STRENGTH AND RELATED PROPERTIES OF FOREST PRODUCTS LABORATORY LAMINATED PAPER PLASTIC (PAPREG) AT NORMAL TEMPERATURE

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STRENGTH AND RELATED PROPERTIES OF FOREST PRODUCTS LABORATORY LAMINATED PAPER PLASTIC (PAPREG)[1] AT NORMAL TEMPERATURE[2]

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Summary

This report presents the results of a series of tests made at ordinary room temperature and humidity to determine certain of the physical and mechanical properties of the high-tensile paper-base plastic laminate termed "papreg" developed by the Forest Products Laboratory.

The fore part of this report presents the results of a comprehensive series of tests to determine some of the basic engineering properties of a standardized product adopted during the development work. The study was made to obtain strength data for design purposes, to ascertain properties in relation to the fiber direction, and to make available the range of values that may be expected from stock sheet materials of a specific grade.

Although satisfactory laminates were produced from a number of species processed by the sulfate and sulfite pulping methods, evaluations for basic properties, made at the Laboratory, were confined to a standardized papreg made from black spruce Mitscherlich-type sulfite paper impregnated with a hot-press phenolic resin. The base materials, pulp and resin, were obtained commercially. Although the material tested was produced under laboratory-controlled conditions, its properties are believed to be representative of those of products of similar composition when produced by commercial laminators employing the same conditions and manufacturing technique. The study is believed to be sufficiently comprehensive to indicate the degree of uniformity obtainable, in low-pressure laminates of this type, through reasonable control of manufacturing procedure.

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[1] This report is one of a series prepared by the Forest Products Laboratory to aid the Nation's war program. Results here reported supersede the preliminary data presented in the previous report of the same title and number.

[2] Separate reports presenting the effect of abnormal temperature and other service-condition factors affecting the strength of papreg are available in a series of reports numbered 1521 to 1521-C, inclusive.

The tests included tension, compression, flexure, bearing, shear, hardness, loss of weight on drying, and water absorption of 1/8-inch papreg; and compression, flexure, shear, and impact strength of 1/2-inch papreg.

The appendix of this report presents data on interlaminar strength, column strength, abrasion, linear thermal expansion, flammability, Poisson's ratios, and directional properties of papreg. The data in the appendix were obtained from a limited number of tests and for that reason are indicative only.

The investigations provide a measure of the isotropy of papreg, and show that the strength values of the laminates depend upon the orientation of the predominant direction of fibers in the constituent sheets of paper. The investigations also show that cross-laminated papreg is essentially isotropic in the plane of the laminations and, to a certain degree, has strength properties intermediate between those for the two principal directions of the parallel-laminated type. It is concluded that the material shows reasonable structural possibilities in all essential properties with, perhaps, the exceptions of impact resistance, compressive yield strength, and ductility. Papreg has a smooth hard surface and good resistance to abrasion and fire and has a specific gravity of about 1.4 at a resin content of about 36 percent.

Introduction

Paper-making experiments have shown that papers suitable for high-strength laminates may differ greatly in minimum tensile strength between the machine direction (lengthwise, 10,000 pounds per square inch) and the crosswise direction of the sheet (4,000 pounds per square inch). This difference in properties is reflected in the strength of papreg, which may be made with the machine direction of all sheets in the same direction (parallel laminated), with some of the sheets oriented at right angles to others (cross laminated), or with the orientation of sheets at various angles. In this series of tests, the properties were determined largely for both parallel-laminated and cross-laminated material in the two principal directions, lengthwise and crosswise; that is, parallel and perpendicular to the machine direction of the paper when parallel laminated, and parallel and perpendicular to one edge of a panel when cross laminated.

Test Material

The base paper was made on the Laboratory paper machine from a commercial unbleached black spruce, Mitscherlich type, sulfite pulp. The thickness of this paper was approximately 2.5 mils. The paper was impregnated with a thermosetting phenolic resin. The resin content was 36.3 percent, based on weight of treated paper, and the volatile content was 4.5 percent.

The impregnated paper was molded to form parallel-laminated and cross-laminated flat panels, approximately 12 inches square and 1/8 or 1/2 inch in thickness. In making the parallel-laminated panels, the machine direction (fiber grain) of each lamination was placed parallel to that of adjacent laminations. The cross-laminated material was assembled so that the machine direction (fiber grain) of each lamination was at right angles to that of the adjacent laminations. Each of the 1/8- and 1/2-inch panels was molded from approximately 70 and 280 sheets of treated paper, respectively, and pressed for 12 and 25 minutes, respectively, at 250 pounds per square inch. The temperature of the hot press platens was 163° C. (325° F.). The panels were removed from the press immediately after pressing and allowed to cool in air at room temperature. The material is identified as "Improved Standard - June 1943."

Approximately 200 panels, formed and processed in this way, were manufactured for test purposes and stored under normal room temperatures and humidities. These panels were comprised of 4 groups as follows:

Group I - Parallel laminated, nominal 1/8 inch thick,
Group II - Cross laminated, nominal 1/8 inch thick,
Group III - Parallel laminated, nominal 1/2 inch thick,
Group IV - Cross laminated, nominal 1/2 inch thick.

Panels were selected from the different groups for the tests covered in this report. Sixteen panels were taken from group I, 8 from group II, 10 from group III, and 8 from group IV. Each of the selected panels was trimmed to approximately 11 inches square before cutting test specimens.

Preparation of Test Specimens

The location and direction of test specimens with respect to the trimmed edges of the panels before machining are indicated in the specimen cutting diagram, figure 1. Two lengthwise and two crosswise specimens were taken from each panel for all strength tests except for the flatwise and edgewise flexure tests of the 1/2-inch material. For these tests, only one lengthwise and one crosswise specimen was taken from each panel.

The specimens were machined with high-speed steel tools in such a manner as to be virtually free from tool marks or evidence of overheating, and were not otherwise finished. The type and dimensions of specimens conformed to L-P-406, Federal Specifications for Plastics, Organic, General Specifications (Methods of Tests) December 9, 1942.

Conditioning of Specimens

All specimens for strength determinations were conditioned at 24° C. (75° F.) and 50 percent relative humidity prior to testing. Nominal 1/8-inch specimens were conditioned for at least 48 hours and nominal 1/2-inch specimens for at least 96 hours. The majority of specimens were conditioned for several days longer than the minimum conditioning time, prior to test.

Conditioned specimens were placed in an air-tight metal container when removed from the conditioning room, a few at a time, for testing. Except for the few minutes required to weigh and measure each specimen, specimens were not otherwise exposed to test-room conditions until placed in test position.

All preconditioned specimens were tested at normal room temperature 24° ± 2.8° C. (75° ± 5° F.) and humidity (40 ± 5 percent relative humidity).

Testing Procedure

Except where otherwise noted, properties of papreg here reported were obtained from specimens tested in accordance with Federal Specification L-P-406. Tension, compression, flexure, bearing, impact, and modulus-of-rigidity tests were conducted as hereafter described.

Tension

Tensile specimens were tested in self-alining Templin grips in a motor-driven, 10,000-pound capacity, universal testing machine. The machine was operated at a no-load speed of 0.049 inch per minute while taking load-elongation data up to approximately 75 percent of ultimate load, and then increased to 0.157 inch per minute and maintained at this rate until failure. Two-inch gage length extensometers equipped with a spiral-staff type 0.0001-inch dial were used to measure elongations. A separable nonaveraging (punch-type) extensometer was used on the parallel-laminated crosswise specimens, and an averaging nonseparable (knife-edge) type was used on the parallel-laminated lengthwise and cross-laminated specimens.

Compression

Edgewise ultimates of the 1/8-inch papreg were determined on specimens 1 inch wide by 1/2 inch long. To overcome the difficulty in placing such a small specimen in position to assure axial loading, two specimens placed 1 inch apart and parallel to each other were centered under a spherical loading head by means of a jig, and loaded simultaneously. The testing machine was operated at a no-load speed of 0.023 inch per minute. All other compressive properties of the 1/8-inch papreg were obtained by testing individual specimens, each 1 inch wide by 4 inches long, as laterally supported columns in the apparatus shown in figure 2. The tests were conducted on a 10,000-pound-capacity hydraulic testing machine at a uniform rate of loading of 0.012 inch per minute. Deformations, to approximately 0.02 inch strain, were measured at equal increments of load with a 2-inch gage-length Martens'-mirror compressometer attached to the edges of the specimen.

Edgewise-compression tests of the 1/2- by 1/2- by 2-inch specimens (slenderness ratio = 13.8) were conducted at a no-load speed of 0.006 inch per minute. A 1-inch gage-length Martens'-mirror compressometer attached to the machined edges was used to measure deformations in these tests.

Flexure

The 1/8-inch papreg specimens, 1 inch wide by 4-1/2 inches long, were tested flatwise over a 2-1/2-inch span (span-depth ratio 20:1). Flatwise and edgewise specimens of 1/2-inch papreg, respectively 1 inch and 1/2 inch wide, by 10 inches long, were tested over an 8-inch span (span-depth ratio 16:1). Center loading was applied by means of a loading block attached to the cross head of a 30,000-pound universal testing machine equipped with a hydraulic capsule and a load indicator. The machine was operated at a no-load speed of 0.05 inch per minute until approximately 50 percent of the maximum load was reached and then increased to 0.15 inch per minute and maintained at this rate until failure. Deflections at the center of the span were measured with a 0.001-inch dial gage.

Bearing

Bearing tests were made on 1/8-inch specimens 15/16-inch wide and 4-3/4 inches long with a bearing hole 0.125 inch in diameter, centered in the width at a distance of three hole diameters from one end of the specimen. Specimens were tested in a tensile-type jig similar to that described in Federal Specification L-P-406 and shown in figure 3. The jig was suspended from a fixed cross arm of a 1,000-pound capacity universal testing machine. Load was applied by means of a Templin grip attached to the movable head of the machine. The machine was operated at a no-load speed of 0.012 inch per minute. Deformations of hole diameter were measured by two spiral-staff type 0.0001-inch dial gages attached to the jig. The gages were actuated by the movement of a collar in which were set knife edges bearing against opposite edges of the specimen in a line tangent to the circumference of the hole nearest the end of the specimen.

Impact strength

The standard Izod impact test was conducted on 1/2- by 1/2- by 2-1/2-inch specimens having machined notches. The tests were made with a pendulum-type impact-testing machine of 16 foot-pound capacity, using the 2 and 4 foot-pound ranges.

Modulus of Rigidity (G)

Modulus of rigidity tests were conducted on panels approximately 5 inches square by full thickness of the nominal 1/8-inch papreg, using the plate-shear method developed by the Forest Products Laboratory for measuring the shearing moduli of wood, as described in report No. 1301.

Test Results

Results of the comprehensive series of tests at room temperature on nominal 1/8-inch and 1/2-inch papreg are presented in tables 1 and 2.

Maximum, minimum, and average property values for a specified number of tests are reported. The standard deviation is also given for each property, to provide a measure of the variability and range of values. The standard deviation was calculated according to the formula $\sigma = \sqrt{\frac{\Sigma d^2}{n-1}}$ where d = deviation of the individual results from the average, and n = number of test results.

