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FORT EUSTIS, VIRGINIA

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RESEARCH IN THE FIELD OF FIBERGLASS-REINFORCED SANDWICH STRUCTURE FOR AIRFRAME USE

FINAL REPORT

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July 1964

prepared by:

UNIVERSITY OF OKLAHOMA RESEARCH INSTITUTE
Norman, Oklahoma

HEADQUARTERS
U S ARMY TRANSPORTATION RESEARCH COMMAND
FORT EUSTIS VIRGINIA

This research effort was carried out under Contract DA 44-177-AMC-98(T) by the University of Oklahoma Research Institute, and was an investigation of fiberglass-reinforced plastics for possible use as a primary airframe structure.

The report has been reviewed by the U. S. Army Transportation Research Command and is considered to be technically sound.

The conclusions made by the contractor are considered by this command to be valid.

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Prepared by
University of Oklahoma Research Institute
Norman, Oklahoma

For
U. S. ARMY TRANSPORTATION RESEARCH COMMAND
Fort Eustis, Virginia

PREFACE

This report was prepared by the University of Oklahoma Research Institute under U. S. Army Transportation Research Command (USATRECOM) Contract DA 44-177-AMC-87(T). The report contains the test results, conclusions, and recommendations for research conducted during the period June 10, 1963, to February 29, 1964 in the field of fiberglass-reinforced sandwich structure for aircraft use.

The research program was directed by Dr. Gene M. Nordby, Dean of the College of Engineering at the University of Oklahoma. Mr. Joseph V. Noyes and Mr. W. C. Crisman were the principal research engineers. The research staff consisted of Mr. Donald Hanson, statistician; Mr. Terrell B. Warren, test engineer; Mr. Jim Morrison, machinist; and Mr. Cleon Reed, laboratory technician.

The University of Oklahoma Research Institute expresses appreciation to the J. P. Stevens Company for a sample of 181 high tensile strength (HTS) finish fiberglass fabric, the laminate properties of which are tabulated in Table 19 of this report, and to the Shell Chemical Company for their advice and assistance pertaining to the use of EPON 828-Z resin.

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SUMMARY

The research covered in this report involves investigation of the effects of raw materials usage and fabrication process variables on the final strength properties of fiberglass-reinforced plastic (FRP) sandwich structure suitable for use as a primary airframe structural material. The program encompassed the two types of sandwich fabrication used industrially, the one-step process method and the method whereby pre-laminated facings are bonded to the core in a separate step. The materials chosen for study were the promising Volan A finished 181 fiberglass fabric and EPON 828 epoxy resin activated by curing agent Z. Thin, 3-ply facings of these materials used in conjunction with honeycomb cores were the basic elements of the structural sandwich.

In detail, the scope of the program included determining the effect of curing time, pressure, and temperature as well as lay-up method on the basic strength properties of the sandwich. Following the premise that the best bonded type sandwich would be the combination of the facings cured under the optimum conditions (as for the entire single-step type sandwich) and the optimum adhesive system and cure for a given core material, the facings and their bonding to the core were investigated separately. Advice from the literature and from the manufacturers of the constituent materials was considered carefully in establishing the levels of the fabrication process variables to be studied, to insure that data would be obtained within the optimum range. Where possible, standard test specifications were followed to assess the performance of the materials and processes.

The results of the research program include the isolation of the optimum conditions of fabrication; the expected strength values for these optimum fabrication conditions; the best lay-up method; and the performance of several adhesive system-core material combinations with optimum conditions of cure for each. Among the many by-products of the research effort is a multi-ply coating machine which is capable of impregnating several layers of fabric simultaneously.

CONCLUSIONS

The major conclusions drawn from the research are as follows:

1. The initial resin content of the facings of sandwich material and the uniformity and extent of voids in the impregnation have an important effect on its final strength properties. This is especially true when the facings are thin. The effect is also associated with the flow that takes place during the resin cure cycle.

2. The mechanical coating process produces more controllable and uniform resin impregnations of fiberglass fabric laminations than the hand squeegee method.

3. For the vacuum blanket technique of applying pressure to EPON 828-Z epoxy resin impregnations, 20 inches of mercury is a safe lower vacuum pressure to prevent resin bubbling within the 160- to 200-degree Fahrenheit temperature range.

