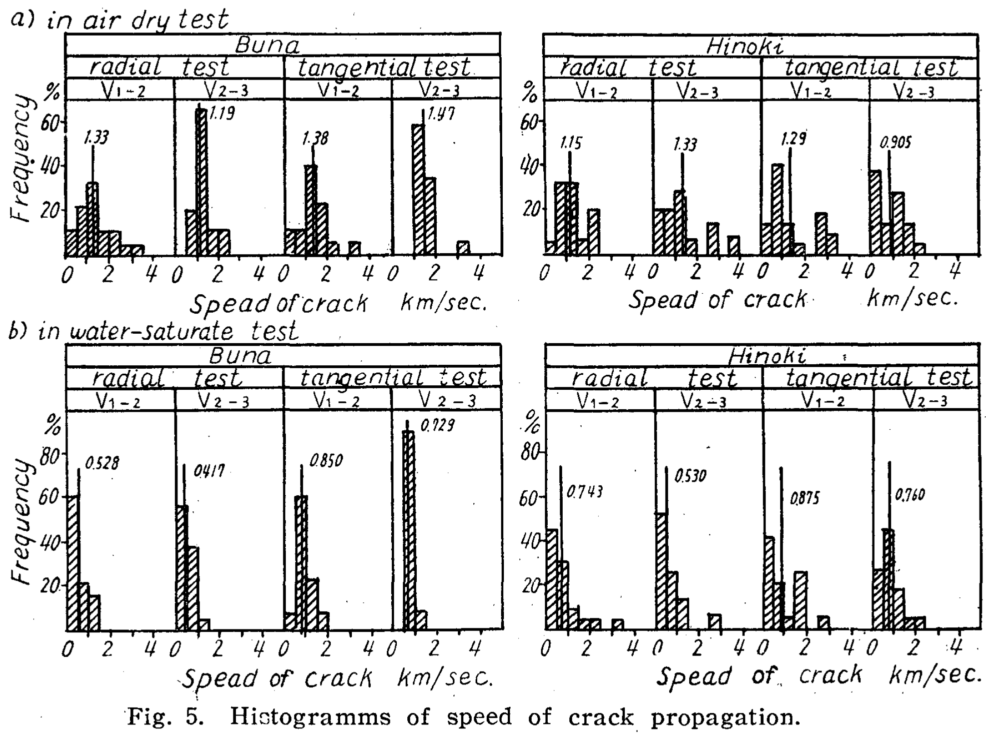


Fig. 5. Histogramms of speed of crack propagation.

are influenced by the factors which influence upon the speed.

For these calculation, we included the effects of annual ring breadth and specific gravity in the effect of species, and, furthermore, we neglected the effects of the variance of moisture contents in the same state—in air dry or in water saturate, though they were variant as shown in Table 1. For the calculation in 3) and 5), we divided the strength in nine regions (10 kg/cm^2 interval) and neglected the effects of variances in the same region.

Table 2. The result of analysis of variance.