In these tables, lengthwise and crosswise refer to the orientation of the predominant direction of fibers in the constituent sheets of paper with respect to the length of the specimen. Consequently, parallel-laminated specimens are either "lengthwise" or "crosswise," whereas cross-laminated specimens are designated "lengthwise and crosswise." Thus values of ultimate shear for "lengthwise" and "crosswise" are respectively perpendicular and parallel to the predominant fiber directions. Because the results of lengthwise and crosswise values for cross-laminated papreg did not differ significantly (as indicated by the ratio of average lengthwise to crosswise values), the values for the two directions are combined in tables 1 and 2. Flatwise and edgewise refer to the application of loads in test. Flatwise refers to load applied to a surface of the original material; that is, in the direction of molding pressure. Edgewise refers to load applied on the edges of the laminations; that is, in a direction perpendicular to that of the molding-pressure direction.

Test results indicate that parallel-laminated papreg has average tensile and flexural strengths of 36,000 pounds per square inch lengthwise, and tensile and flexural strengths of about 20,000 and 24,000 pounds per square inch crosswise, respectively. For cross-laminated papreg, the tensile and flexural strengths are 27,000 and 30,000 pounds per square inch, respectively, or intermediate between those for the two principal directions of the parallel-laminated type. This relationship is common among all tensile and flexural properties and to a degree among most other properties of papreg.

In edgewise compression, the average ultimate strength varies between 18,000 and 22,500 pounds per square inch. Average ultimates are from 6 to 8 percent greater in the 1/2-inch thickness than in the 1/8-inch thickness, whereas in flexural strength and in most other compressive properties, values for 1/8-inch papreg are somewhat greater than corresponding values of the 1/2-inch papreg. These differences are not believed to be significant, because all lie within the variability of the material in the two directions, with the exception of the lengthwise flexural strength of the 1/8-inch parallel-laminate. Young's moduli of elasticity are essentially the same in compression and flexure (1,500,000 pounds per square inch crosswise, and 3,000,000 pounds per square inch lengthwise) and are from 15 to 25 percent less than the tensile modulus. Yield strengths in compression are likewise considerably less than in tension. The similarity of compressive ultimates for the two directions, together with the disparity in tension between these directions suggests that the resin is the major factor in strength in compression.

Typical tensile and compressive stress-strain diagrams indicating the yield strength corresponding to 0.2-percent strain offset are presented in figures 4 and 5, respectively. Deformations in the tensile tests were observed to approximately 0.01-inch-per-inch strain and also immediately before fracture. The broken line portion of the curves indicates that portion for which deformations were not observed. Typical load-deflection curves for flatwise flexure tests up to maximum load at fracture are shown in figure 6. All curves are based on actual load-deformation data for individual specimens having properties in close agreement with the average of the group. The groups of curves show graphically the "grain" effect due to the general orientation of the fibers in the machine direction of the laminations, as well as the behavior characteristics of each type.

Bearing strength values at 4 percent deformation of hole diameter (table average about 20,000 pounds per square inch. The range of values for these 1/8-inch specimens having a hole diameter of 1/8-inch was marked. The marked scatter of bearing values in this series of tests was probably due to variations in test conditions, such as variation in the drilled holes and in the snugness of fit between pin and hole and consequent variations in the initial portions of the stress-deformation curves. Because of experience gained in this series of tests and because of further improvement of the test apparatus, (fig. 3) notably in the collar and means of obtaining deformation data, such variations were minimized in subsequent bearing tests. In fact a limited number of duplicate tests of the same material produced average values of about 25,000 pounds per square inch, and a maximum variation of only 32 percent.

Standard specimens, having a hole of 1/4-inch diameter at a distance of 3/4 inch from one end of the specimen, failed in tension across the net section before the specified 4-percent deformation of the hole diameter occurred. For these tests, the average deformation of hole diameter at failure and corresponding average ultimate stress was 3.65 percent and 28,000 pounds per square inch, respectively, for parallel-laminated (lengthwise) papreg, and 3.69 percent and 26,500 pounds per square inch, respectively, for cross-laminated papreg.

The ultimate shear strength by the Johnson-type, double-shear method is about 20 percent greater edgewise than flatwise; and both edgewise and flatwise shear strength for parallel-laminated papreg are 15 to 20 percent greater perpendicular to the fiber direction than parallel to the fiber direction.

The modulus of rigidity (G) (modulus of elasticity in shear) associated with shear distortions in planes parallel to the laminations is approximately 900,000 pounds per square inch (Forest Products Laboratory plate-shear method).

The results of a few torsion tests to determine the modulus of rigidity associated with shear distortions in planes normal to the laminations may be of interest. The tests were conducted on rectangular specimens of 1/2-inch parallel-laminated papreg which had been molded at 500 pounds per square inch. The predominant direction of fibers was lengthwise in one specimen and crosswise of the length in the other. Two specimens 1-1/2 inches wide by 21 and 12 inches long (taken lengthwise and crosswise, respectively), gripped flatwise and with a detrusion-measuring device applied to their edges, were tested with torque kept within the proportional limit. Following these tests, specimens were cut to a width of 1 inch and the test repeated. Calculations in accordance with Saint-Venant's[3] method for determining the torsion in prisms of rectangular cross section gave modulus of rigidity values (G) as follows:

For specimens with grain lengthwise, 743,000 pounds per square inch in planes parallel to the laminations (G_{LT}), and 274,000 pounds per square inch in planes parallel to the length and normal to the laminations (G_{LR}).

For specimens with grain crosswise of the length, 810,000 pounds per square inch in planes parallel to the laminations (G_{TL}), and 241,000 pounds per square inch in crosswise planes normal to the laminations (G_{TR}).

In reference to this method of test, the G_{LT} and G_{TL} values (which, of course, should be equal for identical material) are considered to be the most reliable and the G_{LR} and G_{TR} values the least.

The behavior characteristics of papreg are indicated in the stress-strain curves of figures 4, 5, and 6. Ultimate failures in tension occur at relatively small strains and without a marked yield point. A limited ductility is likewise suggested by the brittle to brash failures exhibited by the tensile and flexure specimens.

Typical tension, flexure, and bearing failures of 1/8-inch papreg at various angles between grain direction and stress, are shown in figures 7 and 8. Typical flexure, compression, and Izod impact failures of 1/2-inch papreg are shown in figures 9 and 10. The relatively smooth failure surfaces of the edgewise Izod specimens, as compared to the ragged or torn failures of the flatwise specimens, are expressive of the lower edgewise than flatwise impact strength.

In reference to impact strength, the results of a few simple beam (Charpy type) impact tests of notched and unnotched specimens of parallel-laminated papreg is of interest. For lengthwise specimens, the flatwise to edgewise strength ratio was about unity for unnotched specimens and about 7 to 1 for notched specimens, or the same as shown for the notched (Izod type) specimens in table 2. Inasmuch as the unnotched-to-notched ratio of flatwise (Charpy type) impact resistance is only about 2 to 1, this 7 to 1 flatwise-to-edgewise ratio of the notched specimens is believed to be indicative of the notch sensitivity of the resin film between laminations.

Conclusions

Results of the various static tests at room temperature suggest that papreg can be produced as a comparatively uniform product. The plastic compares favorably with newly developed commercial products of the same composition. Papreg laminates have about twice the tensile strength and have higher strength characteristics in most other propoerties than the best paper-base laminates formerly available.

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[3] Todhunter and Pearson, "A History of the Elasticity and Strength of Materials." Vol. II, Part 1. Saint-Venant's memoir, pages 23 to 40. Cambridge University Press.

Papreg shows reasonable structural possiblities in all basic properties with the possible exception of ductility, compressive yield strength, and edgewise impact strength. Experiments have shown that the compressive yield can be improved at the expense of a further reduction in impact strength.

Appendix

Interlaminar Strength

Although extensive data on the interlaminar strength of papreg is not available, a few exploratory tests have been made. A few tests to determine the tensile strength normal to the plane of the laminations averaged 600 pounds per square inch. Shear on kerfed specimens (plywood joint test) ranged from 800 pounds per square inch crosswise to 1,100 pounds per square inch lengthwise. Block-type shear (block-shear joint test) ranged from 1,300 pounds per square inch lengthwise to 1,600 pounds per square inch crosswise. Three-eighths-inch diameter cylindrical specimens tested in a double-shear jig (Specification L-P-406) produced average shear values of about 3,000 pounds per square inch. In bonding-strength tests (Specification L-P-406a) an average force of 1,000 pounds was required to rupture the bond (specimens 1/2 inch thick by 1 inch wide and 1 inch high) by edgewise loading through the medium of a 10-millimeter steel ball.

Directional Properties

Directional properties of papreg, based on a limited number of tests, are presented in table 3. These results indicate that the cross-laminated papreg is essentially isotropic in the plane of the sheet. In general, the properties of parallel-laminated papreg differ significantly between the two principal directions with 45° values intermediate.

Further evidence relative to the laminar isotropy of papreg was obtained by means of tensile tests of specimens taken from single panels of parallel-laminated and cross-laminated papreg at 10° intervals between 0° and 90° to the predominant fiber direction; that is, between directions which are parallel and perpendicular to the face grain direction of the panels.

Test material was identical to the improved standard papreg of tables 1 and 2, except that the resin was an earlier experimental hot-press phenolic which is no longer available. The material is identified as machine run No. 1938. The specimens were prepared, conditioned, and tested in accordance with Specification L-P-406.

Results of these tests, together with computed ultimate tensile strengths for the various angles between stress and grain directions are presented in table 4.

The computed ultimates were determined by means of a formula[4] for obtaining the ultimate tensile strength of plywood elements at any angle (θ) between the face grain direction and the direction of the applied stress, as follows:

$$F_{tu\theta} = \frac{1}{\sqrt{\left[\frac{\cos^2\theta}{F_{tuw}}\right]^2 + \left[\frac{\sin^2\theta}{F_{tux}}\right]^2 + \left[\frac{\sin\theta\cos\theta}{F_{swx}}\right]^2}}$$

where

F_{tuw} and F_{tux} = ultimate tensile strength of plywood parallel and perpendicular to the face grain direction, respectively.

F_{swx} = ultimate shear strength of the plywood when the face grain direction is parallel and perpendicular to the shear stresses.

Computed tensile strengths for the parallel-laminated papreg are based on average lengthwise (0°), and crosswise (90°) values of 34,230, and 18,640 pounds per square inch, respectively, for F_{tuw} and F_{tux}; and 17,710 pounds per square inch for F_{swx} representing the ultimate shear strength (Johnson type) parallel to grain, edgewise. Computed ultimates for the cross-laminated papreg are based on an average value of 27,350 pounds per square inch for F_{tuw} and F_{tux}, and 18,530 pounds per square inch for F_{swx}. All of the values represent the average of at least 12 tests.

Flammability

Flammability (rate-of-burning) tests of 1/2- by 6-inch specimens of 1/8-inch papreg conducted in accordance with Specification L-P-406, Method B-13, indicated the material to be self-extinguishing. The average flaming time following removal of the Bunson burner after the first and second application was 0.2 and 0.5 minute, respectively, and the average glowing time was 1.7 and 2.3 minutes, respectively. The average spread of char per application was 0.3 and 0.5 inch, respectively, and ranged between 0.25 and 0.75 inch. Specimens increased about 50 percent in thickness at the extreme end of the charred portion.

Abrasion

A few abrasion tests of papreg of 1.4 specific gravity were conducted in accordance with Specification L-P-406a, Method No. 1091, on a Taber abraser employing CS-17 wheels and 1,000-gram load. One thousand revolutions produced an average loss in weight of 16.8 milligrams.

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[4] Equation 2.50 in section 2.611 on page 62 of ANC bulletin 18 (June 1944) prepared by Forest Products Laboratory and Army-Navy-Civil Committee on Aircraft Design Criteria.