4. Room temperature B-staged lay-ups of 828Z-181 Volan A laminations are more convenient to work with and can be expected, in most cases, to produce slightly higher strengths.

5. Post-cure time between one and three hours at 300 degrees Fahrenheit, for the pre-cure and mold (cure) conditions investigated, does not have a major influence on the room temperature strength properties developed from resin cure.

6. Within the levels of cure pressure, temperature, and time examined in this project (10-70 psi, 160-230°F, and 60-90 minutes), the optimum strength properties and their specific cure conditions are as given in Tables 2 and 3.

7. For the 60-minute cure time, within the range of post-cure times investigated (1 to 3 hours), higher molding pressures and temperatures are required to develop strength properties comparable to those obtained for 90 minutes' cure during the mold phase of fabrication.

8. A serious condition of resin starvation on the upper facing can be expected when the wet lay-up of the facings is used directly in the fabrication of sandwich by the single-step method. This condition is not nearly so severe when the 10-hour room temperature B-staged lay-up is used.

9. Of the three adhesives studied, the Armstrong A-12 produces the strongest core-to-facing bond on 20 percent phenolic-impregnated kraft paper honeycomb core; the EPON 828-Z epoxy resin and the Scotchweld AF-110B produce the strongest bond on 20 percent phenolic-impregnated HRP fiberglass honeycomb core; and the AF-110B produces the strongest bond on aluminum honeycomb core.

10. The separately bonded-type sandwich material investigated can be expected to develop a maximum of 30 percent higher compressive strength than the single-step-type sandwich.

11. The optimum conditions of fabrication for tensile and compressive properties are not the same; hence further testing is required to establish flexural optimum strength properties.

RECOMMENDATIONS

On the basis of the investigations made in this research program, it is recommended that:

1. Further research be conducted to determine the effect of resin content on the final strength properties of FRP laminates, to include the effect of air voids in the pre-preg.

2. The multi-ply coating machine be further developed to determine a means of minimizing or eliminating the occurrence of air voids in the pre-preg output.

3. For FRP sandwich or laminates employing EPON 828 epoxy resin activated with curing agent Z and 181 Volan A finished fiberglass fabric, when fabricated within the envelope of conditions used in this project (cure time: 60-90 minutes; cure pressure: 13-70 psi; cure temperature: 160-230°F; and post-cure time at 300°F: 1-3 hours), the following conditions be utilized to achieve optimum or peak values, as be the case, of the desired strength properties: 1) pre-cure according to the scheme of dwelling to within 7 minutes of the gel point of the resin (Figure 1) or, allowing one minute for heat-up to mold temperature, when the gel time is less than 7 minutes; 2) cure in the mold phase at 90 minutes according to the conditions of temperature and pressure given in Table 2 or 3; 3) and post-cure between 1 and 3 hours at 300°F. Use of the B-staged method of lay-up is recommended when handling ease is a criterion.

4. Armstrong A-12 adhesive be used to effect the core-to-facing bond of phenolic-impregnated kraft paper core to FRP facings of 828-Z epoxy resin and fiberglass fabric, that either EPON 828-Z epoxy facing resin or Scotchweld AF-110B adhesive be used to effect this bond on phenolic impregnated fiberglass core, and that AF-110B be used for the bond on aluminum core.

5. Research be done in the area of the single-step method of fabricating sandwich to minimize or eliminate the resin flow from the upper to the lower facing. Optimizing this method of sandwich fabrication is considered important in that for the molding of curved surfaces the inexpensiveness, simplicity, and speed of fabrication of the single-step method may far outweigh the increase in strength gained in the sometimes difficult prelaminating of the inner and outer facings required for the bonded sandwich. The investigation of techniques required to mold sandwich into compound curvatures should be included in this research effort.

6. Flexural tests be performed to expand the results of this research program.

DISCUSSION

INTRODUCTION

A knowledge of the manner in which the strength properties of a material vary with changes in the basic fabrication process is necessary before it can be accepted as a primary structural element. This is particularly true of fiberglass-reinforced plastic (FRP) materials because of the large number of fabrication process variables and the sensitivity of the material properties to each of these variables. The goal of the research program presented in this report was to contribute to this body of knowledge in the realm of FRP sandwich materials for aircraft structural use.