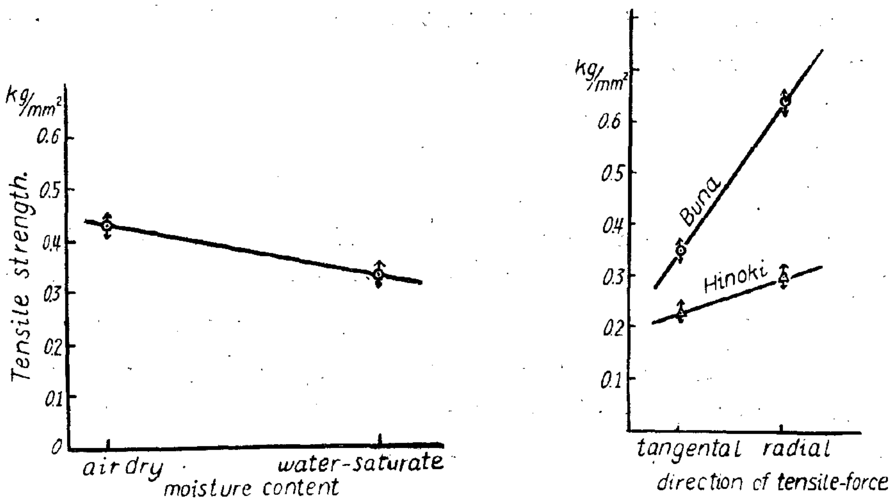
a) For speed — b) For tensile strength

factor	degree of freedom	(1) sum of square	(1) mean square		(2) sum of square	(2) mean square		b) degree of freedom	b) sum of square	b) mean square	
A	1	18259	18259	○	1285	1285		1	17228	17228	◎
B	1	349392	349392	◎	262757	262757	◎	1	5733	5773	◎
C	1	1126	1126		9702	9702		1	26460	26460	◎
V	1	11070	11070		11645	11645		—	—	—	
A × B	1	14713	14713		7711	7711	○	1	18	18	
B × C	1	18926	18926	○	15619	15619	○	1	450	450	
C × A	1	13902	13902		18007	18007		1	6223	6223	◎
V × A	1	1448	1448		1121	1121		—	—	—	
V × B	1	1247	1247		1833	1833		—	—	—	
V × C	1	1803	1803		1422	1422		—	—	—	
e	269	1141050	4242		1023078	3808		167	19793	119	
σ	8	1062.39	132.80	◎	1726.89	215.86	◎				
e	272	10861.23	39.93		9918.80	36.47					

A : the directions of the tensile force (the planes where crack propagates)
B : moisture contents
C : the species
V : the positions where the speeds are measured
σ : tensile strength — e : error
◎ : significant in 1% level
○ : significant in 5% level

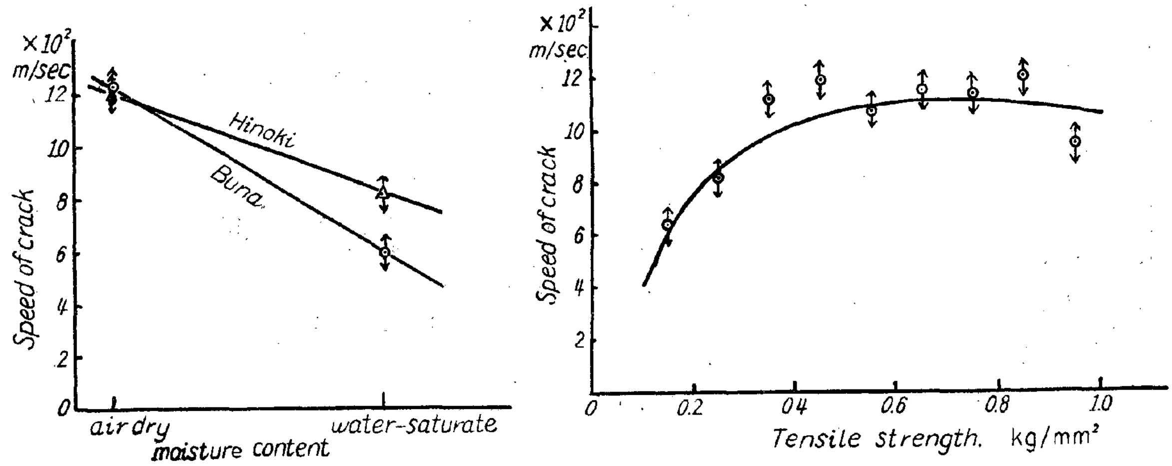
The results of these calculations are shown in Table 2 and Figs. 6 and 7. Table 2 indicates that the moisture content and the strength of specimens produce direct influences upon the speed of crack, and that the plane where the crack propagates does not produce an influence upon the speed directly but through the strength, and that the species produce an influence only upon the strength. And Fig. 7 seems to indicate that the speed of crack becomes slower as the moisture content increases and that the weaker groups of specimens have slower speeds.

Now, when the crack originates in the specimen, the elastic energy stored in it by the external force will be consumed for the propagation of crack[8]. When the specimen is weaker and when the moisture content is higher, it is expected that this energy will be smaller. Because, in the latter case, it will be more consumed for the plastic deformation than in the lower moisture content before the origination of crack and after the begining of its growth. This consideration seems to explain the results shown in Fig. 7 qualitatively. But we must carry out



(a) (a)

Fig. 6. Tensile strength *vs.* moisture content (a) or *vs.* direction of force (b) diagram gained by analysis of variance.
Arrows show confidence interval of our experiment calculated by analysis of variance in 5% level.