Linear Thermal Expansion

A few measurements to determine the linear thermal expansion of papreg were made on 1-centimeter square specimens taken from parallel-laminated and cross-laminated panels 1/2 inch in thickness. Specimens were 1 centimeter long for the measurements in the direction of compression, 10 centimeters long for the parallel-laminated lengthwise measurement and 3 centimeters long for all other measurements in the plane of the laminations.

Measurements were made at temperatures, within 2° C. or 4° F. of 50° C. (122° F.), 25° C. (77° F.), 0° C. (32° F.), -25° C. (-13° F.), -40° C. (-40° F.), and at -50° C. (-58° 1.) by means of a quartz dilatometer of the optical-lever type. Results of measurements on individual specimens in centimeters per centimeter per °C. were as follows:

Linear coefficients of parallel-laminated papreg:

0.00000573 in the plane of the laminations, lengthwise
0.00001514 in the plane of the laminations, crosswise
0.0000651 perpendicular to the plane of the laminations, flatwise.

Linear coefficients of cross-laminated papreg:

0.00001089 in the plane of the laminations parallel to the fiber direction of one-half of laminations
0.0000622 perpendicular to the plane of the laminations, flatwise, between 52.3° C. (126.2° F.) and -25.2° C. (-13.4° F.).

The expansion was linear or essentially linear over the whole range investigated, except that for the cross-laminated material in the plane of the laminations the expansion-temperature graph curves toward the temperature axis above 25° C. (77° F.). The linear coefficient of thermal expansion in the plane of the laminations for the cross-laminated papreg lies midway between that of the lengthwise and crosswise linear coefficients of parallel-laminated papreg, in the same manner that the tensile and flexural properties do.

Poisson's Ratios

The results of a few determinations of Poisson's ratios on papreg are available. Six specimens 3-1/2 inches long, 1 inch wide, and 1/2 inch thick were tested. Two of the specimens were of cross-laminated material. Two were of parallel-laminated material tested lengthwise. Two were of parallel-laminated material tested crosswise. The following definitions apply to parallel-laminated material:

μ_{LT} = Poisson's ratio of contraction in the direction parallel to the plane of the laminations and perpendicular to the machine direction of the paper to extension in the machine direction, due to a stress applied in the machine direction.

μ_{LR} = Poisson's ratio of contraction in the direction normal to the plane of the laminations and perpendicular to the machine direction of the paper to extension in the machine direction, due to a stress applied in the machine direction.

Similarly μ_{TL}, μ_{TR}, μ_{RL}, and μ_{RT}.

The same definitions may be used for cross-laminated material, since for this material $\mu_{LT} = \mu_{TL}$, $\mu_{LR} = \mu_{TR}$, and $\mu_{RL} = \mu_{RT}$.

The results of the few tests are as follows:

Parallel laminated specimens tested crosswise, $\mu_{TL} = 0.195$ and $\mu_{TR} = 0.450$; tested lengthwise, $\mu_{LT} = 0.394$, and $\mu_{LR} = 0.508$. For cross-laminated material, $\mu_{LT} = 0.283$ and $\mu_{LR} = 0.484$.

Column Tests of Papreg

The results of three groups of tests to determine the lengthwise and crosswise column strength of parallel-laminated and cross-laminated papreg are available. Nineteen specimens of nominal 1/8-inch papreg, each 1 inch wide and ranging in length from 3 to 9 inches, were tested in each group. The material is identified as improved-standard (June 1943).

Each specimen was tested in edgewise compression as a fixed-end column. Ends were squared and clamped to produce an approximately fixed-end condition by means of two clamping and loading jigs made from 1/2-inch papreg. Each jig consisted of a bed plate or loading block 2-1/2 inches wide by 10 inches long to which was bolted one of a pair of end-clamping bars 1/2 inch square by 2-1/2 inches long. One bar of each pair was attached to the bolted bar by means of two thumb screws positioned to clear the sides of the 1 inch wide specimens.

All specimens were tested to maximum load at a uniform rate of cross head motion of about 0.02 inch per minute in a pendulum type testing machine of 10,000-pound capacity, using the 5,000-pound load range.

Results of test data converted to compressive stress are plotted for corresponding ratios of $\frac{L}{K}$ in figures 11 and 12. Presented also with each set of test data are a pair of computed Euler curves, one based on the initial tangent modulus (modulus of elasticity) and the other on successive tangent moduli throughout the plastic range of the test material. Tangent modulus values were determined from the typical compressive stress-strain curves of figure 5. Having determined the tangent modulus values for a number of $\frac{P}{A}$ values, corresponding values of modulus and stress were substituted in the fixed-end Euler-column formula and values of $\frac{L}{K}$ computed. The results are represented by the longer smooth curves of figures 11 and 12. Stress values plotted at $\frac{L}{K} = 14$ represent the average ultimate compressive stresses given in table 2.

Table 1.--Strength and related properties of nominal 1/8-inch papreg[1] at normal temperature 24° ± 2.8° C. (75° ± 5° F.)

Thickness at test, specific gravity, type of test, and property		Parallel laminated: Lengthwise: Number of tests	Parallel laminated: Lengthwise: Average	Parallel laminated: Lengthwise: Minimum	Parallel laminated: Lengthwise: Maximum	Parallel laminated: Lengthwise: Standard deviation	Parallel laminated: Crosswise: Number of tests	Parallel laminated: Crosswise: Average	Parallel laminated: Crosswise: Minimum	Parallel laminated: Crosswise: Maximum	Parallel laminated: Crosswise: Standard deviation	Cross laminated: Lengthwise and crosswise[2]: Number of tests	Cross laminated: Lengthwise and crosswise[2]: Average	Cross laminated: Lengthwise and crosswise[2]: Minimum	Cross laminated: Lengthwise and crosswise[2]: Maximum	Cross laminated: Lengthwise and crosswise[2]: Standard deviation	Cross laminated: Lengthwise: Average	Cross laminated: Crosswise: Average	Cross laminated: Ratio Lengthwise/Crosswise
Thickness (in the molding-pressure direction)	Inch	32	0.126	0.122	0.130	0.0019	32	0.126	0.124	0.130	0.0017	32	0.125	0.123	0.128	0.0015			
Specific gravity (based on weight and volume at test)		32	1.413	1.392	1.423	.0070	30	1.406	1.395	1.416	.0064	32	1.407	1.392	1.422	.0065			
Test and property:																			
1. Tension		32					32					32							
Ultimate strength	P.s.i.		35,610	30,520	40,400	2,321		20,010	17,720	21,720	853		27,160	23,130	30,520	1,591	27,260	27,060	1.007
Yield strength at 0.2 percent offset	P.s.i.		32,780	27,600	38,300	2,575		14,560	13,500	16,830	838		23,160	20,290	26,940	1,665	23,650	22,670	1.043
Yield strength at 0.7 percent strain	P.s.i.		23,090	21,000	30,020	2,223		10,860	9,580	12,760	980		16,760	15,610	18,280	706	16,950	16,560	1.024
Proportional-limit stress	P.s.i.		14,480	9,340	20,420	3,011		7,880	6,350	10,550	856		9,760	8,000	12,170	1,072	9,930	9,610	1.033
Secant modulus at 0.2 percent offset	1,000 p.s.i.		2,951	2,706	3,410	147		1,352	982	1,720	174		2,177	2,010	2,462	111	2,190	2,160	1.014
Modulus of elasticity	1,000 p.s.i.		3,645	3,100	4,700	377		1,713	1,420	2,440	261		2,692	2,446	3,236	181	2,709	2,674	1.013
Elongation[3]	Percent		1.20	0.83	1.37	0.16		1.88	1.15	2.34	0.30		1.29	1.04	1.60	0.14	1.29	1.29	1.000
2. Compression -- Edgewise[4]		31					32					32							
Ultimate strength	P.s.i.		20,970	17,940	23,730	1,276		18,260	14,080	19,000	859		19,150	16,660	20,720	1,071	18,920	19,370	.977
Yield strength at 0.2 percent offset	P.s.i.		15,170	13,900	17,020	537		9,940	9,460	10,500	266		11,690	10,850	12,580	503	11,990	11,400	1.052
Yield strength at 0.7 percent strain	P.s.i.		15,260	14,220	16,740	448		8,990	8,500	9,380	187		11,800	10,580	12,640	467	11,990	11,600	1.034
Proportional-limit stress	P.s.i.		7,220	5,200	8,280	248		4,170	3,170	5,140	447		5,030	4,480	5,740	291	5,020	5,040	.996
Secant modulus at 0.2 percent offset	1,000 p.s.i.		2,202	2,090	2,448	65		1,210	1,126	1,276	36		1,695	1,475	1,816	62	1,715	1,676	1.023
Modulus of elasticity	1,000 p.s.i.		3,118	2,997	3,568	107		1,597	1,465	1,712	56		2,369	2,018	2,503	91	2,375	2,363	1.005
3. Flexure -- Flatwise[5] (2-1/2-inch span, center loading)		32					32					32							
Modulus of rupture	P.s.i.		36,590	34,120	38,780	1,171		24,300	22,620	26,020	785		30,540	28,220	32,800	1,153	31,340	29,740	1.054
Proportional-limit stress	P.s.i.		15,900	12,520	19,040	1,473		10,510	8,400	12,120	1,148		12,240	10,140	16,060	1,325	12,620	11,860	1.062
Modulus of elasticity	1,000 p.s.i.		3,016	2,808	3,231	99		1,481	1,335	1,580	51		2,241	2,112	2,342	58	2,242	2,240	1.001
4. Bearing -- 1/8-inch pin diameter (tensile loading)		26					27					25							
Bearing strength[6]	P.s.i.		20,150	10,320	27,720	5,025		21,360	13,860	26,980	2,932		19,020	12,600	26,050	3,999	19,180	18,860	1.017
Ultimate bearing stress	P.s.i.		34,060	31,700	35,730	980		30,860	28,720	33,370	1,275		32,170	29,600	34,950	1,377	32,750	31,580	1.037
5. Shear (Johnson-type shear tool)		31					32					32							
Ultimate strength (flatwise)[2,7]	P.s.i.		16,980	15,080	17,980	700		14,010	12,220	16,340	733		15,550	14,540	16,260	415	15,530	15,570	.997
6. Modulus of rigidity (plate shear method)[8]	1,000 p.s.i.	16	909	849	1,053	29						8	887	808	965	33			
7. Indentation hardness (Rockwell)	M numbers	62	110	105	112							28	110	105	113				
8. Loss in weight on drying at 221° F. for 24 hours		16										7							
Loss in weight (2- by 2-inch specimens)	Percent		1.99	1.54	2.59								2.60	2.17	2.95				
9. Water absorption (24-hour immersion)		16										9							
Increase in weight (2- by 2-inch specimens)	Percent		2.21	1.85	2.42								2.36	2.20	2.42				
Increase in length (2- by 2-inch specimens)	Percent		.01	.00	.05								.03	.00	.05				
Increase in width (2- by 2-inch specimens)	Percent		.06	.05	.10								.02	.00	.05				
Increase in thickness (2- by 2-inch specimens)	Percent		1.67	1.21	1.99								1.82	1.49	2.12				

[1] A laminated paper plastic made by the Forest Products Laboratory from a commercial, unbleached, black spruce pulp (Mitscherlich sulfite), converted on the Laboratory paper machine, impregnated with a phenolic-type resin, hot pressed at 250 pounds per square inch, and identified as "Improved Standard - June 1943." The specimens were prepared, conditioned, and tested in accordance with Federal Specifications for Plastics, Organic, L-P-406 (December 9, 1942) except as noted. Machined edges of specimens were not otherwise finished prior to test. Attachment of extensometers to tensile specimens produced knife-edge marks or minute punch marks on the flatwise surfaces of the specimens. All compressive properties except ultimate strength were obtained by testing 1- by 4-inch specimens as laterally supported columns.

