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DYNAMIC TENSION TESTING EQUIPMENT FOR PAPERBOARD AND CORRUGATED FIBERBOARD

Summary

Methods and equipment have been developed to determine the dynamic tensile characteristics of paperboard and corrugated fiberboard. A flywheel-type test machine has been constructed and suitable instrumentation has been developed. Preliminary investigations of paperboard indicate that tensile strength increases approximately as a logarithmic function of the loading rate.

DYNAMIC TENSION TESTING EQUIPMENT FOR PAPERBOARD AND CORRUGATED FIBERBOARD

By

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Introduction

The objective of this work was to develop a method, the testing equipment, and the instrumentation with which dynamic stress-strain information may be obtained for paperboards and built-up corrugated fiberboards as used in corrugated fiberboard containers. Much information is available on the properties of these materials when subjected to static or low rates of loading, and this information has been valuable in the design of corrugated containers to resist the compressive stacking loads experienced in shipping and storage.

In shipment and handling, however, corrugated containers frequently receive impacts that can cause the container to fail and damage its contents.

Many materials are rate sensitive and their mechanical properties may change as the rate of loading is changed. The rate sensitivities of various structural materials differ greatly, but relatively little information is available on the rate sensitivity of wood or wood products such as paper. Thus, a need exists to determine the mechanical properties of these materials at loading rates equivalent to conditions in use.

This investigation is specifically concerned with the effect of rate of loading on the mechanical strength properties of paperboard, used as structural components in corrugated fiberboard containers, at loading rates comparable

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[1] Maintained at Madison, Wis., in cooperation with the University of Wisconsin.

to those encountered in typical usage. These loading rates may vary from static to those produced by a free fall of 10 feet (impact velocity of 304.4 inches per second).

The terms 'dynamic'' and 'impact'' are relative to material usage and require definition. A certain rate of loading may be high for one material and low for some other material. For the paperboard considered in this report, a dynamic rate of loading is one that produces failure of the material in a second or less, and any rate slower than this shall be considered static. An impact shall be considered a dynamic application of load resulting from a collision.

Background

It has long been recognized that the mechanical properties of a material may be influenced by the rate at which a load is applied to the material. Ludwik (5)[2] in 1909 determined that the strength of metals increases as a logarithmic function of the loading rate. Tiemann (12) investigated the effect of speed of testing on the strength of wood in 1908. Liska (4) in 1948 found that the ultimate compressive strength of several woods increased approximately 8 percent for each tenfold decrease in loading time. These investigations were all made at relatively low loading rates using conventional testing equipment.

Early high-speed tension tests on metals were made by Mann (7) in 1936 and Manjoine and Nadai (6) in 1940, using specially designed impact machines, at strain rates up to 1,000 inches per inch per second.

Later investigators, using testing equipment especially designed for high-speed testing (3), have found that rate of loading could have an important effect not only on yield point and ultimate strength, but also on elongation at yield and rupture, ductility, brittleness, and energy absorption capabilities of the material. Many materials were found to have critical rates of loading at which some mechanical property would change drastically (10). Rubbers, plastics, and other visco-elastic materials are particularly rate sensitive.

Problems of Dynamic Tensile Testing

There are a number of problems associated with dynamic tensile testing which require satisfactory solution if reliable information is to be obtained.

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[2] Underlined numbers in parentheses refer to Literature Cited at the end of this article.

Most of these problems exist in tensile testing at any rate of loading, but they become increasingly troublesome as the rate of loading increases.

Stress wave propagation.--When a material is loaded, either in service or in testing, one end is usually fixed in position, and a deforming force, tensile or compressive, is applied to the other end. This force initiates a stress at the point of loading, and this stress is propagated through the material at approximately the sonic velocity of that material. Some portion of this stress wave is reflected back from the fixed end, dependent on end conditions, causing the stress and resulting strain in the material to increase locally in small instantaneous increments. The magnitude of these localized jumps in strain is a function of the loading rate (8).

When the loading rate is very low in comparison to the sonic velocity in the material, the local strain is essentially uniform throughout the material; when the loading rate is high, strain is not uniform. As the loading rate becomes very high, a condition is reached where failure occurs at the loaded end of the material before any strain or force is transmitted to the fixed end.

The sonic velocity for a material is determined by the relationship (8)

$$C = \sqrt{\frac{E}{P}}$$

where C = sonic velocity, E = Young's modulus, and P = mass density.

Typical sonic velocities	Feet per second
Steel	16,400
Aluminum	16,800
Polystyrene	6,100
Fibers	3,000 to 18,000

The rate at which the strain wave reflections occur is a function of the sonic velocity and the length of the specimen.

$$f = \frac{C}{2\ L}$$

where f is the frequency of wave reflection in cycles per second, C is the sonic velocity in inches per second, and L is the specimen length in inches. Thus, in an infinitely long specimen no reflection will occur, while in a very short specimen the frequency will be high. In the conventional method of tensile testing, the force is applied at one end of the specimen and the measurement is taken at the opposite end. It is evident that the measurement obtained will not truly represent the conditions existing in the specimen if the loading rate is high enough to make strain rate propagation significant. However, in many cases, only the gross behavior of the material is of interest.

With paperboard materials it is possible to adjust the specimen length so that the period of the strain wave reflections is very short compared to the period of loading. In this case, the wave propagation effects should appear as superimposed oscillations on the load–deformation curve. Thus both the wave propagation effects and the gross behavior of the material may be seen. The localized instantaneous strains could be determined by mounting small resistance strain gages on the specimen at various places, but with paperboard specimens such a procedure would seriously alter the characteristics of the specimen. Therefore, use of the conventional technique for tensile testing, with the force gage in series with the specimen, appears to be the most feasible method for the range of loading rates of interest to this investigation, provided that any stress wave effects may be properly identified and evaluated.

Achievement of desired loading condition.––The most apparent problem is that of achieving the desired condition of loading. At lower, conventional rates of testing, machine design has become standardized and the machines are highly refined and capable of providing precisely the test condition desired. However, these machines utilize revolving screws and are not capable of producing high rates of loading.

Many different methods have been used to produce high loading rates. The simplest class of machines uses gravity as the source of energy, either in the form of falling weights, guided or in free fall, or as a pendulum, such as used for the Charpy and Izod impact tests. These devices, although simple mechanically, usually have, limited ranges of loading rates, and become unwieldy and cumbersome if impact velocities and input energies are large. Another machine uses a rotating flywheel as the source of energy. The flywheel is brought to the desired peripheral velocity before the specimen is engaged by a movable claw. The flywheel can provide a large amount of available energy and a constant rate of loading which can be precisely controlled.

Still another basic type of machine uses a piston to produce the loading force. The piston may be actuated by pneumatic, hydraulic, or explosive techniques. A number of commercial models are available. This type of machine is relatively compact and easy to operate, but loading rates are difficult to regulate precisely and a constant rate of loading during test cannot usually be obtained.

One other general class of machine uses a flying projectile to produce the loading. The projectile itself may be propelled by any of the techniques previously mentioned, or by a slingshot device. These machines can produce very high rates of loading, but are space consuming, cumbersome, and potentially dangerous to operate.

All of these machines except the piston type produce impact loading with the resultant shock excitation that often becomes troublesome and obscures the data. The piston machines, which initiate loading from a static position, avoid this problem but introduce other problems of varying loading rates due to the very rapid acceleration of substantial masses, and the accompanying undesirable inertial effects.