(a) (b)

Fig. 7. Speed of crack *vs.* moisture content (a) or *vs.* tensile strength (b) diagram gained by analysis of variance.
Arrows show confidence interval of our experiment calculated by analysis of variance in 5% level.

more works to know the detail of these mechanisms of propagation of crack, that is, to explain these results quantitatively.

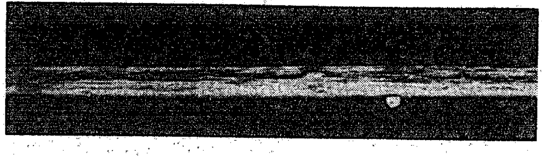
From the fact that the maximum frequency of the speed in air-dry test exists near 1,000 *m/sec*, it will be supposed that the fracture caused by the tensil force perpendicular to the grain in air-dry test often occurs with little plastic deformation and grows by the elastic energy stored in the specimen in a almost same way of brittle fracture. This speed is nearly equal to the speed of fracture of glass, 1,500 *m/sec*[2], or to the speed of brittle crack of steel, 1,050 *m/sec*[3]. On the other hand, from the fact that the maximum frequency of the speed in water-saturate test exists below 500 *m/sec*, the regions of plastic deformation will probably often exist before and after the begining of fracture. The fact found in cellophane sheet by E. Orowan[5] that the ductile fracture in high humidity and brittle fracture in low humidity occured respectively may indicate that our consideration will be correct.

Photos. 3~6 show the patterns of the breaking planes gained in our experiment. All of these are somewhat likely to the chevron pattern[9] which appears in the case of brittle fracture. The fact that there is little difference in patterns between air-dry test and water-saturate test or between the faster speed and the slower one seems to indicate that plastic deformations occur in the smaller scale.

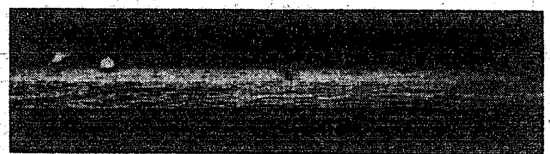
Further, S. Amijima *et al.*[4] measured the speed of cracks parallel to the

A) In air-dry test

a) faster one ($V_{1-2}=1.3$ *km/sec* ; $V_{2-3}=1.1$ *km/sec*)

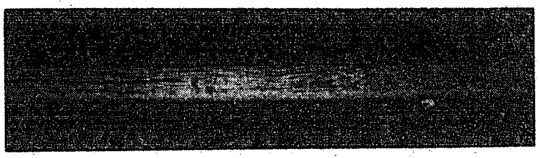


b) slower one ($V_{1-2}=0.53$ *km/sec* ; V_{2-3} cannot be measured)



B) In water-saturate test

a) faster one ($V_{1-2}=0.54$ *km/sec* ; $V_{2-3}=0.41$ *km/sec*)



b) slower one ($V_{1-2}=0.007$ *km/sec* ; $V_{2-3}=0.16$ *km/sec*)

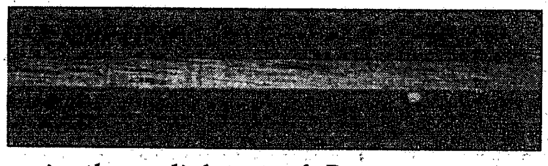
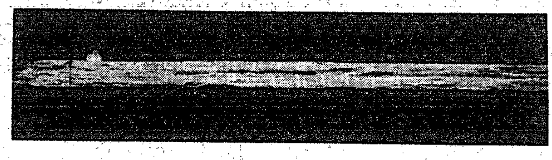


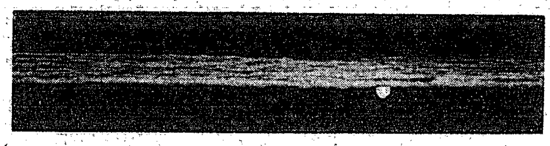
Photo. 3 Typical patterns of breaking in the radial test of Buna. The fracture propagated from left to right.