[2] An equal number of specimens were taken from each of the two principal directions of each panel.

[3] Elongation immediately before fracture measured over a 2-inch gage length.

[4] Load applied to the edges of the laminations (perpendicular to molding-pressure direction).

[5] Load applied to the surface of the original material (parallel to molding-pressure direction).

[6] Stress of 4 percent deformation of hole diameter. Specimens were 4-3/4 inches long by 15/16 inch wide by molded thickness; diameter of hole was 0.125 inch; distance from the end of the specimen to the circumference of the bearing hole was 0.31 inch.

[7] Values of shear for "lengthwise" and "crosswise" are respectively perpendicular and parallel to the predominant fiber direction.

[8] Modulus associated with shear distortion in the original surfaces and planes parallel thereto. Specimens, 5- by 5- by nominal 1/8-inch, were tested in accordance with the Forest Products Laboratory method of measuring the shearing moduli in wood.

Z M 61882 F

Table 2.--Some strength properties of nominal 1/2-inch papreg[1] at normal temperature 24° ± 2.8° C. (75° ± 5° F.)

Thickness at test, specific gravity, type of test, and property		Parallel laminated										Cross laminated							
		Lengthwise					Crosswise					Lengthwise and crosswise[2]					Lengthwise	Crosswise	Ratio
		Number of tests	Average	Minimum	Maximum	Standard deviation	Number of tests	Average	Minimum	Maximum	Standard deviation	Number of tests	Average	Minimum	Maximum	Standard deviation	Average	Average	Lengthwise / Crosswise
Thickness (in the molding-pressure direction)	Inch	10	0.512	0.497	0.523	0.0097	10	0.508	0.494	0.519	0.0090	16	0.501	0.488	0.515	0.0090	...	...	...
Specific gravity (based on weight and volume at test)		10	1.417	1.409	1.426	.0049	10	1.409	1.405	1.414	.0031	16	1.407	1.391	1.416	.0091	...	...	...
Test and property:																			
1. Compression-Edgewise[3] (1/2- by 1/2- by 2-inch)		20					20					32							
Ultimate strength	P.s.i.		22,530	20,990	23,990	727		19,430	18,350	21,680	729		20,790	19,470	22,880	911	20,750	20,820	0.997
Yield strength at 0.2 percent offset	P.s.i.		14,040	12,820	14,700	421		9,730	8,880	10,570	462		11,290	10,540	12,240	439	11,200	11,380	.984
Yield strength at 0.7 percent strain	P.s.i.		14,130	13,130	14,910	407		8,590	8,140	9,590	321		11,340	10,720	11,820	320	11,270	11,410	.988
Proportional-limit stress	P.s.i.		7,910	6,420	9,660	884		4,280	3,060	5,480	629		5,430	4,100	7,390	841	5,550	5,300	1.047
Tangent modulus at 0.7 percent strain	1,000 p.s.i.		773	692	837	...		833	770	901	...		785	712	908	...	786	782	1.005
Secant modulus at 0.2 percent offset	1,000 p.s.i.		2,049	1,894	2,272	86		1,139	1,063	1,242	46		1,621	1,526	1,710	52	1,609	1,632	.986
Modulus of elasticity	1,000 p.s.i.		2,913	2,578	3,312	166		1,496	1,346	1,754	96		2,279	2,125	2,444	95	2,272	2,285	.994
2. Compression-Flatwise[4] (1-inch cubes)		3										3							
Ultimate strength	P.s.i.		42,200	40,500	43,700	...							45,600	45,000	45,900	...	...	...	...
3. Flexure-Flatwise[4] (8-inch span, center loading)		10					10					16							
Modulus of rupture	P.s.i.		31,710	29,580	33,880	1,371		19,540	14,950	24,160	2,489		28,710	25,820	31,090	1,522	28,880	28,540	1.012
Proportional-limit stress	P.s.i.		14,410	12,630	15,880	920		7,850	6,860	11,000	1,201		11,000	9,120	13,160	1,058	10,900	11,100	.982
Modulus of elasticity	1,000 p.s.i.		2,847	2,757	2,930	60		1,418	1,367	1,479	35		2,061	1,901	2,199	97	2,067	2,055	1.006
4. Flexure-Edgewise[3] (8-inch span, center loading)		9					10					16							
Modulus of rupture	P.s.i.		28,870	26,500	30,700	1,502		20,790	18,780	22,640	1,239		26,590	24,500	28,500	1,319	26,500	26,680	.993
Proportional-limit stress	P.s.i.		14,960	13,450	15,860	884		7,940	6,440	9,940	1,039		8,240	6,700	10,770	1,092	8,220	8,260	.995
Modulus of elasticity	1,000 p.s.i.		2,726	2,557	2,953	138		1,402	1,320	1,501	64		2,184	2,008	2,321	105	2,168	2,200	.985
5. Shear (Johnson-type shear tool)[1]		20					20					32							
Ultimate strength (edgewise)[3,5]	P.s.i.		20,500	18,980	21,320	581		17,840	16,340	19,000	684		18,670	17,120	20,200	922	18,670	18,670	1.000
6. Impact strength (Izod)		20					20					32							
Flatwise, notch on face	Foot-pound per inch of notch		4.69	3.52	6.56	...		2.43	2.03	2.95	...		3.82	3.15	4.53	...	3.71	3.94	...
Edgewise, notch on edge	Foot-pound per inch of notch		.67	.60	.71	...		.60	.54	.66	...		.66	.61	.77	...	.66	.66	...

[1]A laminated paper plastic made by the Forest Products Laboratory from a commercial, unbleached, black spruce pulp (Mitscherlich sulfite), converted on the Laboratory paper machine, impregnated with a phenolic-type resin, hot pressed at 250 pounds per square inch, and identified as "Improved Standard - June 1943." The specimens were prepared, conditioned, and tested in accordance with Federal Specifications for Plastics, Organic, L-P-406 (December 9, 1942) except that machined edges of specimens were not otherwise finished prior to test.

[2]An equal number of specimens were taken from each of the two principal directions of each panel.

[3]Load applied to the edges of the laminations (perpendicular to molding-pressure direction).

[4]Load applied to the surface of the original material (parallel to molding-pressure direction).

[5]Values of shear for "lengthwise" and "crosswise" are respectively perpendicular and parallel to the predominant fiber direction.

Z M 61883 F

Table 3.—Directional properties of nominal 1/8-inch papreg at normal temperature, 24° + 2.8° C. (75° + 5° F.)

Angle between grain direction and stress, or specimen length	Compression (edgewise)					Bearing (1/8-inch diameter pin)			Static bending (flatwise)				Shear (flatwise) (Johnson-type)	
	Number of tests	Ultimate strength	Yield strength at 0.2 percent offset	Proportional limit stress	Modulus of elasticity	Number of tests	Strength at 4 percent deformation of hole diameter	Ultimate bearing stress	Number of tests	Proportional limit stress	Modulus of rupture	Modulus of elasticity	Number of tests	Shearing strength
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
Degrees		P.s.i.	P.s.i.	P.s.i.	P.s.i. x 10^3		P.s.i.	P.s.i.		P.s.i.	P.s.i.	P.s.i. x 10^3		P.s.i.
							Parallel laminated							
0	5	20,750	12,240	5,860	2,807	6	24,920	35,060	4	14,940	36,410	2,905	8	17,110
45	5	18,550	10,270	3,700	1,983	9	21,300	33,930	4	11,520	35,280	2,512	8	16,870
90	5	19,950	9,500	3,570	1,545	4	22,940	31,300	4	8,650	25,810	1,777	8	14,920
							Cross laminated							
0	16	18,900	11,990	5,020	2,375	5	25,920	34,280	4	15,560	31,760	2,359	16	15,530
45	5	19,550	10,810	4,460	2,151	5	26,470	36,350	4	13,400	36,060	2,409	4	16,240
90	16	19,370	11,400	5,040	2,363	5	25,920	34,280	4	11,920	33,940	2,638	16	15,570

ZM58055F

Table 4.--Results of tensile tests of nominal 1/8-inch papreg at various angles to the face grain direction, obtained at normal temperatures 24° ± 2.8° C (75° ± 5° F.)

Angle between stress (length of specimen) and grain direction	Number of tests	Proportional limit stress	Modulus of elasticity	Elongation	Ultimate strength (test)	Ultimate strength[1] (computed)
Degrees		Lb. per sq. in.	1,000 lb. per sq. in.	Percent	Lb. per sq. in.	Lb. per sq. in.
			Parallel laminated			
0	1	7,480	3,253	1.46	33,100	34,230
10	1	9,100	2,993	1.65	35,500	33,300
20	1	8,980	2,730	1.80	33,410	31,200
30	1	6,780	2,585	1.80	30,100	28,200
45	2	5,660	2,135	1.76	24,400	24,050
60	1	9,050	1,734	1.96	21,400	21,000
70	1	7,500	1,612	1.70	18,660	19,250
80	1	7,460	1,555	1.90	18,440	18,600
90	1	6,850	1,548	2.08	18,860	18,640
			Cross laminated			
0	1	9,200	2,561	1.56	29,150	27,350
10	1	6,520	2,580	1.16	30,600	27,300
30	1	9,920	2,306	....	26,490	27,000
40	1	9,700	2,282	1.80	28,360	26,900
45	1	8,980	2,362	1.72	27,720	26,700
50	1	10,700	2,351	1.72	28,070	26,900
60	1	11,300	2,248	1.67	27,320	27,000
70	1	10,420	2,396	1.46	26,440	27,200
80	1	10,480	2,439	1.33	25,580	27,300
90	1	9,580	2,539	1.37	26,580	27,350

[1] 0° and 90° values represent the average of at least 12 tests.

LEGEND: $\frac{1}{8}$-INCH SPECIMENS.

T- TENSION, $\frac{3}{4}$ BY 9 INCHES (BEFORE SHAPING)

M-COMPRESSION, 1 BY $\frac{1}{2}$ INCH (FOR EDGEWISE ULTIMATE ONLY)

C-COMPRESSION, 1 BY 4 INCHES (FOR OTHER EDGEWISE PROPERTIES)

F-FLEXURE, 1 BY $4\frac{1}{2}$ INCHES ($2\frac{1}{2}$-INCH SPAN, FLATWISE)

B-BEARING, $\frac{15}{16}$ BY $4\frac{1}{2}$ INCHES

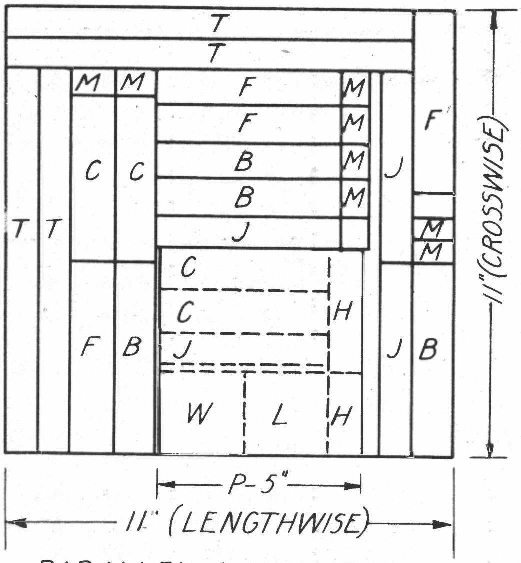
J-SHEAR, $\frac{3}{4}$ BY 4 INCHES (JOHNSON TYPE-FLATWISE)

W-WATER ABSORPTION, 2 BY 2 INCHES.