Clamping and specimen configuration.--A problem encountered in tensile testing at any rate of loading concerns the choice of a suitable specimen configuration and the mounting of the specimen in the testing device. Ideally, the specimen would be symmetrical and straight sided, and would be held by grips which would not apply excessive crushing forces, permit slippage, or produce uneven stress and strain distribution. Since most gripping methods do produce one or more of these undesirable effects, a dumbbell-shaped specimen is often used to prevent specimen failures at the grips and to reduce slippage and crushing by providing a greater gripping area. This technique, however, results in a gage length in the necked-down portion considerably shorter than specimen length and introduces uncertainties as to effective gage length and actual strain rate across the gage length. Furthermore, some externally applied device, such as an extensometer, is then necessary for the measurement of strain, Such a device cannot be used in high-speed testing due to its inertial effects and loading on the specimen.

A number of considerations affect the choice of a suitable gage length. As a primary consideration, the gage length should have some reasonable relation to the size of the material in typical usage. Values which best characterize the gross behavior of the material will be obtained by relatively long gage lengths which approach this limit. Long gage lengths also minimize errors due to grip slippage and slip and deformation in the test machine. However, a longer gage length will require a proportionately higher rate of loading to produce an equivalent strain rate since

$$R = \frac{V}{L}$$

where $\underline{R}$ equals the strain rate in inches per inch per second, $\underline{V}$ represents the loading head velocity in inches per second, and $\underline{L}$ is the specimen length in inches.

Stress wave propagation effects must also be considered when the strain rate is very high, as discussed previously. Thus, choice of gage length is necessarily a compromise between opposing factors.

Standard test methods (1, 11) for tensile breaking strength of paper and paperboard recommend straight-sided specimens with a gage length of 180 mm. (7.1 inches) and a width between 0.5 and 2.0 inches. Other researchers (9, 13) have varying opinions about the effect of specimen configuration on measured stress-strain characteristics.

Response of instrumentation.--A problem which frequently does not receive proper attention concerns the response characteristics of the instrumentation. This problem increases in severity directly as the rate of testing increases and the duration of the test decreases. To obtain data of an acceptable degree of accuracy and resolution, the instrumentation must be able to respond to changes which occur in very short periods of time. Many transducers and recording devices have moving mechanical elements that are limited in their response by inertial effects and distort the recorded data from the true values. Ballou and Roetling (2) have shown theoretically the effect of instrumentation response on high-speed stress-strain data. To record high rate tensile data adequately the instrumentation system must have a uniform response over a bandwidth extending from zero to several thousand cycles per second, the upper minimum limit dependent on the rate of loading. It should be noted that deficiencies in the instrumentation will usually cause recorded values to be lower than true values.

An associated problem is that of "ringing." Ringing is the resonant response of a transducer at its natural frequency and is caused by shock excitation of the transducer due to impact loading. Such spurious oscillations may obscure the data or mask stress wave effects. This problem is serious and not easily overcome, since it is very difficult to construct transducers with good response characteristics whose natural frequencies are sufficiently high.

Method and Equipment Used

In the selection of a suitable type of machine for dynamic tension tests of paperboard, the advantages and limitations of each type of machine were considered in relation to the desired test conditions, which are:

1. Wide range of loading rates.
2. Constant velocity of loading head to produce a constant rate of strain. This requires a very “stiff” machine in which the available kinetic energy is much larger than the energy required to rupture the specimen, and loading of the specimen does not cause the rate of loading to decrease.

Flywheel Testing Machine

The flywheel machine appears to best meet the requirements and has several distinct advantages. Loading rates can be varied over a wide range, from 100 to 3,000 inches per inch per minute. The loading rate may be controlled quite precisely by varying the rotational velocity of the flywheel, and the constant rate of strain may be obtained, since a large amount of kinetic energy can be stored in the flywheel.

The loading device consists of a flywheel in the form of a cast steel cylinder, a retractable claw fitted on the flywheel, and a rigid frame to support the specimen as shown in figure 1.

The cylinder is filled with concrete to increase its mass and has a total weight of 370 pounds. The effective radius at the engagement point on the claw is 9.5 inches. The flywheel is driven by a variable speed electric motor (3/4 horsepower) which is coupled to the flywheel with pulleys and V–belt. The belt is operated without tension to eliminate vibration transmission and force pulsations from the motor. Thus, due to rotational inertia, the flywheel obtains a very uniform velocity which may be precisely regulated. The motor also provides dynamic braking to stop the flywheel quickly after the test is completed.

The forked claw (fig. 2) pivots on a heavy pin and is balanced dynamically. The claw is manually set to the retracted position. The flywheel is brought to the desired velocity and the claw is released in the last revolution before impact. An electric solenoid momentarily engages the hinged bar which retains the claw in the retracted position. Removal of this bar allows an internal spring to move the claw into operating position so that it can engage the specimen.

The specimen is supported vertically in a rigid frame which is adjustable to permit variation of specimen gage length from 3 to 12 inches. The specimen is suspended from the force gage (fig 2), which is mounted on the crossmember of the frame. This crossmember is of laminated wood to damp any shock–induced vibrations.

Specimen Clamps

As previously noted, one of the major problems of tensile testing is that of properly gripping and loading the specimen. The problem is especially troublesome in this case, due both to the dynamic nature of the test and to the characteristics of the material being tested.

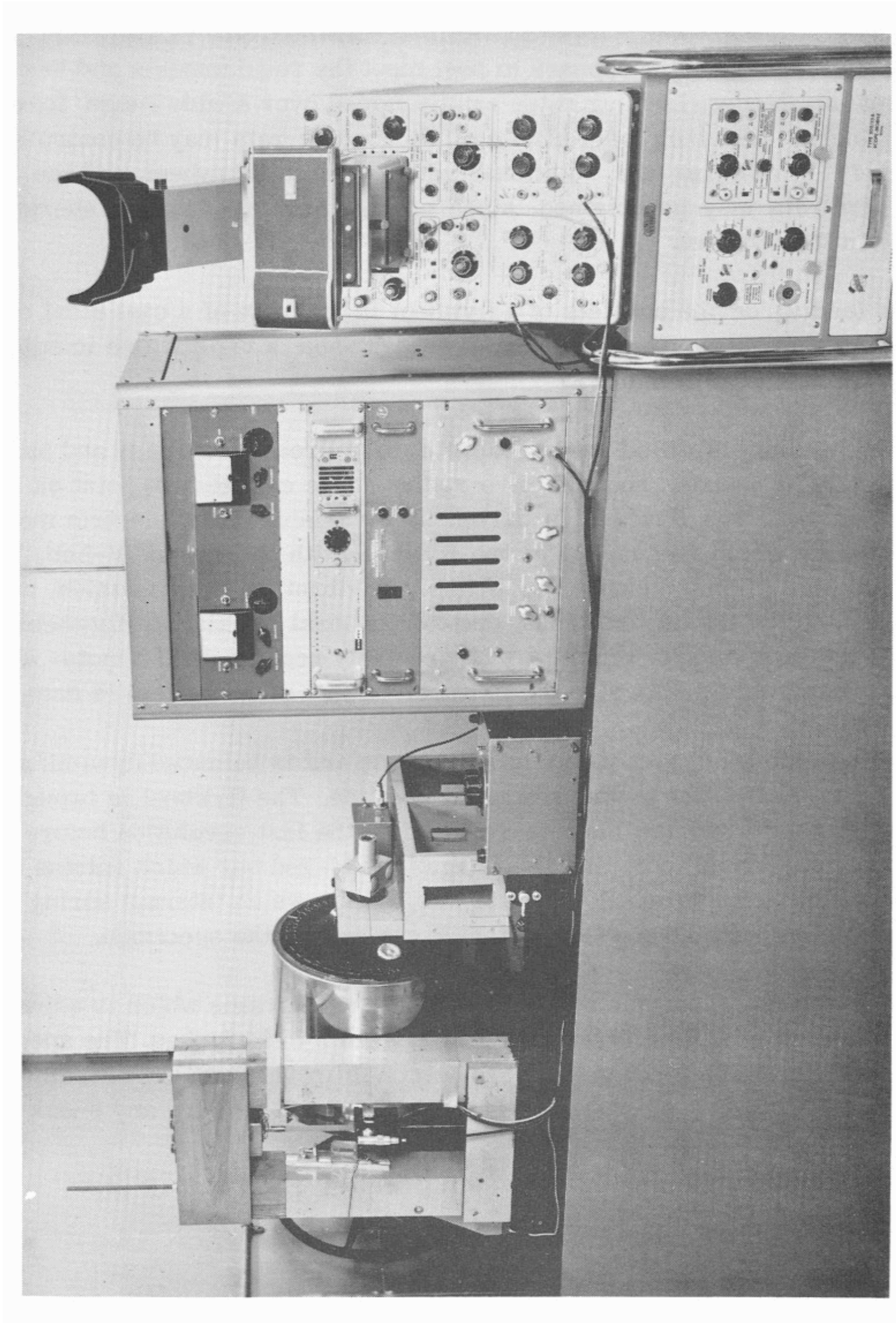

Figure 1.--Overall view of dynamic tensile testing equipment.