The principal materials used were hexagonal-cell honeycomb core, electrical (E) glass 181-weave Volan A-finished fiberglass fabric, EPON 828 epoxy resin, and curing agent Z. Limited data were obtained for HTS finish 181 fiberglass fabric.[1] Consideration was given to both the separately bonded and single-step fabricated thin facing sandwich. A program was conducted to detect the relation between the curing cycle variables and the mechanical properties of FRP facing sandwich fabricated by the single-step process and of bare FRP facings pre-laminated for use in the separately bonded-type sandwich. The program was carried out for the wet and the B-staged type of lay-up. For the separately bonded-type sandwich, an adhesive study was performed to indicate optimum bonding conditions for suitable adhesives and core materials. All testing was done at room temperature.

PROGRAM ANALYSIS AND DESIGN

To study the relation between the resin curing cycle variables and final strength properties of the FRP materials, and hopefully to locate the optimums, a rather large statistically designed experiment was planned for wet and B-staged lay-ups. Though it was realized that no one area could be studied intensely because of the time and expense involved, valuable trends were expected to be established along with areas suitable for more detailed examination. Duplication or replication was not planned becuase experimental error is not usually uniform across a program of this magnitude. The literature (reference 1) indicates that higher order interactions are quite acceptable as approximations of experimental error necessary to perform an analysis of variance. The exact lay-out of the program is displayed by Tables 5 and 12. Each variable and the ranges to be examined were given careful consideration.

First it should be mentioned that the total curing cycle associated with the production of FRP can be separated into three sub-cycles: pre-cure, mold, and heat treatment, often called afterbake or post-cure. The pre-cure

[1] Table 19

period allows time for the material to be brought up to the desired mold temperature. The mold portion of the cure cycle serves to compact the material and to establish its shape. Post-cure at an elevated temperature effects further cross-linking of the epoxy molecule thus to improve the mechanical properties.

With these preliminaries in mind the variables can be discussed in detail. In reference 2, an interaction was noted between pressure and temperature during the mold phase. To minimize this, the usual pre-cure phase of just heat-up to mold temperature was modified at the low cure temperatures. Here the pre-cure used was the systematic procedure of heat-up to mold temperature plus dwell to within 7 minutes of gel point (determined by inspection). At the higher temperatures where the gel time was less than 7 minutes, one minute for heat-up was allowed.

In setting the specific values of the molding variables, effort was made to bracket those suggested by the manufacturer. Thus, 160, 180, 200, and 230 degrees Fahrenheit were the temperatures selected. Initially for the single-step sandwich panels the recommended value of 90 minutes was accepted for the mold time; however, as the program progressed and the laminate study began, a second time value of 60 minutes was used also. The object was to obtain an indication of the optimum value, which was anticipated to give less interaction between the mold phase and the post-cure. The molding pressures first chosen for the single-step panels were 13 and 30 psi, the usual vacuum blanket technique being used for the low pressure (in that this is common practice) and a gydraulic press for the high pressure. Because of a resin vaporization problem encountered early in the single-step work, the 13-psi pressure was changed to 10 psi. All of the laminate fabrication was scheduled on the hydraulic press at three pressures--13, 30, and 70 psi.

For the post-cure phase, only the time was permitted to vary. At the recommended 300 degrees Fahrenheit, 2- and 3-hour periods were used for the single-step panels and 1, 2, and 3 hours for the laminates. Thus the fabrication conditions, at most, encompassed 3 post-cure times at each of 3 cure pressures under each of 4 cure temperatures for 2 cure times in each case.

It was believed that the best separately bonded type of sandwich could be obtained through separate optimization of the facings and the core-to-facing adhesive system. To this end the facings were studied along with the single-step sandwich as previously outlined. The adhesive program was designed to investigate the performance of three commercially available adhesives on paper, fiberglass, and aluminum honeycomb cores for an appropriate range of bonding conditions. The three basic epoxide adhesives to be used were: 3M Company's EC-1595, a single-component thixotropic paste; Armstrong Resin Company's A-12, a two-component thixotropic paste; and 3M Company's AF-110B, a B-staged supported film.