L-LOSS OF WEIGHT ON DRYING, 2 BY 2 INCHES

H-HARDNESS, 1 BY 2 INCHES AND 1 BY 3 INCHES

P-PLATE SHEAR, 5 BY 5 INCHES. MODULUS OF RIGIDITY DATA WAS OBTAINED PRIOR TO CUTTING SPECIMENS INDICATED BY BROKEN LINES.



PARALLEL LAMINATED PANELS, NO. 62 TO 77 INCLUSIVE (GROUP I)
CROSS LAMINATED PANELS, NO. 46 TO 53 INCLUSIVE (GROUP II)

CUTTING DIAGRAM FOR NOMINAL $\frac{1}{8}$-INCH PANELS

LEGEND: $\frac{1}{2}$-INCH SPECIMENS.

F-FLEXURE, 1 BY 10 INCHES, (8-INCH SPAN, FLATWISE)

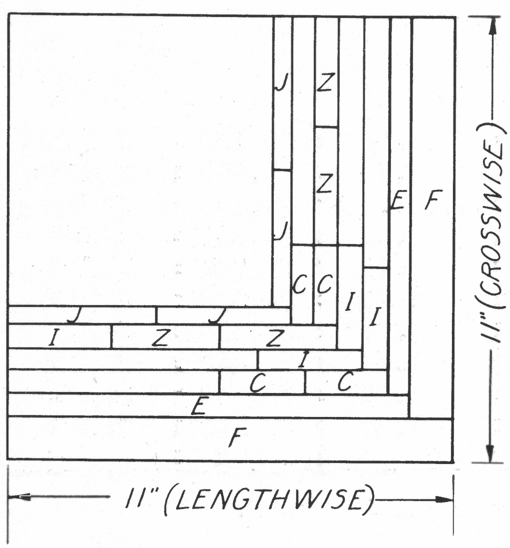
E-FLEXURE, $\frac{1}{2}$ BY $9\frac{1}{2}$ INCHES (8-INCH SPAN, EDGEWISE).

C-COMPRESSION, $\frac{1}{2}$ BY 2 INCHES (EDGEWISE)

I-IMPACT, $\frac{1}{2}$ BY $2\frac{1}{2}$ INCHES (IZOD, NOTCHED FLATWISE)

Z-IMPACT, $\frac{1}{2}$ BY $2\frac{1}{2}$ INCHES (IZOD, NOTCHED EDGEWISE)

J-SHEAR, $\frac{1}{8}$ BY $3\frac{1}{2}$ INCHES (JOHNSON TYPE, EDGEWISE)



PARALLEL LAMINATED PANELS, NO. 23 AND 25 TO 33 INCLUSIVE (GROUP III)
CROSS LAMINATED PANELS, NO. 13 TO 17 AND 19 TO 21 INCLUSIVE (GROUP IV)

CUTTING DIAGRAM FOR NOMINAL $\frac{1}{2}$-INCH PANELS

Figure 1.--Cutting diagrams for specimens taken from nominal 1/8-inch and 1/2-inch papreg panels.

Z M 61875 F

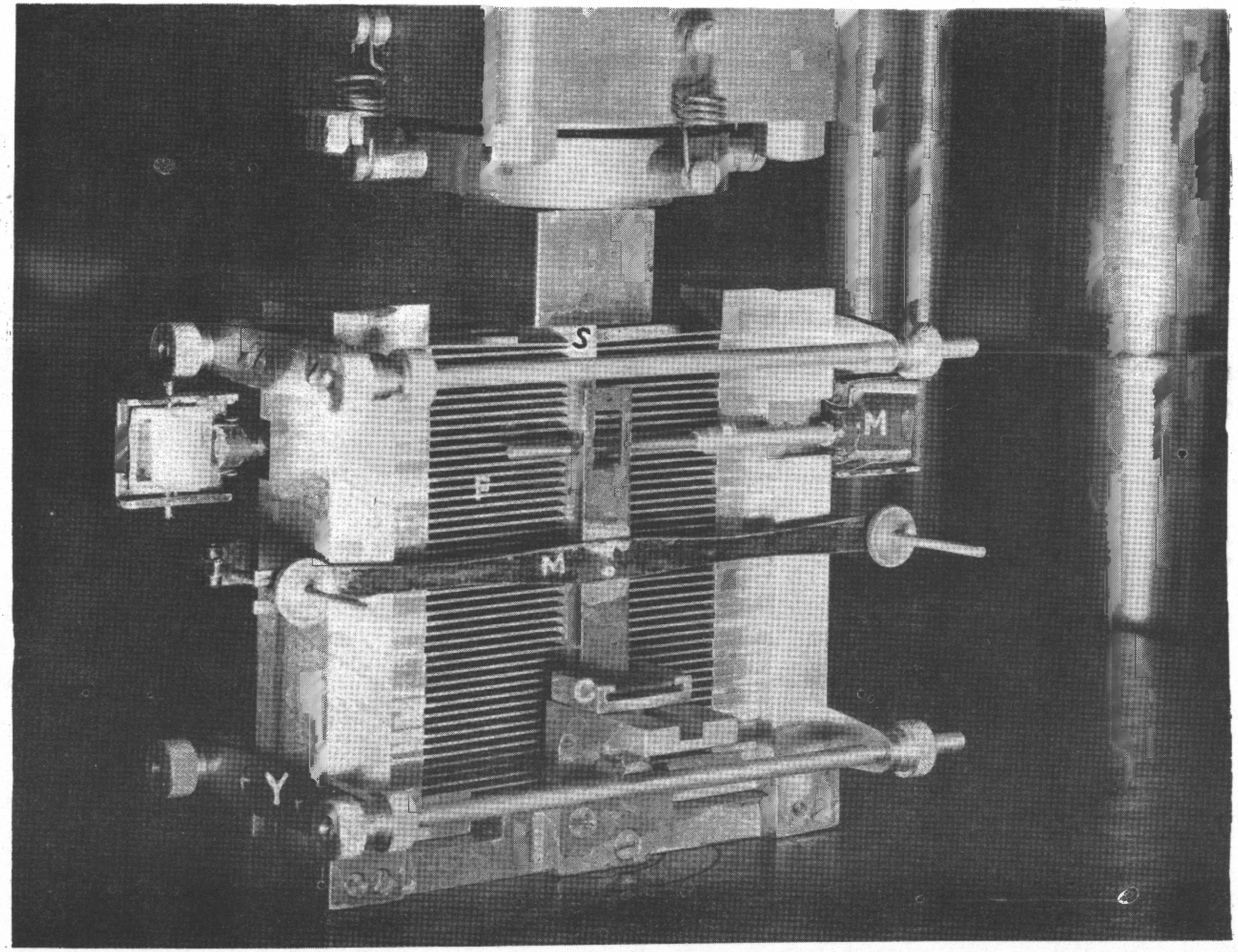


Figure 2.--Specimen ready for test in the apparatus used for the laterally supported column compression test: C, clips to hold the lower gage points of the gage; F, spring-steel fingers to provide lateral restraint to specimen; M, Martens' mirror gages; S, specimen; Y, yokes.

Z M 47775 F

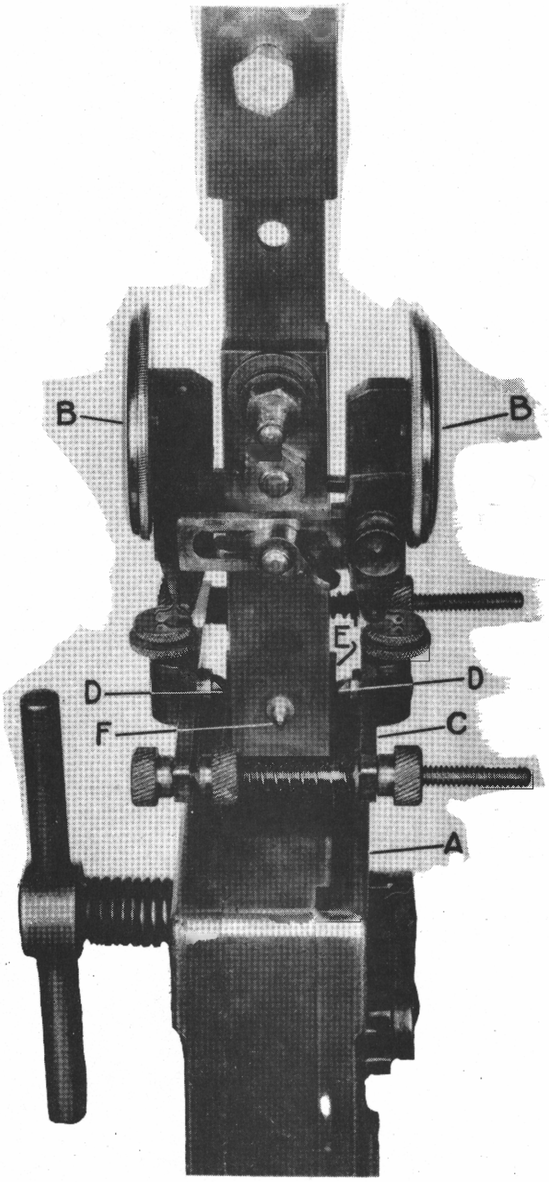


Figure 3.--Apparatus assembly for bearing test of papreg (tensile loading): A, Templin grip; B, dial gage; C, collar; D, knife edge; E, specimen; F, 1/8-inch diameter steel pin.