A) In air-dry test

a) faster one ($V_{1-2}=1.3$ *km/sec* ; $V_{2-3}=1.4$ *km/sec*)

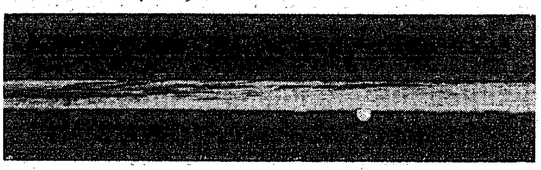


b) slower one ($V_{1-2}=0.25$ *km/sec* ; V_{2-3} cannot be measured)



B) In water-saturate test

a) faster one ($V_{1-2}=0.83$ *km/sec* ; $V_{2-3}=0.63$ *km/sec*)



b) slower one ($V_{1-2}=0.20$ *km/sec* ; $V_{2-3}=0.64$ *km/sec*)

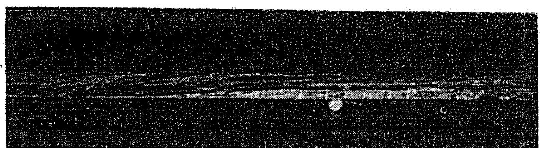
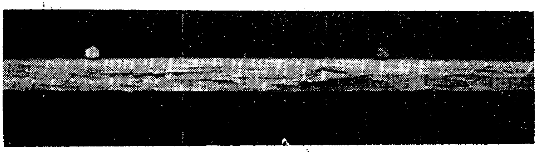


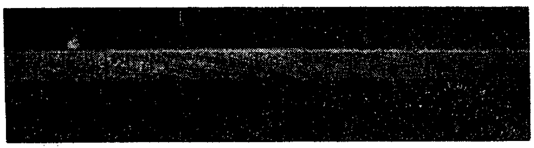
Photo. 4 Typical patterns of breaking in the tangential test of Buna. The fracture propagated from left to right.

A) In air-dry test

a) faster one (V_{1-2}=2.1 *km/sec* ; V_{2-3}=3.6 *km/sec*)

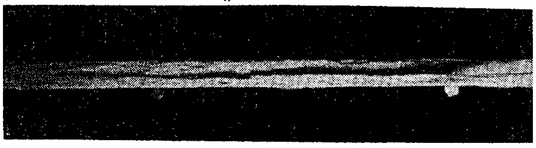


b) slower one (V_{1-2}=0.16 *km/sec* ; V_{2-3}=0.34 *km/sec*)



B) In water-saterate test

a) faster one (V_{1-2}=0.86 *km/sec* ; V_{2-3}=0.42 *km/sec*)



b) slower one (V_{1-2}=0.19 *km/sec* ; V_{2-3}=0.005 *km/sec*)

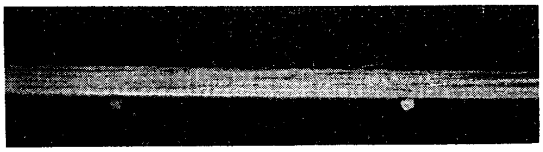
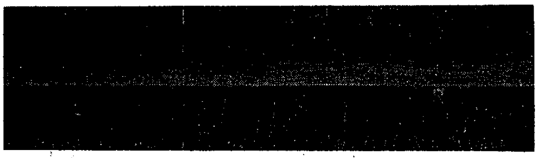


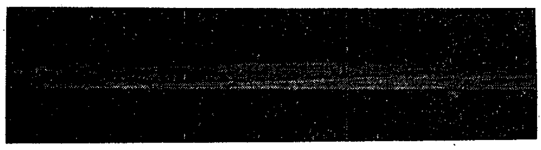
Photo. 5 Typical patterns of breaking in the radial test of Hinoki.
The fracture propagated from left to right.

A) In air-dry test

a) faster one (V_{1-2}=1.1 *km/sec* ; V_{2-3}=1.5 *km/sec*).