Time and temperature were believed to be the critical core-to-facing bond variables; therefore, only the pressure deemed sufficient to hold the parts in position and insure full contact was applied during the bond cure. For each adhesive, the ranges of time and temperature were chosen so as to bracket the manufacturer's suggested values. Table 20 serves to display the adhesive program in detail. The bonding of paper core with AF-110B and EC-1595 was not scheduled because of the high temperatures involved. The single-step sandwich core-to-facing bond strength data was chosen to show the adhesive qualities of the basic resin system.

The performance of the materials fabricated according to these programs would be determined by the strength properties developed by standard test specimens. Should no standards be available, a suitable specimen would be developed. Edgewise compression along the paralleled core-ribbon and fabric-warp direction was the test planned for the evaluation of the single-step fabricated sandwich. Six specimens for this test were desired from each panel. Plate shear tests would also be conducted for each panel and three specimens were desired for both the perpendicular and parallel-to-core ribbon directions. Both compression and tension parallel-to-warp were planned for the laminates. Twenty-four specimens were desired from each of the three postcure time slices cut from each molding. The flatwise tension test was scheduled for evaluation of the bonds with seven specimens desired from each sandwich panel. In conjunction with the testing, it was planned to monitor the resin content of each fabrication condition.

FABRICATION PROCESSES

As mentioned previously, 181 Volan A finish fiberglass fabric was used exclusively in this research program. Further, only 3-ply facings of nominal thickness 0.030 were used. The predominate core used was "Aircomb" type 125-35-20 phenolic-impregnated paper of 3/4-inch thickness and 0.42-inch cell size. Any deviation from this core is shown with the associated experimental data.

The very promising structural resin, EPON 828 epoxy activated by curing agent Z was also used throughout the program. The mixing ratio used was 20 parts curing agent to 100 parts resin by weight. To insure complete mixing of the high viscosity room temperature resin with the normally crystallized curing agent, the resin was first heated to 120 degrees Fahrenheit and the curing agent to 150 degrees. The materials were then quickly mixed and put to use. Rapid and complete impregnation of the glass fabric was obtained, and the rapid cooling of the resin applied over the wide expanse of the fabric permitted good quality room temperature B-staging.

Before fabrication could be initiated, it was necessary to establish the relation between temperature and gel-point time for several degrees of room temperature B-staging. This was done by inspection. Twelve-inch-square, 3-ply patches saturated with resin were placed on a heated press platen, covered with a felt insulation blanket, and probed periodically with a small wooden stick until the resin string pulled out would break at 2- or 3-inch lengths. For each temperature and state of B-staging, the time between heat application and resin string break was the desired time value. Figure 1 is a plot of the data thus obtained.

Fabrication effort started with the single-step sandwich panels. The dimensions of the panels made at low pressure on the vacuum press were 38 by 15 inches, and the dimensions of the panels made on the hydraulic press were 28 by 22 inches. In the beginning, the fiberglass fabric was impregnated by a hand-operated coating machine which drew a continuous single ply of fabric through a resin vat and onto a take-up roll. As needed, the single ply of fabric was cut and removed from this roll and successively stacked on a 1/32-inch-thick aluminum caul to obtain the desired facing thickness. The caul was then placed on the heated press platen set at cure temperature; a polyethylene film was stretched across the wet laminate; and for approximately 3 minutes, the excess resin was hand-squeegeed out of the wet laminate so that the appearance of a uniform distribution of resin was obtained.