Z M 58910 F

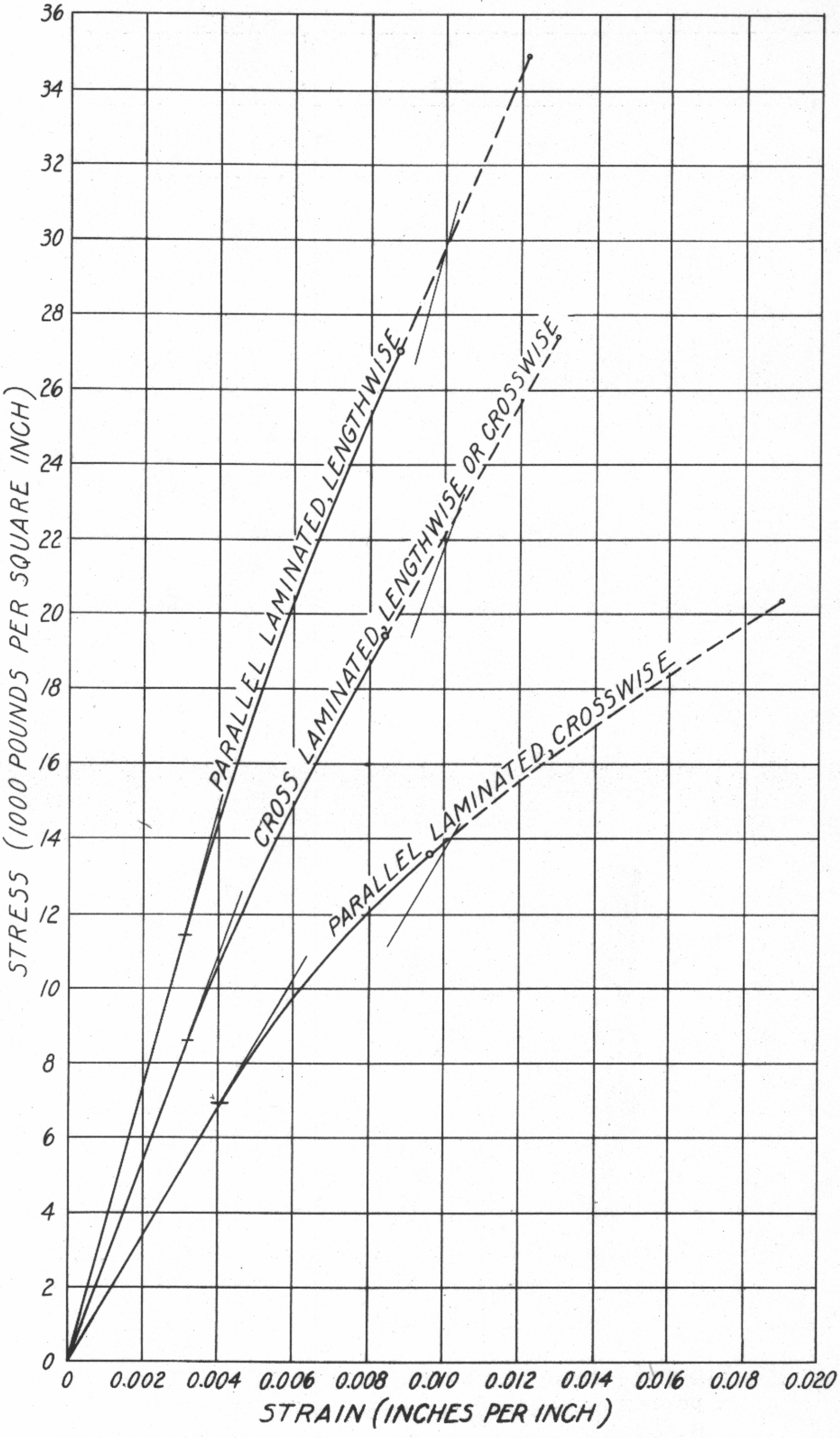


Figure 4.--Typical tensile stress-strain curves for papreg at normal temperature, 24° ± 2.8° C. (75° ± 5° F.)

Z M 58050 F

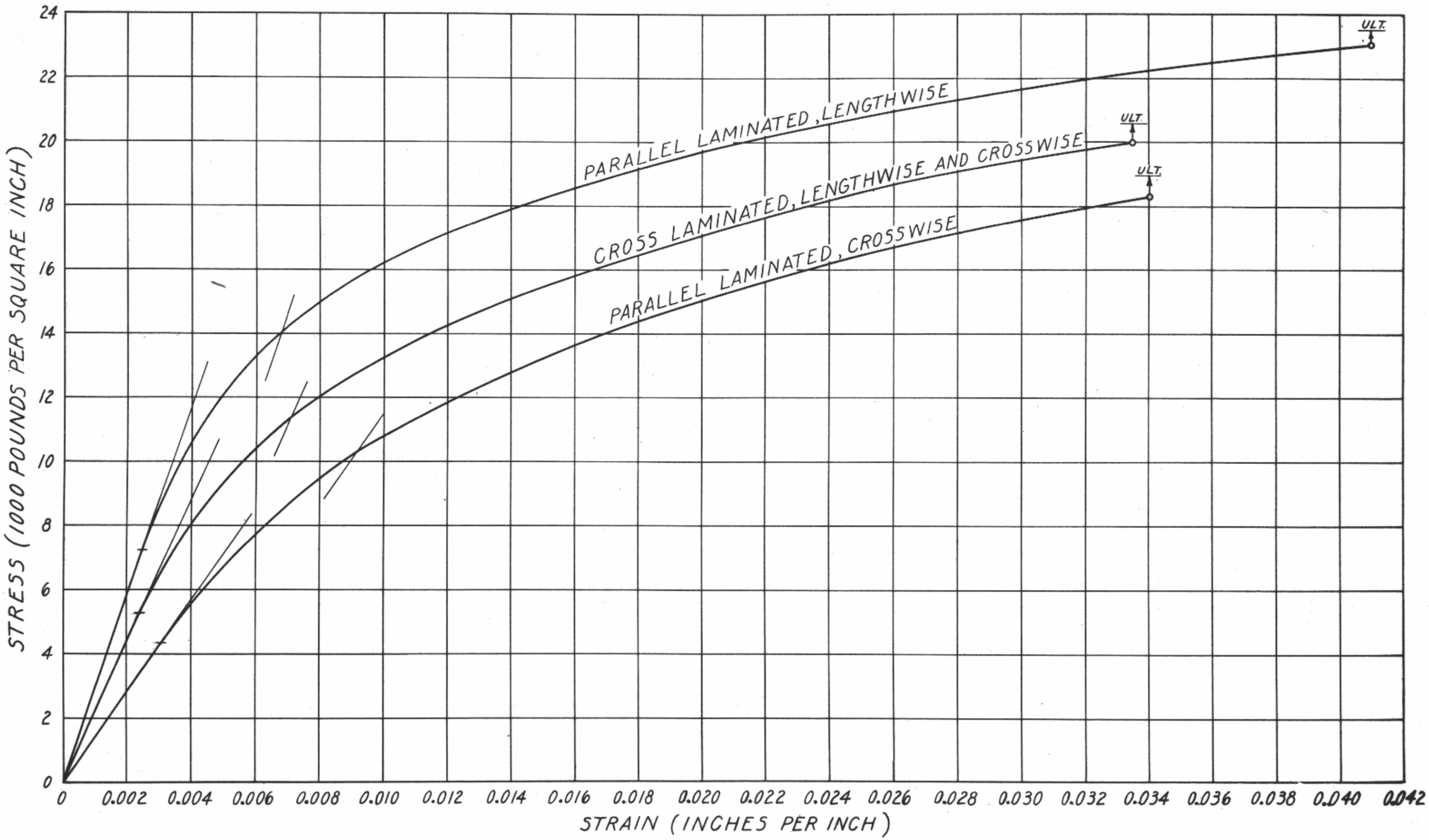


Figure 5.--Typical compressive (edgewise) stress-strain curves for papreg at normal temperature, 24° ± 2.8° C. (75° ± 5° F.).

Z M 58051 F

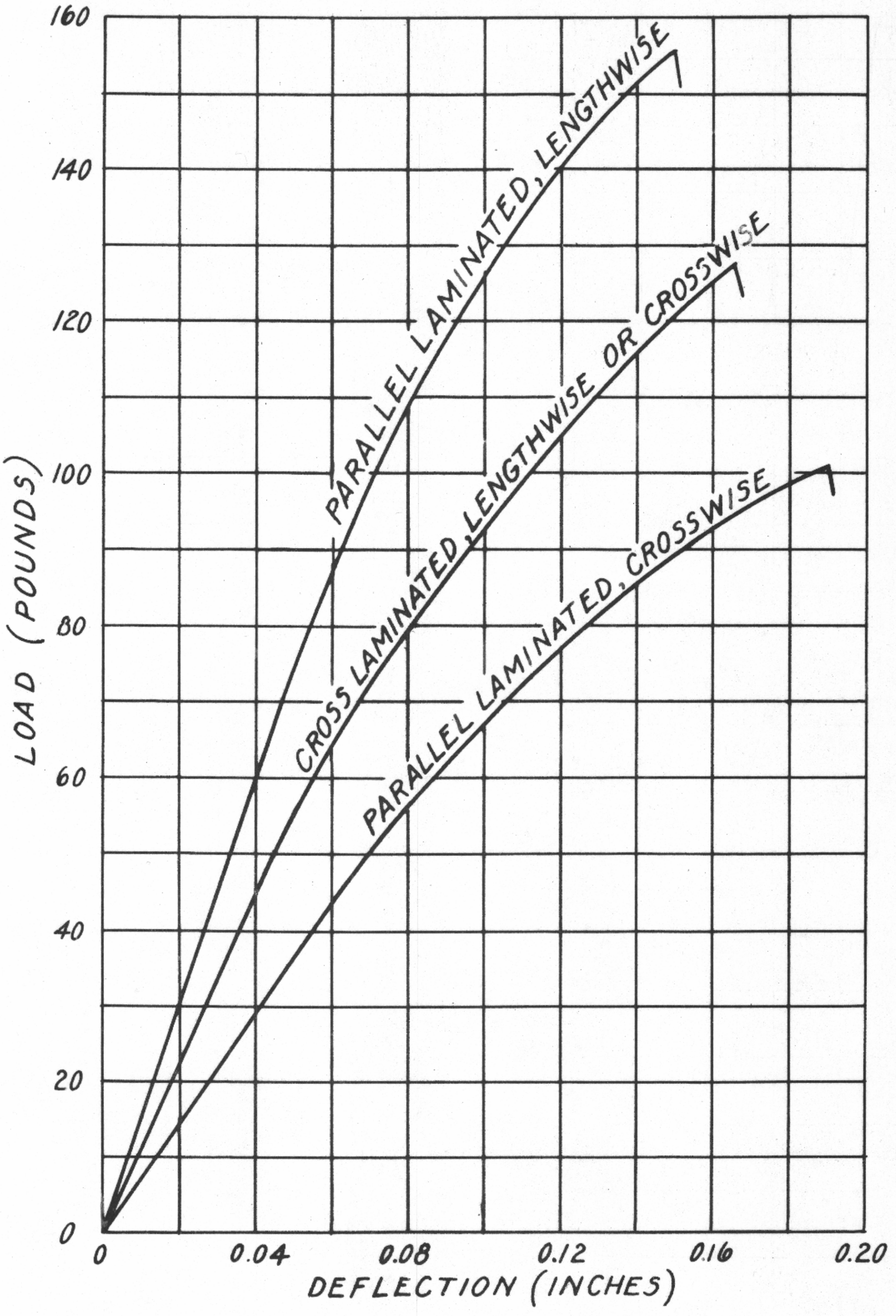


Figure 6.--Typical flexure load-deformation curves for papreg at normal temperature, 24° ± 2.8° C. (75° ± 5° F.). Specimens were 1/8 by 1 inch, and were center loaded on a 2-1/2-inch span.