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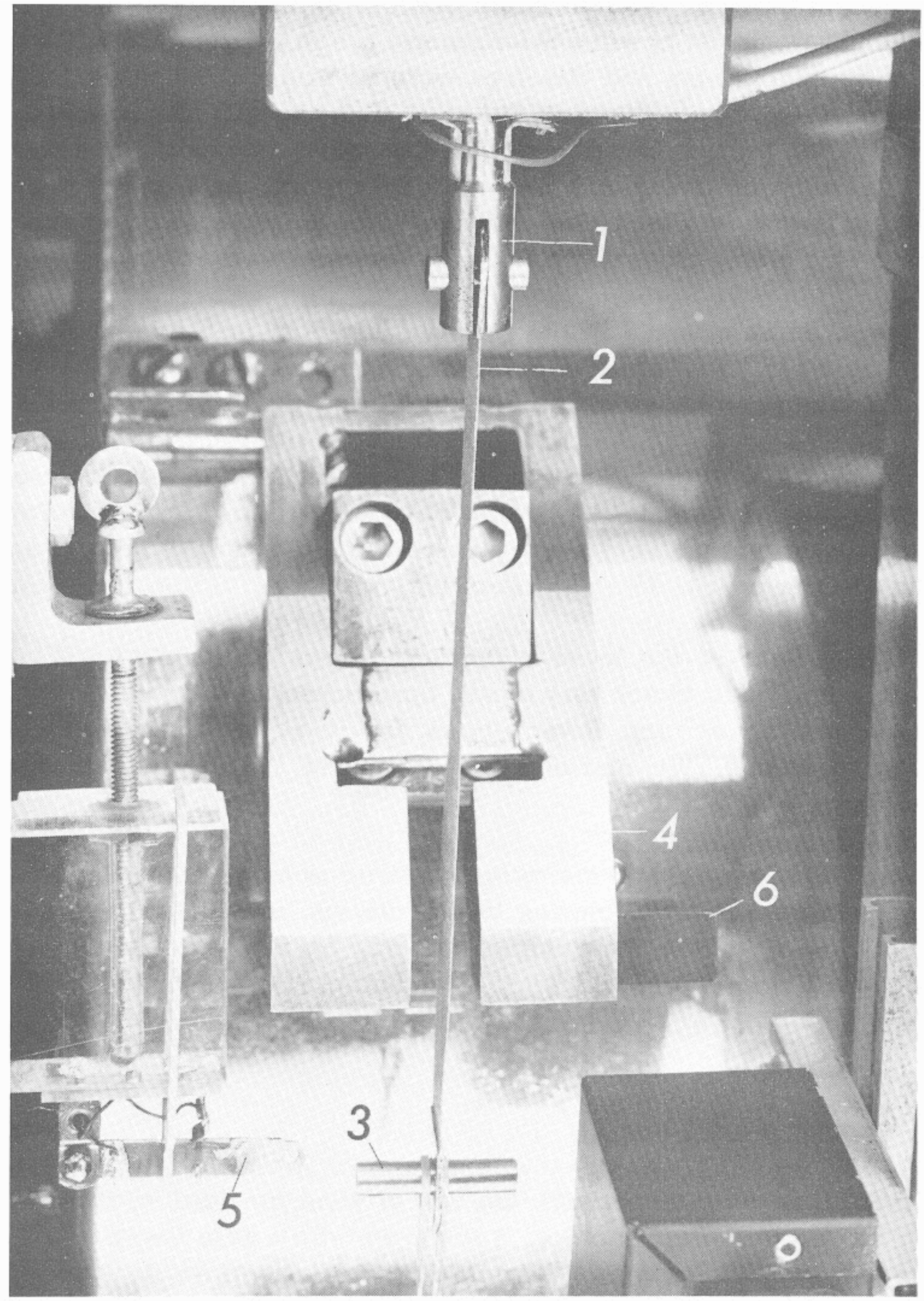

Figure 2.--View through loading frame showing (1) force gage, (2) specimen, (3) impact bar, (4) forked claw, (5) oscilloscope trigger, and (6) photo cell shutter.

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The clamping system used is unique and was developed particularly for this work, While it would not be suitable for general use in tensile testing, it provides minimum inertial effects and slip–free uniform loading of the specimen. Each clamp consists of a pair of small flat steel plates as shown in figure 2. One of these plates is bonded to each side of the end of the specimen with sodium silicate, an adhesive commonly used with fiberboard. Each clamp plate has a 0.25–inch hole that is alined with a similar sized hole punched in the end of the specimen. This allows close control of gage length.

The specimen is mounted in the testing machine by means of steel pins 0.25 inch in diameter. The upper end of the specimen is pinned to the specially designed force gage. A steel pin 1.25 inch in length, is inserted in the lower clamp to serve as the impact bar (fig. 2) that is engaged by the claw. Proper alinement of the specimen and impact bar is easily accomplished due to the pinned ends, and is maintained by means of an elastic loop attached to the lower pin. The loop provides a very slight pretension (0.25 pound) to remove any curl from the specimen.

The total weight of the lower clamp and impact bar is only 0.023 pound so that their inertial effects are very small. Upon impact and rupture ,of the specimen, the impact bar and lower clamp are propelled several inches into a cushioned receptacle. The clamp plates are cut off the ruptured specimen and salvaged for reuse.

Although this method of clamping requires considerable preparation, it provides minimum inertial loading by the clamps, uniform slip–free loading, and easy alinement. This clamping system may be used with corrugated fiberboard specimens as well as with single and multiple layers of sheet material.

Specimen Configuration

This clamping system permits the use of straight–sided specimens. After some preliminary experimentation, a specimen with a gage length of 6.0 inches and a width of 0.75 inch was chosen (fig. 3). These dimensions are close to those recommended by ASTM and TAPPI. Specimens ranging from 3 to 12 inches in length were used in preliminary testing, but since no significant effect due to specimen length was noted, the 6.0–inch length was chosen as optimum.

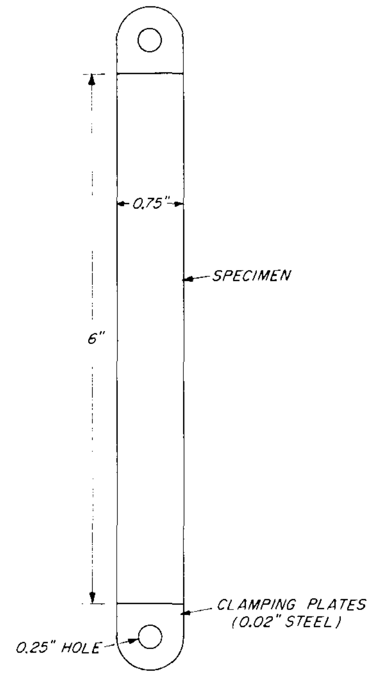

Figure 3.--Tension specimen and clamping plates.