The caul was then removed from the platen and set aside until another wet laminate could be prepared and squeegeed to provide the opposite facing of the sandwich panel. Upon completion of both wet facing lay-ups, they were either used directly or allowed to cool and B-stage at room temperature. When ready for use, the polyethylene cover film was stripped off of each, and one of the cauls with a laminate was inserted in the open press (vacuum or hydraulic[1]) which was preset at the desired curing temperature. A pre-cut slice of "Aircomb" core material was then placed on top of this lower facing so that the core ribbon paralleled the fabric warp. The second caul and laminate were then inverted and placed on top of the core slice with the laminate against the core. The press was then closed and the pre-cure cycle timed from closure. The actual pre-cure duration used was the planned gel-point time minus 7 minutes further diminished by the time on the heated press platen during the squeegee operation. Upon completion of the pre-cure phase, the curing pressure was applied. Then after the completion of the mold phase, the panels were removed (cut in half if vacuum molded) and placed in an electrically heated air recirculating post-curing oven at 300 degrees Fahrenheit for the planned post-cure durations. These panels or half panels were cut into the desired number of specimens which were then prepared for testing.

[1]Press equipment is described in Appendix I.

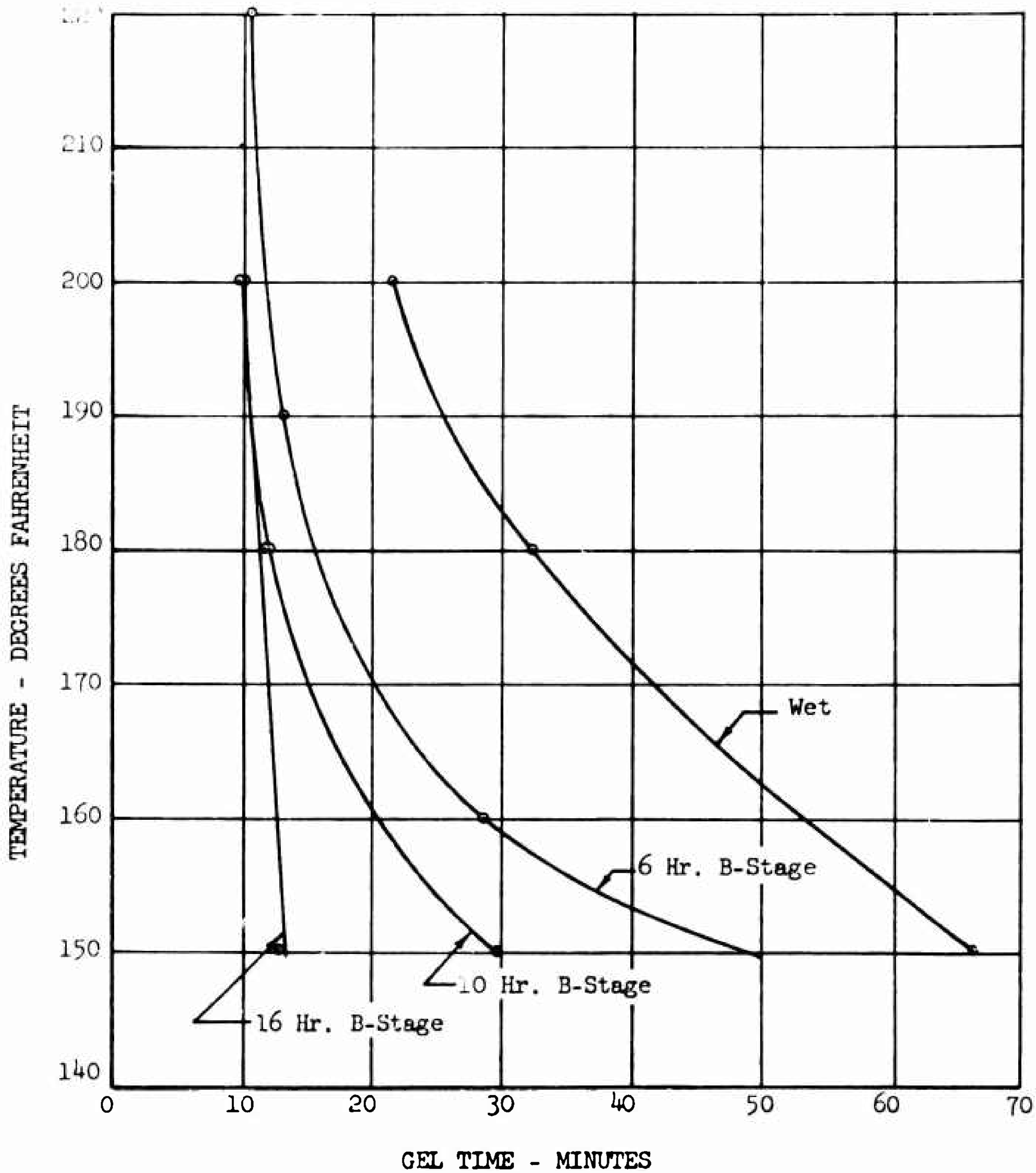


Figure 1. The Effect of Temperature on the Gel Time of Shell EPON 828-Z Resin in a 3-Ply Lay-Up of 181 Volan A Fabric.