Z M 53052 F

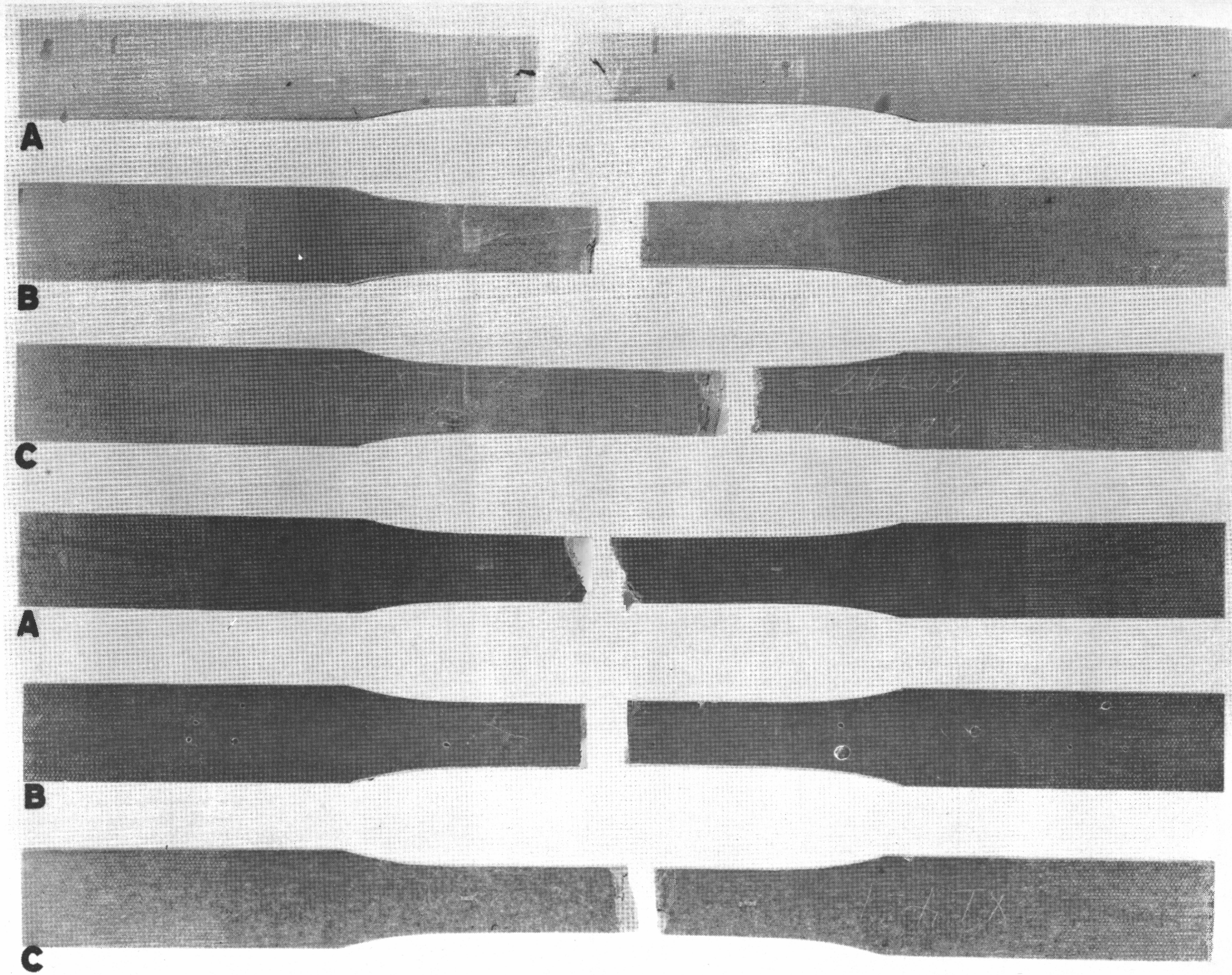


Figure 7.--Typical tensile failures of 1/8-inch papreg. A, lengthwise; B, crosswise; parallel-laminated; C, 0° or 90° cross-laminated. A knife-edge-type extensometer was used on the upper group and a punch-type on the lower group.

Z M 61876 F

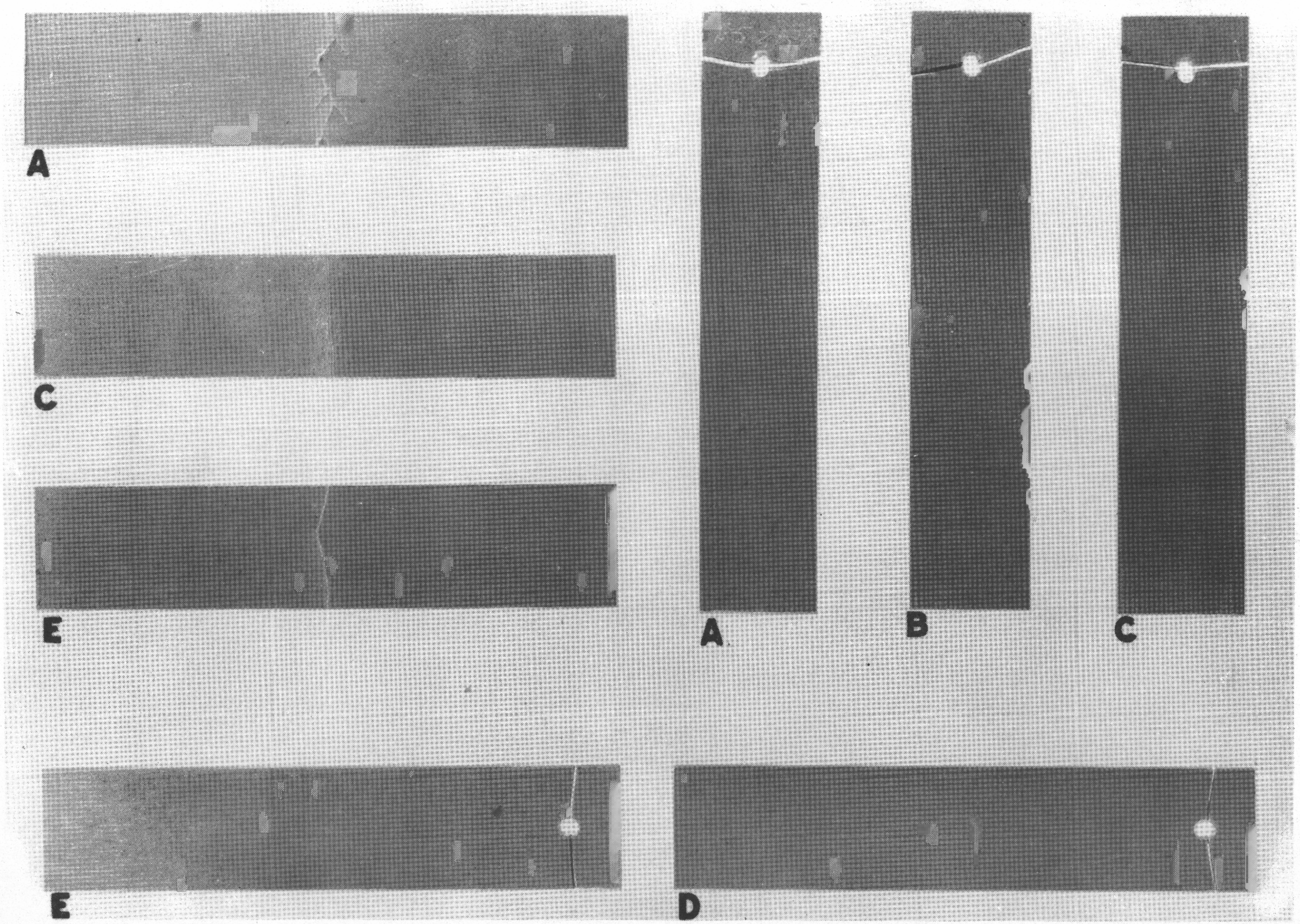


Figure 8.--Typical flexure failures and 1/8 inch diameter bearing failures of 1/8-inch papreg at various angles between grain direction and stress. Flexure specimens are shown flatwise from the tension side. A, 0°; B, 45°; C, 90° parallel-laminated; D, 0°; and E, 45° cross-laminated.

Z M 61877 F

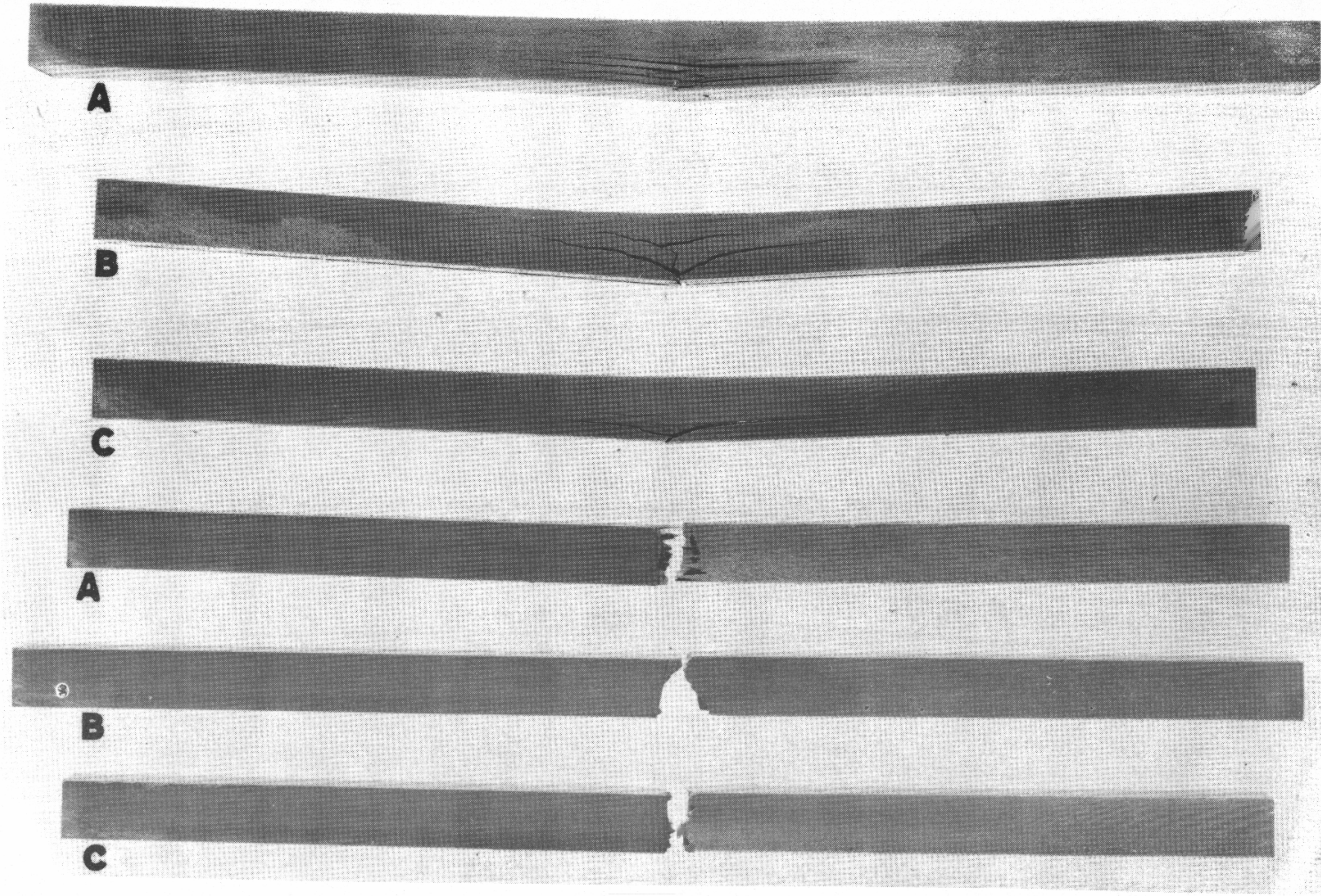


Figure 9.--Typical flexure failures of 1/2-inch papreg. The top group of three are edgewise views of flatwise failures. In the bottom group, edgewise failures are shown, with top views at the left and bottom views at the right. A, lengthwise; B, crosswise, parallel-laminated; C, 0° or 90° cross-laminated.