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Instrumentation

The accurate measurement of impact velocity, force, and displacement is necessary for dynamic tensile testing. The methods and equipment used for the measurement of each of these quantities are shown in figures 1 and 4.

Impact Velocity Measurement

As previously noted, impact velocity is controlled by means of a variable speed motor which drives the flywheel. A photo-electric system is used to measure flywheel velocity. A small mirror is mounted on one end of the flywheel and a light source and photo tube are mounted in a small box adjacent. Once each revolution, a narrow beam of light is reflected into the phototube. This produces a sharp electrical pulse that is fed to an electronic time interval meter, which measures the time interval between successive pulses to within 10 microseconds. Since the radius of the impact point on the claw is determined by measurement, the equivalent linear impact velocity can be determined and preadjusted to within 1 percent of the desired value. The actual loading head velocity during a specimen test may also be computed from recorded time-displacement data.

Force Measurement

The tensile forces transmitted through the specimen are measured by a specially designed force gage which also serves as the upper specimen clamp as shown in figure 2. The force is measured by determining the strain in a tubular steel link. Four A-7 strain gages are used in a bridge circuit, with two gages mounted as active gages on a thin wall section of the steel tube, and the other two gages are used as passive temperature-compensating elements. The force gage has a maximum load rating of 250 pounds and a natural frequency of about 11,000 cycles per second. A bridge control box (fig. 4) provides a voltage source and parallel resistance reference calibration. Gage calibration sensitivity was calculated and checked by actual loading in a universal testing machine.

The output from the bridge control box is fed to a wide-band high gain d.c. preamplifier and then to one channel of a calibrated dual-beam oscilloscope.

Displacement Measurement

Since direct measurement of specimen elongation is not feasible either by use of electrical strain gages or by mechanical extensometers, an indirect method of measuring loading head displacement is used, which employs a light beam and a photo-voltaic cell. Determination of specimen elongation by measurement of loading head movement is permissible because of the unique clamping method that provides a rigid, slip-free coupling.

A collimated light beam is directed through an accurately measured rectangular aperture onto' the face of a silicon photo-voltaic cell. The output voltage of this cell is directly proportional to the area of the cell exposed to light. A small vane, which acts as a shutter (fig. 2), is attached to the moving claw and passes very closely in front of the aperture plate, reducing the exposed area of the silicon cell as the claw moves by. The aperture size and position are adjusted so that the entire loading and elongation of the specimen to rupture occurs within the limits of the aperture. The output signal from the silicon cell is fed to the second channel of the calibrated dual-beam oscilloscope, producing a displacement versus time record. Since a common time base is used for both beams of the oscilloscope, the specimen elongation at any instant of time may be determined and related to the tensile force applied at that instant.

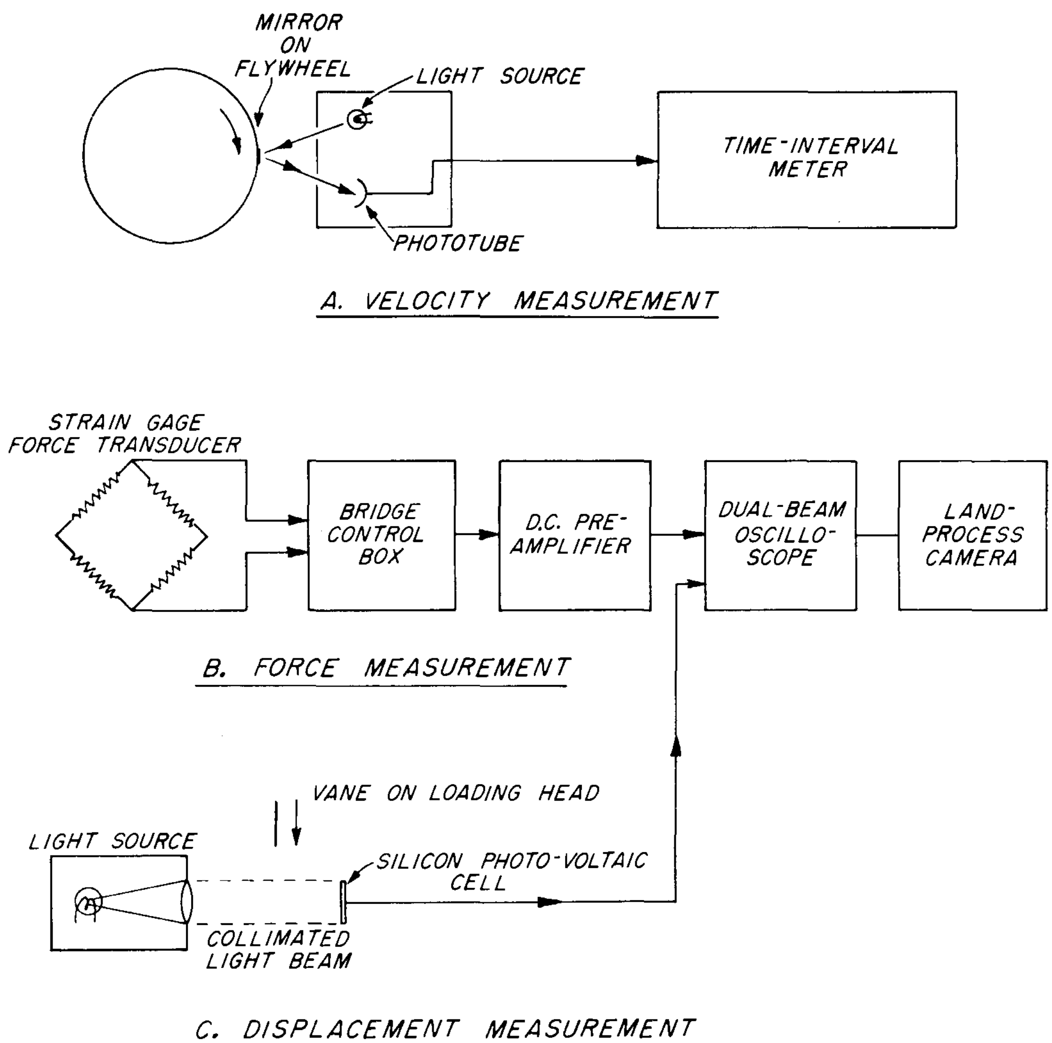

Figure 4.--Block diagram of instrumentation.

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The slope of the displacement–time trace gives the instantaneous velocity at any instant during the test. The displacement gage is self calibrating, since the output signal is recorded at both the fully open and fully closed positions of the shutter. Measurements can be made to 0.002–inch at any loading rate with a 0.20–inch–wide aperture. Greater resolution can be obtained with narrower apertures.

Photographic Recording of Data

Data records are obtained ,by photographing the oscilloscope trace with a Land process camera. The oscilloscope is set for single sweep operation and is triggered by an external signal just prior to engagement of the claw and initiation of the test. The trigger signal is provided by a small switch (fig. 2) which is opened by mechanical action of the claw, opening the circuit to a small battery. The position of the switch is adjustable to provide proper timing at all impact velocities.

Experimental Procedure

Materials Tested

Two different paperboards were tested during the development of this equipment. One was a kraft linerboard averaging 0.0077 inch in thickness with a nominal weight of 26 pounds per 1,000 square feet. The other paper was also a kraft linerboard, with an average thickness of 0.0127 inch and a nominal weight of 42 pounds per 1,000 square feet. These paperboards have been tested and used at the Forest Products Laboratory for experimental production of corrugated fiberboard, so information on their physical properties was available. Tests were made on each paper in both the machine direction and cross–machine direction of the sheet.