It became apparent that the hand squeegee technique would not produce panels of uniform or predictable resin content. Also, small air pockets which were trapped between plies during stacking of the wet fabric proved very difficult to remove by handworking. Consequently, a multi-ply coating machine was constructed which could simultaneously impregnate a number of plies of fiberglass fabric and perform this operation with a controllable and reproducible resin content. The machine is described in Appendix I. The impregnations produced on the machine were 3-ply of 180-inch length and 44-inch width. The machine output, whether wet or room temperature B-staged, was cut up and placed in cold storage (50F) for later use as needed--usually within 10 days. The air voids present in the hand lay-ups were also present in the machine pre-preg but to a much lesser degree.

Fabrication of the laminates was begun after the development of the coating machine. The molding size used for the laminates was 26 by 20 inches. A pre-cut patch of the uncured laminate (in either the initially wet or B-staged condition) was removed from the freezer unit and allowed to warm up to room temperature (about 25 to 30 minutes) before the polyethylene cover films were removed. It was then placed between two aluminum cauls which had been coated with a thinned solution of silicone parting agent (Dow-Corning DC-7). Of course the silicone could not be used had bonding of the laminates to cores or test fixtures been anticipated (in this case Teflon cauls were used). The cauls with impregnate were then placed in the hydraulic press and the pre-cure period timed from closure of the upper platen against the sheets. The pre-cure and mold phases parallel those discussed previously for the single-step panels. After completion of the press phase, the cured laminate was removed and cut into three equal pieces. Each of these pieces was placed in the post-curing oven simultaneously, and then removed, in order, after the elapse of the specified 1-hour, 2-hour, and 3-hour post-cure periods. Each of the three strips was then cut into the desired number of tension and compression specimens and ground to final width and length dimensions.

Fabrication of the sandwich panels for the adhesive system study was accomplished after the staff had considerable experience with the single-step sandwich and the laminates. The facings used for the bonded sandwiches were 3-ply impregnations laminated at 200 degrees Fahrenheit and 50 psi for 60 minutes with no post-cure. Their dimensions were 6.5 by 8.5 inches. The three cores were "Aircomb" type 125-35-20 phenolic-impregnated paper, HRP type GF-11 phenolic-impregnated fiberglass, and 5052 aluminum alloy with the dimensions listed in Table 20. As previously discussed the adhesives tested were EC-1595, A-12, and AF-110B.

After the facings were produced, they were lightly sanded on the bonding side, degreased with Acetone and air dried in a 150-degree Fahrenheit recirculating air oven. The paste adhesive systems were then applied to the facings by a 3-inch-long notched-edge scraper (8 notches per inch at 3/64-inch depth) and the film supported adhesive, by cutting the desired size and placing it on the facings. For each bonding run, a set of four sandwich specimens utilizing the same core material and adhesive system was placed on aluminum cauls and inserted in the press. Pressure was set at an equivalent 10 psi on each sandwich panel, and the bonding duration was timed from the closure of the press. Individual specimens were then removed from the press after the elapse of each of the four time periods (see Table 20). The panels were then cut into 1-inch-square specimens for the flatwise tension testing.