Z M 61878 F

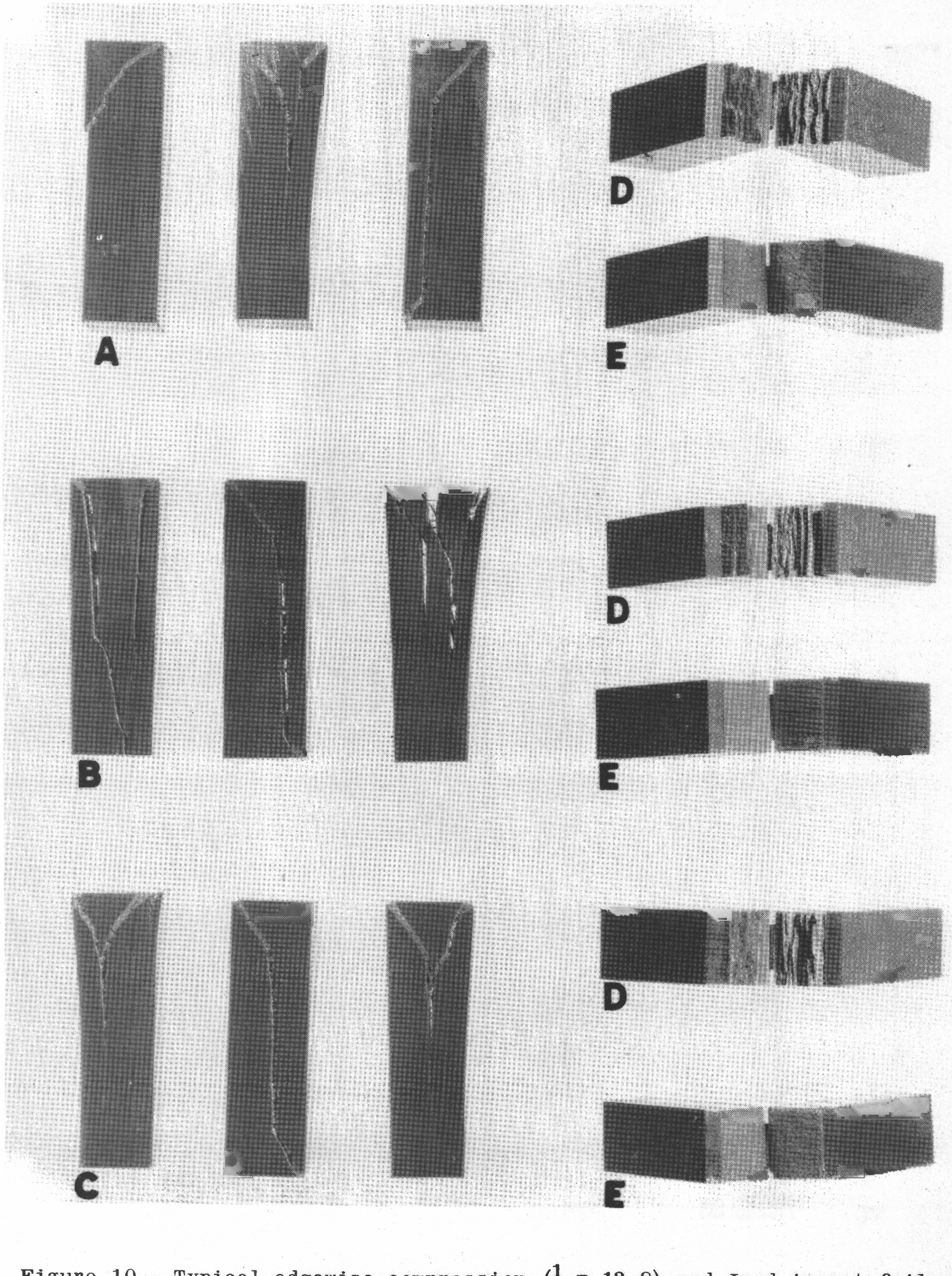


Figure 10.--Typical edgewise compression ($\frac{l}{r} = 13.8$) and Izod impact failures of 1/2-inch papreg. A, lengthwise; B, crosswise, parallel-laminated; C, 0° or 90° cross-laminated; D, Izod specimens notched flatwise; and E, Izod specimens notched edgewise.

Z M 61879 F

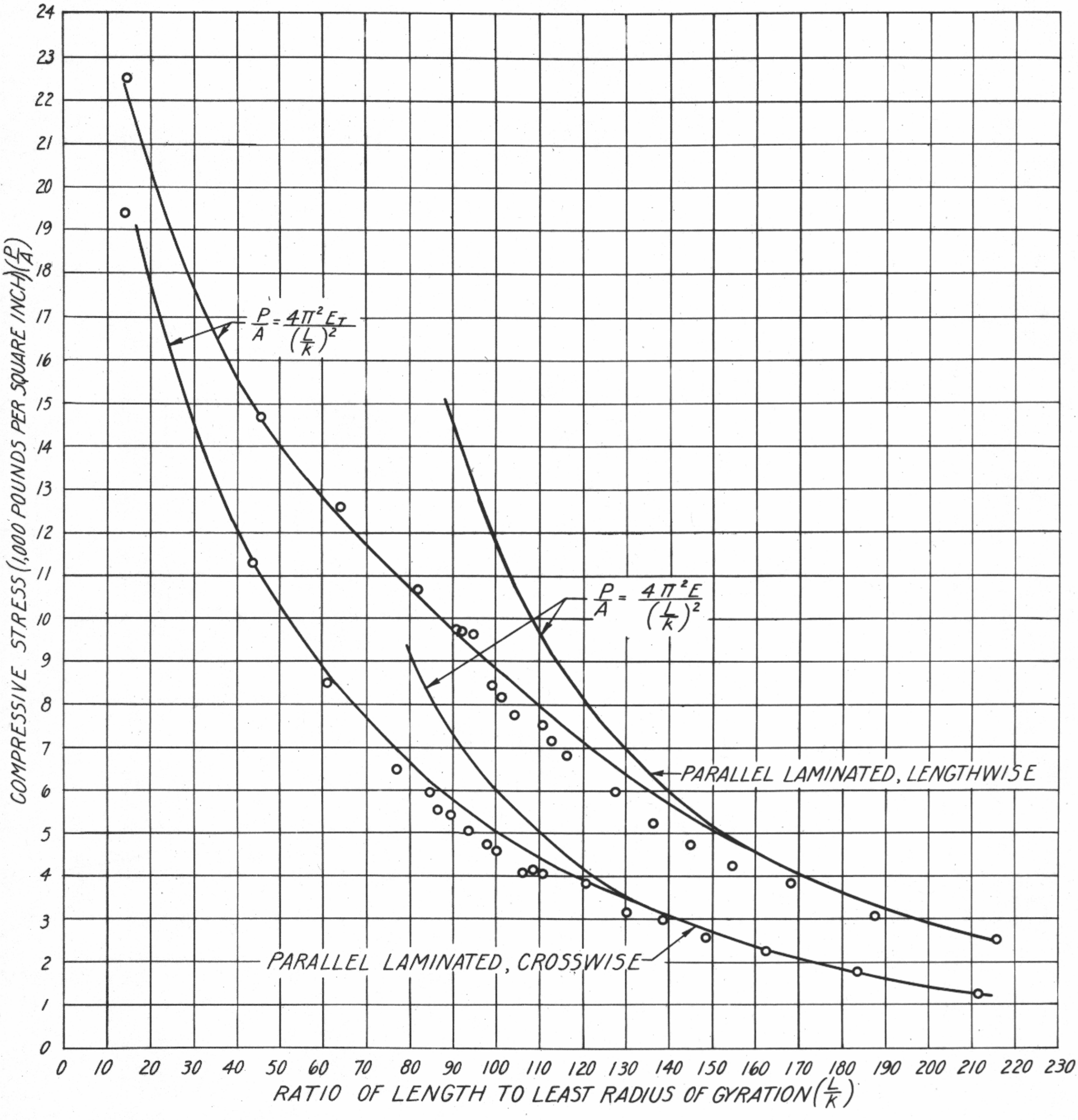


Figure 11.--Fixed-end-column strength of parallel-laminated papreg for various ratios of L/k. Points show individual test results, whereas lines represent computed Euler curves for fixed-end columns. The shorter lines are standard Euler curves and the longer lines are modified Euler curves based on successive tangent moduli.

Z M 61880 F

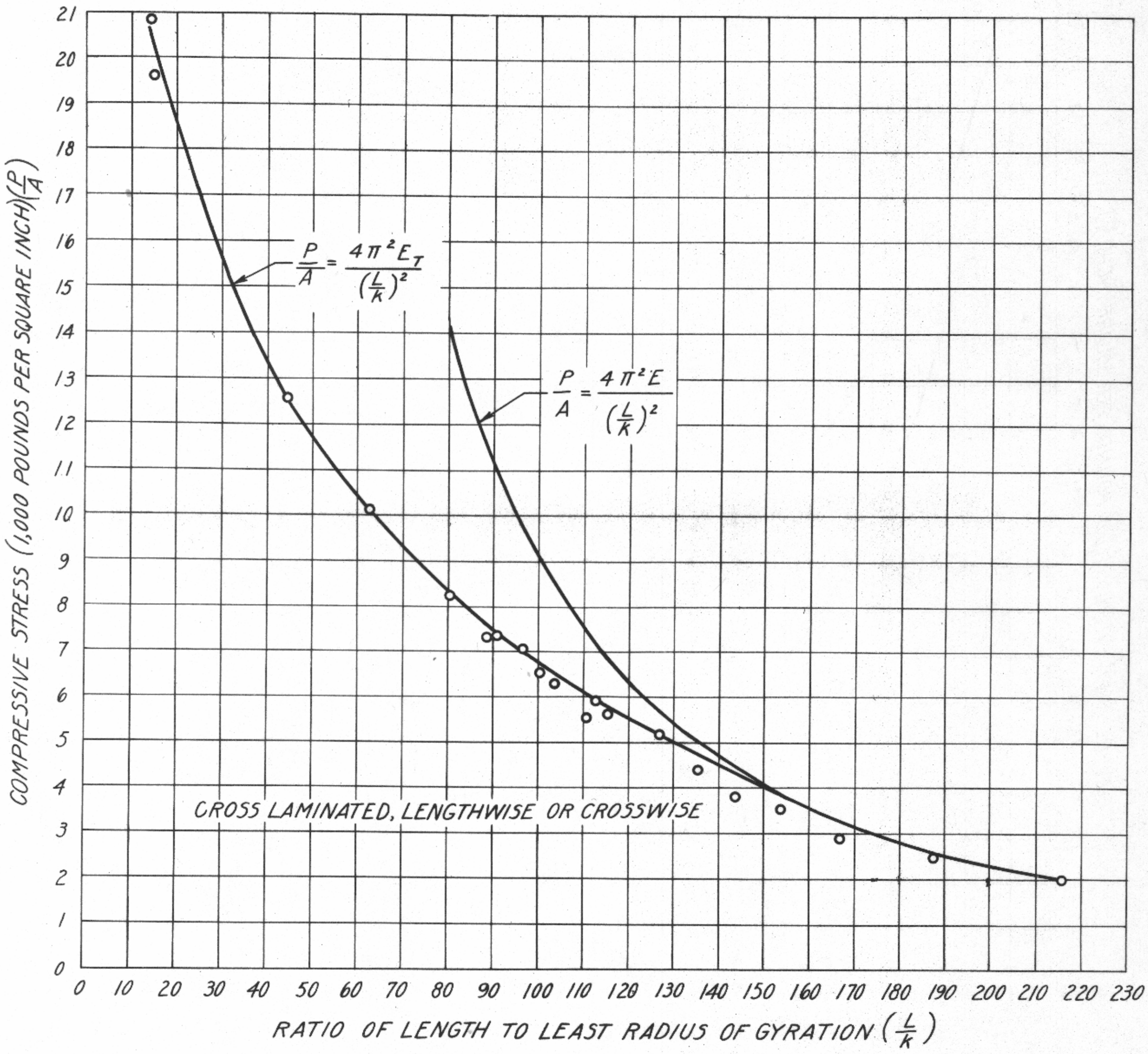


Figure 12.--Fixed-end-column strength of cross-laminated papreg for various ratios of L/k. Points show individual test results, whereas lines represent computed Euler curves for fixed-end columns. The shorter line is a standard Euler curve and the longer line is a modified Euler curve based on successive tangent moduli.

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