Specimen Preparation

Sheets were cut from rolls of specimen material20 inches wide. These sheets were then stacked and cut to 8–inch squares with the outer 2 inches in width of each sheet trimmed and discarded. Specimens were cut to size on a 19–inch paper trimmer. This method of cutting produced better, more uniform specimens than several other methods of cutting which were tried. The specimens were then punched 6.75 inch center to center, as shown in figure 3. The metal clamping plates were bonded to the specimen with the sodium silicate adhesive, and were kept in alinement with the punched holes, which defined the gage length, by means of an alinement pin and spring clamps until the adhesive had hardened. Measurements of width and thickness were made on each individual specimen. All specimens were preconditioned a minimum of 24 hours at 80° F. and 36 percent relative humidity, and then conditioned at least 48 hours at 73° F. and 50 percent relative humidity before testing. All tests were conducted at this condition.

Testing of Specimens

Tension tests were made at six different rates of strain: 0.0033, 0.833, 200, 750, 1,500, and 3,000 inches per inch per minute. Tests performed at the lowest two rates were made on a conventional mechanical testing machine using revolving screws, and represent the lowest and highest rates obtainable on this machine with the gage length used. Tests at the higher rates of strain were made on the dynamic tension testing equipment. Ten specimens of each material were tested at each test condition, making a total of approximately 240 specimens tested, for the preliminary data reported here.

The same specimen configuration and clamping system were used for testing on both machines. On the conventional testing machine, short pins were inserted through the specimen clamps and tightened in the machine clamps in such a manner that slippage could not occur. Autographic load-deformation curves were obtained for the specimens tested on this machine.

On the dynamic tension testing machine, the specimen was mounted as previously described, and the flywheel was adjusted to the desired velocity. Force gage calibration traces were prerecorded by the oscilloscope camera. The camera shutter was opened, the claw release was actuated to initiate the event, and the shutter was closed after rupture had occurred.

At the two highest rates of loading, excessive shock excitation and ringing of the force transducer were noted. It was found that this effect could be reduced by slipping 1/2-inch lengths of plastic tubing over the impact bar. Tests showed that the plastic did not compress enough to have any detectable effect on impact velocity or specimen deformation.

Data and Results

Since the data available were obtained during the construction and development of this testing equipment and are limited and preliminary in nature, a detailed statistical analysis has not been made. However, a number of test results are of interest.

Table 1.--Dynamic tensile characteristics determined on two paperboard[1]

Material	Strain rate	Grain direction	Maximum load	Maximum load	Ultimate stress	Maximum elongation	Ultimate strain
	Inch per inch per minute		Pounds	Pounds per inch of width	P.s.i.	Inch	Percent
Kraft liner 42-pound basis weight	0.033	MD	61.87	82.4	6,950	0.100	1.67
		CMD	29.71	38.8	3,050	.197	3.28
	.833	MD	71.60	95.4	7,580	.107	1.79
		CMD	34.52	45.1	3,560	.186	3.10
	200	MD	88.03	117.3	9,170	.098	1.64
		CMD	42.26	56.3	4,320	.169	2.83
	750	MD	95.07	126.5	9,990	.094	1.56
		CMD	43.31	57.7	4,460	.145	2.42
	1,500	MD	98.88	132.0	10,410	.092	1.53
		CMD	45.07	60.2	4,610	.146	2.44
	3,000	MD	103.60	137.9	10,820	.100	1.66
		CMD	46.31	61.8	4,740	.139	2.32
Kraft liner 26-pound basis weight	.033	MD	35.75	47.7	6,090	.091	1.52
		CMD	16.41	21.6	2,760	.220	3.66
	.833	MD	41.77	55.7	7,140	.092	1.53
		CMD	18.96	24.9	3,130	.208	3.46
	200	MD	49.9	67.3	8,850	.086	1.43
		CMD	21.0	28.6	3,700	.149	2.48
	750	MD	56.3	75.1	9,550	.093	1.55
		CMD	21.37	29.4	3,800	.149	2.49
	1,500	MD	55.10	73.5	9,450	.086	1.43
		CMD	22.50	30.3	3,990	.165	2.75
	3,000	MD	57.09	76.8	9,820	.077	1.26
		CMD	23.25	31.9	4,200	.154	2.57

[1]Each value represents an average of ten specimens except for a few values with less than ten specimens.

A summary of test data is given in table 1. Each value given represents an average of ten tests, except in a few cases where slightly less than ten clean ruptures were obtained. Any test where the rupture occurred in the clamp or within 1/4 inch of the clamp was rejected, although it was found that the ultimate strength and elongation for these specimens usually were equal to those values obtained with clean breaks, All but a few specimens ruptured in the active gage length in a seemingly random manner. The clamping system used was found to be very satisfactory, except with a 69-pound kraft linerboard that delaminated within the clamp area.

The nature of the specimen failure was definitely related to the rate of loading. At lower rates of loading an elastic recoil effect was noted, in which multiple compressive buckling of the specimen occurred after the initial single tensile failure. At higher loading rates, the compressive buckling did not occur and clean single fractures were obtained. At a strain rate of 3,000 inches per inch per minute the specimen material appeared to be brittle, shattering and producing multiple fractures.

A typical data record is shown in figure 5. The upper trace displays the force-time relationship, and the lower trace shows the displacement-time relationship of the loading head. A pair of force calibration traces also are recorded.

Some evidence of shock excited ringing may be seen on the force record. The degree of such excitation varied with the loading velocity. An experiment was conducted to determine whether these oscillations were due to stress wave propagation effects or solely to ringing of the transducer. Specimens of similar material, but varying in length from 3 to 12 inches, were tested at a fixed rate of loading. If the oscillatory responses were caused by stress wave propagation, the frequency of the responses would vary inversely to the length of the specimen. No such relationship was found, indicating that the oscillatory responses were only caused by transducer ringing. Furthermore, the frequencies observed were all about 11,000 cycles per second, which is the resonant frequency of the transducer. Since

$$f = \frac{C}{2\,L}$$

where $\underline{C}$ equals a sonic velocity of 120,000 inches per second, and $\underline{L}$ is the specimen length in inches; the frequency due to stress wave reflections should have varied from 5,000 to 20,000 cycles.