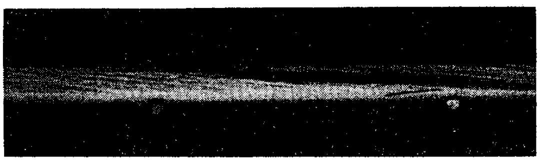


b) slower one (V_{1-2}=0.52 *km/sec* ; V_{2-3}=0.09 *km/sec*)

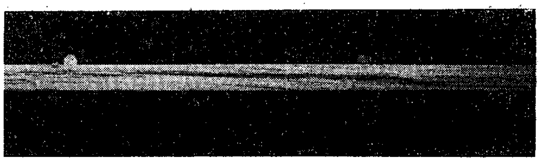


B) In water-saturate test

a) faster one (V_{1-2}=0.51 *km/sec* ; V_{2-3}=0.86 *km/sec*)



b) slower one (V_{1-2}=0.099 *km/sec* ; V_{2-3}=0.10 *km/sec*)



Pohto. 6 Typical patterns of breaking in the tangential test of Hinoki.
The fracture propagated from left to right.

grain in the tangential test of Sugi (*Cryptomeria japonica* D. Don) in air dry state by similar method as used here and gained 3 *m/sec* or so, which are the same order of the minimum value in our water-saturate test. The cause for a discrepancy between their results and our ones is not known yet.

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Summary

These experiments were a part of the studies to know the mechanism of fracture of wood.

The speed of propagation of crack created in radial or tangential planes by the tensile force perpendicular to the grain were measured by the electronic recording method using a cathode-ray oscillograph. The species used were Buna (*Fagus crenata* Blume) and Hinoki (*Chamaecyparic obutusa* Sieb. et Zucc.) in air dry condition or in water-saturate condition.

The experimental results are shown in Table 1. The variance of speed was very large. The max. frequency of speed values was near 1,000*m/sec* in air-dry specimens and often was below 500*m/sec* in water-saturate specimens.

The results of analysis of variance shown in Table 2 and Fig. 7 indicates that the factors influencing upon the speed are the moisture content and the tensile strength of the specimens and that the speed decreases as the moisture content increases and the weaker groups of specimens have slower speed.

From these facts, it seems to be that the fracture of the specimen in air-dry condition often occurs with little plastic deformation and grows in a brittle manner and, on the other hand, in water-saturate condition many regions of plastic deformation will probably often exist before and after the begining of the fracture. But the detail of their mechanism is not known yet.

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摘　　要

木材の破壊機構を知る研究の一環として，繊維に垂直な均一な引張り力によつて出来る破壊面の速度を測定した。

引張り力はアムスラー型木材試験機により半径面と接線面との二方向に垂直に働かせた。ブナ，ヒノキの二樹種の気乾材，飽水材を用い，樹種，引張力の方向の影響と共に水分による破壊面速度えの影響も考察した。試片の大いさ，形は **Fig. 4** の通りである。

アルミ箔（厚さ約 30μ，巾約 0.5 *mm*）を等間隔（25 *mm*）に試片にはりつけ，箔が破断面の通過と同時に切断される時に起る電圧の変化を陰極線オツシログラフの電子線の運動によつてとらえ，二つの箔間の距離を破壊面が進むに要する時間を知る方法をとつた。この回路は **Fig. 1** に示す通りである。

実験績果を **Table 1** に示す。これによれば破壊面の速度のばらつきは大きく，気乾材で 70～80 *m/sec* より 3,000 *m/sec*，飽水材で 4～5 *m/sec* より 3,000 *m/sec* の値が存在した。ばらつきの様子は **Fig. 5** のヒストグラムに示される通りであり，速度の最頻値は気乾材で 1,000 *m/sec* 附近に，飽水材で 500 *m/sec* 以下に多く現れる。

これら速度に影響を与える因子を知るべく強度（速度の測定と同時に各試片について測定した）を補助因子とする逐次修正法による分散分析を行つた。その結果は **Table 2, Fig. 6, 7** の通りである。すなわち，速度に影響するのは含水率と強度であり，含水率が多くなれば，速度が遅くなり，また強度の低いものは速度が遅い。

一般にぜい性破壊においては破壊面の進行エネルギーは物質中に貯えられた弾性エネルギーによつて与えられ，その進行速度は非常に早く（音速に近い）塑性変形が起るとその速度は一般に遅くなると考えられる。この考え方によれば上の現象が定性的によく説明されるようである。そして，最頻値より気乾状態の材の横引張力による破壊は塑性変形の殆んどない，ぜい性的挙動を示す場合が多く，飽水状態の材の場合はその破壊の前後に塑性変形が多少存在する場合が多いと考えられる。なお，その機構の詳細はこの実験のみからは不明で今後の研究に残されている。