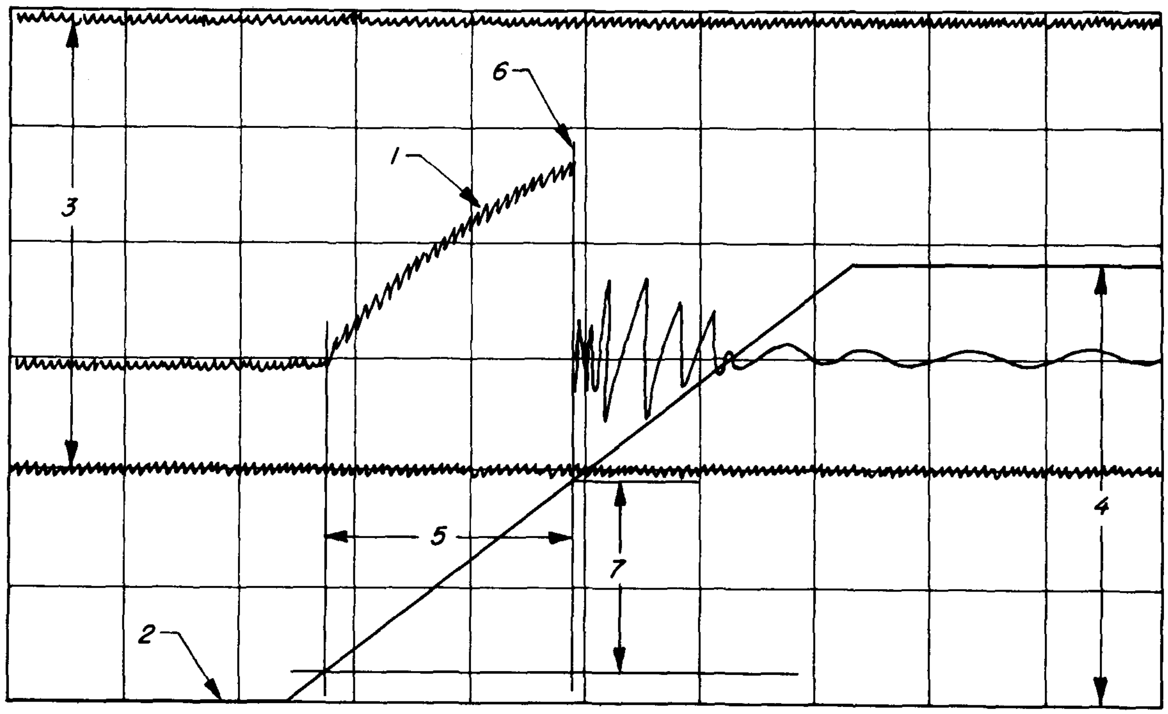

Figure 5.--Typical data record from oscilloscope trace. Loading rate = 75 inches per second (1) force-time trace; (2) displacement-time trace; (3) force calibration (134.6 lb.); (4) displacement calibration (.200 in.); (5) time duration of loading (1.19 millisecond); (6) rupture point; (7) elongation at rupture (.0906 in.).

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Since the highest impact velocity likely to be encountered in service is about 300 inches per second, as compared to a calculated sonic velocity for kraft paper of about 120,000 inches per second, it seems reasonable that stress wave propagation effects would not be significant.

The effect of strain rate on ultimate tensile strength is shown in figures 6 and 7. Tensile strength increases as the loading rate increases, approximately as a logarithmic function of the loading rate, following the relationship

$$S_v = S_1 + K \log \frac{V_v}{V_1}$$

where S_V = ultimate stress at any specified rate of loading in pounds per square inch, S_1 = ultimate stress at a measured rate of loading, K = material constant, V_V = specified rate of loading (inches per inch per minute), and V_1 = rate of loading (inches per inch per minute) at which S_1 was determined.

The effect of strain rate on the ultimate strain characteristics of the kraft liners is shown in figure 8. Increase in strain rate had no apparent effect on ultimate strain in the machine direction of the paper, but produced a definite decrease in ultimate strain in the cross-machine direction.

Variability of the test data is shown by the vertical lines in figures 6 and 7, which show the range of the data at each rate of strain. This degree of variability appears to be typical of the materials tested.

The two kraft liners show very similar characteristics, although they were produced by different manufacturers and differ greatly in weight. Comparisons between sheet materials can best be made in terms of strength per inch of width, as shown in figure 9, since the thickness of the sheet, which affects stress values, is dependent on other manufacturing variables besides basis weight. The effect of variations in density is eliminated by this method of comparison.

Conclusions

Although the data reported are preliminary since they were obtained during the development of the testing equipment, a number of conclusions and recommendations can be made as a result of the work completed.

Paperboards used for the manufacture of corrugated fiberboard containers are moderately rate sensitive. The ultimate tensile strength increases approximately as a logarithmic function of the loading rate, following the relationship

$$S = S_1 + K \log \frac{V}{V_1}$$

Ultimate strain is not greatly affected by rate of loading. Material failure appears to be controlled by strain limitations rather than by stress. Each paper has a characteristic strain limit at which fiber separation occurs.

Material strength values have little meaning if loading rates are not specified. Comparisons between materials cannot be accurately made, even at "static" rates of testing, unless the strain rate is standardized or corrections are made for differences in strain rates.

The test method and equipment used have been quite satisfactory, although greater sensitivity of the force transducer would be desirable. However, due to the time and expense involved in dynamic high rate testing, it would be highly advantageous to be able to compute dynamic characteristics from data obtained on conventional testing machines. On the basis of this work, it appears that mechanical properties at high strain rates can be reasonably predicted from static data, once the strain rate sensitivity of the material has been determined.

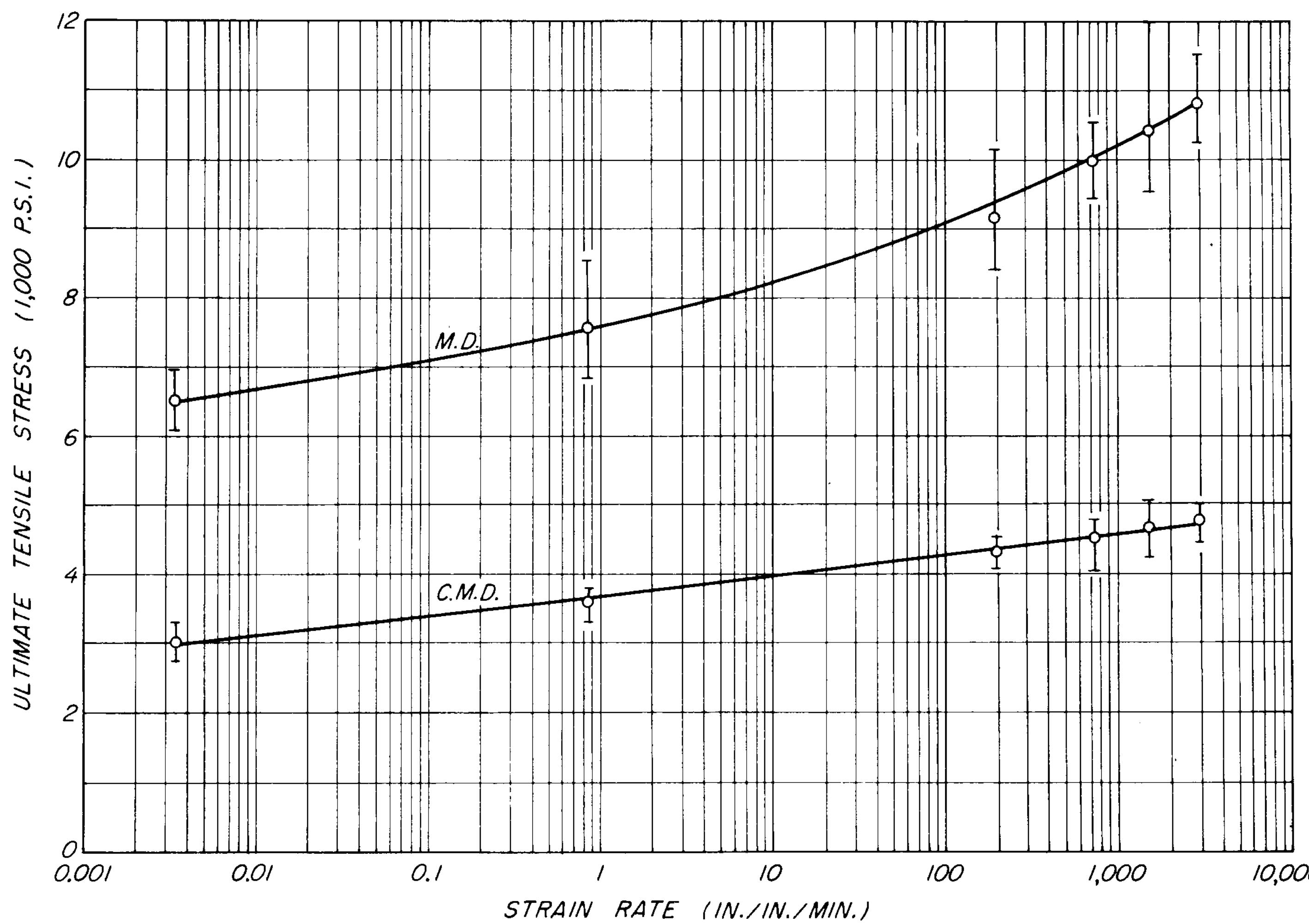

Figure 6.--Dynamic tensile characteristics of 42-pound kraft linerboard in the machine and cross-machine directions.

M 124 672

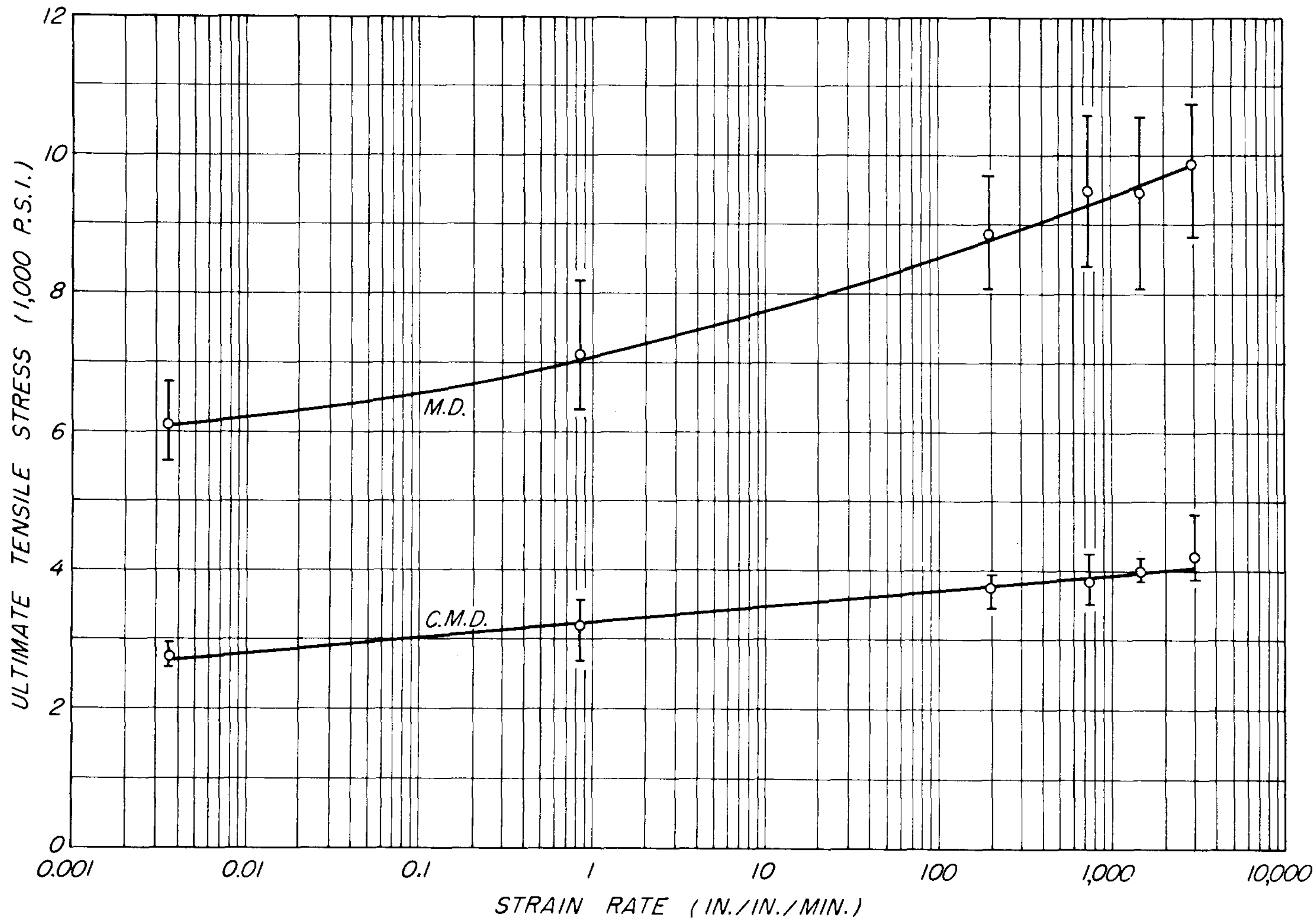

Figure 7. --Dynamic tensile characteristics of 26-pound kraft linerboard in the machine and cross-machine directions.

M 124 673

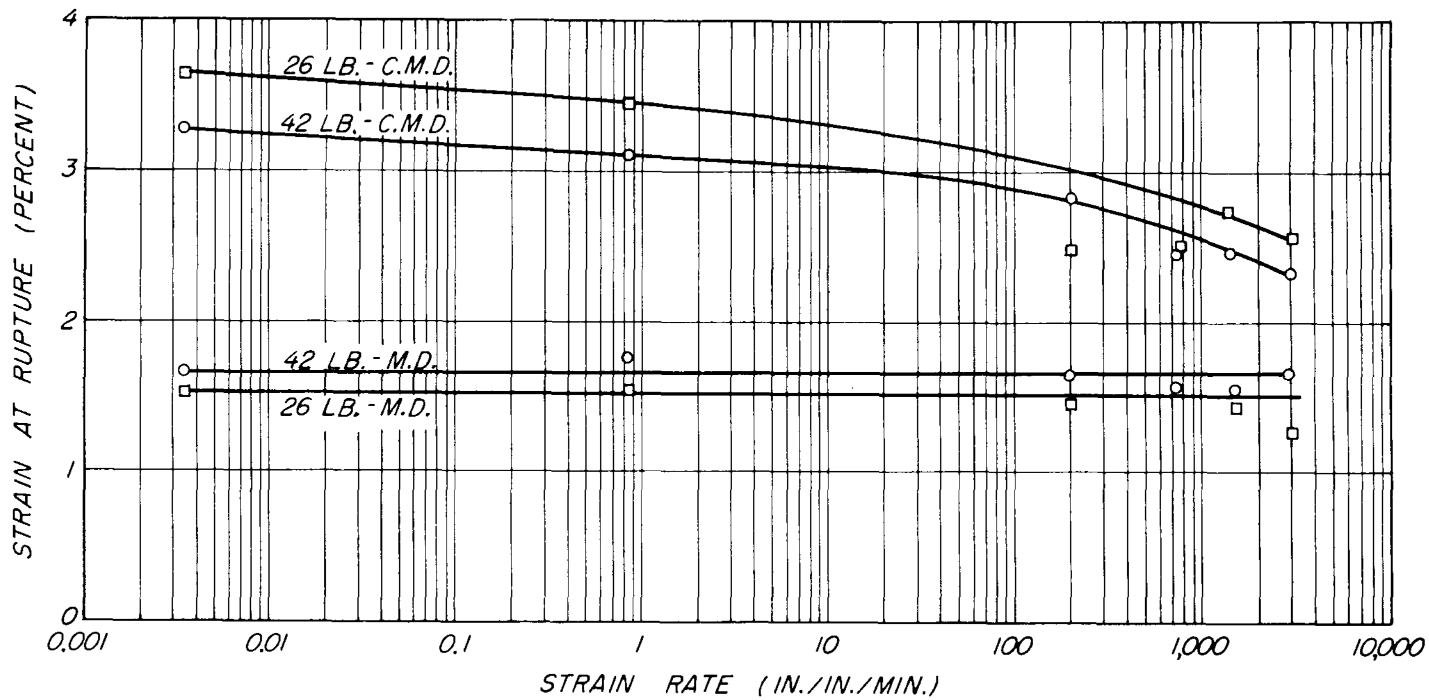

Figure 8--Effect of strain rate on strain at rupture for two weights of kraft linerboard.

M 124 674

FPL-081

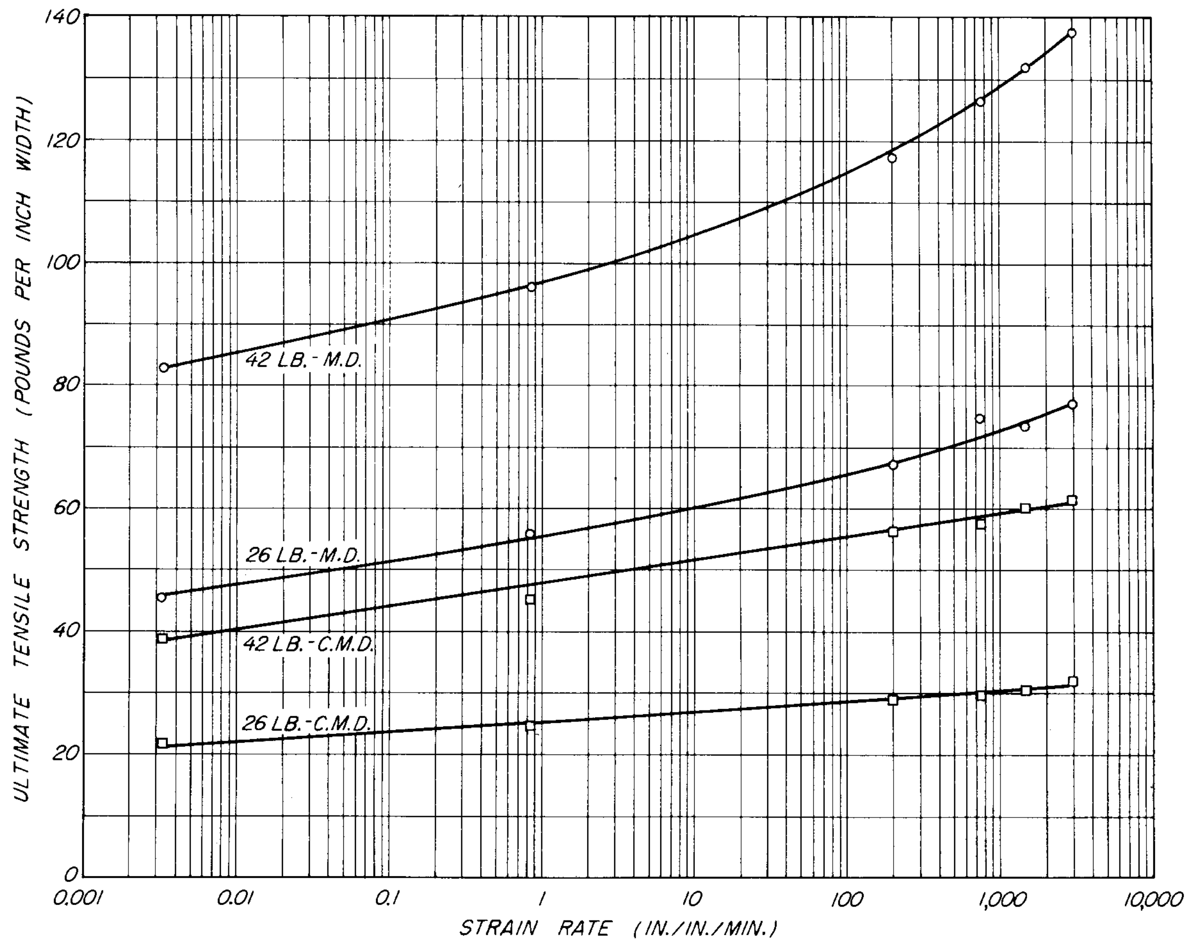

Figure 9.--Comparative strength characteristics for two weights of kraft linerboard.

M 124 675

FPL-081

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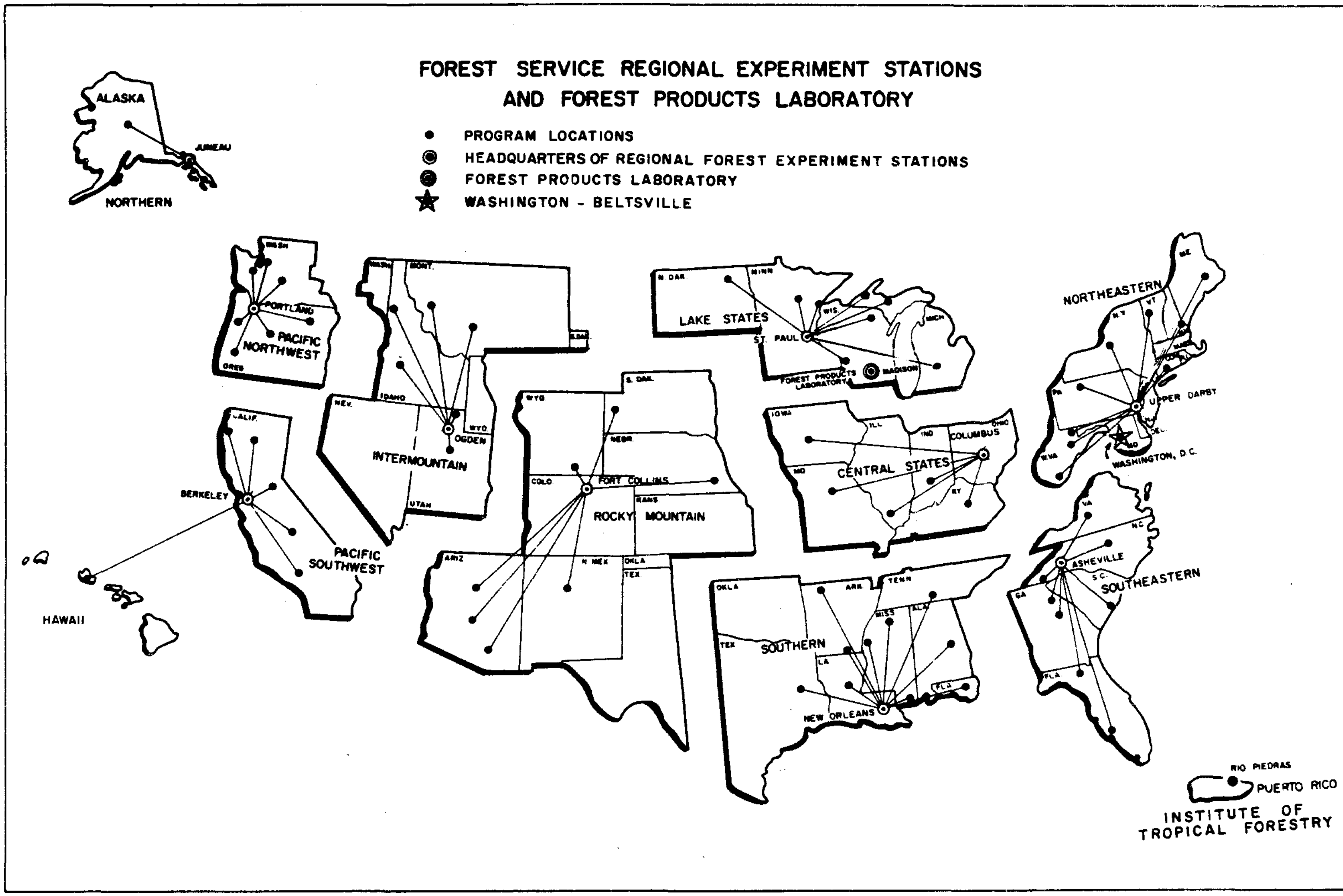

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