TEST SPECIMEN PREPARATION

The single-step fabricated sandwich was prepared for edgewise compression testing according to MIL-STD-401A. Test specimens were cut to 4- by 4-inch nominal dimensions from the large sandwich panels. The cutting was performed by a high-speed abrasive circular saw so as to minimize tearing of the FRP facings and the core-to-facing bond. The loaded ends of the specimens were locally reinforced by potting them with polyester resin which had been filled with 30 percent by weight of high-strength molding plaster. The specimens were then fastened in the vise of a Cincinnati No. 2 tool grinding machine and the reinforced ends were ground flat and parallel with each other and 90 degrees to the plane of the facings. A No. 53 drill turning at 4800 rpm was used to drill gage-length holes in both facings of half the specimens tested from each fabrication condition. These holes served to mount and locate the gage points of the sandwich panel compressometer shown in Figure 4. All edgewise compression specimens were loaded along the paralleled core-ribbon and facing-warp direction.

Single-step sandwich plate shear specimens were cut to the 2-inch by 6-inch nominal size according to MIL-STD-401A. Specimens were cut from each panel fabricated in both the perpendicular and parallel to core ribbon direction. The 5/8-inch-thick steel plates were bonded to each facing of the specimens for the plate shear test. The plates were prepared for bonding by being thoroughly stripped of any prior glue film, then washed and lightly sandblasted in the bonding area: Care was taken not to touch the sandblasted area prior to glue application. EPON 6 was the adhesive used and was applied with a notched scraper. The shear specimen was positioned between the plates such that the line of action of the test load would pass through diagonally opposite corners. The plates and specimens were then placed in a 175-degree Fahrenheit oven for 2 hours to cure the adhesive fully. The bonded plates and specimen were then removed from the oven, cooled, and placed in the loading grips for testing as shown in Figure 7.

The facing-to-core bond test specimens (whether the basic resin or a separate adhesive effected the bond) were also prepared according to MIL-STD-401A. Specimens of dimensions 1 by 1 inch were cut from each panel fabricated and tested in flatwise tension. The facing surfaces of the specimens were lightly sanded and degreased with acetone. The specimens were then bonded to 1-inch-square aluminum blocks with EPON 6 adhesive, the surface of the blocks being prepared for bonding in the same manner as the shear plates. The bonding cure was also carried out identically. Figure 14 shows the bonded blocks and specimen installed in the testing machine.

Because of the small thickness of the FRP laminates tested in this program it was necessary to design a special thin-sheet-type compression fixture (Figure 9) and to size the compression specimens precisely to fit this fixture. The sizing of the tension speciemns was not quite so critical, but a certain amount of experimentation was still required to produce consistent test results in spite of the characteristically brittle nature of the laminated material.

The thin compression specimens were originally machined as shown by A in Figure 2. Invariably this configuration fractured in a region close to where the faired radii met the straight reduced section, thus making accurate measurement of the failed cross-section area virtually impossible. Considering the relative brittle nature of the material which precludes the relief of stress concentration, the occurrence of this behavior is not altogether surprising. Straight-sided specimens were therefore produced which failed at the various locations shown in B, C, and D of Figure 2, all within the test fixture supported length of the specimen. Thus, accurate measurements of the cross section area could be made regardless of where the specimen fractured. The exact dimensions of the final configuration were 0.75 x 3.675 inches for the ultimate stress test and 1.0 x 3.675 inches for the modulus test. The specimens were cut with a large sheet-metal shear and dressed to the desired dimensions on the previously mentioned grinder.

As shown in Figure 3, the thin tension specimens were originally shaped as for sheet metals. Similar to the behavior of the above-mentioned compression specimen, the shaped tension specimens failed at the point of tangency of the fairing radii. Efforts to alleviate the problem by reducing the area reduction ratio as at B and C of Figure 3 proved to be fruitless. Finally, the configuration D was arrived at as producing consistent breakage results. This was accomplished by grinding the specimens straight sided and very slightly influencing the center of the specimen with a 0.007-inch notch on each side as shown by the pointers in D of Figure 3. This influence precluded the occurrence of specimen failure in the testing grips and also forced fracture of the specimen inside the gage length of the strain extensometer. The notching was done by a $\frac{1}{2}$-inch-diameter, high-speed carbide router and was controlled to within $\pm$ 0.0005 inch between specimens. Ultimate stress and modulus values were thus calculated based on the width of the slightly reduced section, which was measured on each specimen with a tapered-anvil micrometer. The final dimensions established for the specimens were 0.75 and 9 inches. The tension specimens were cut and ground to size as were the compression specimens.

1/2 FRAMES

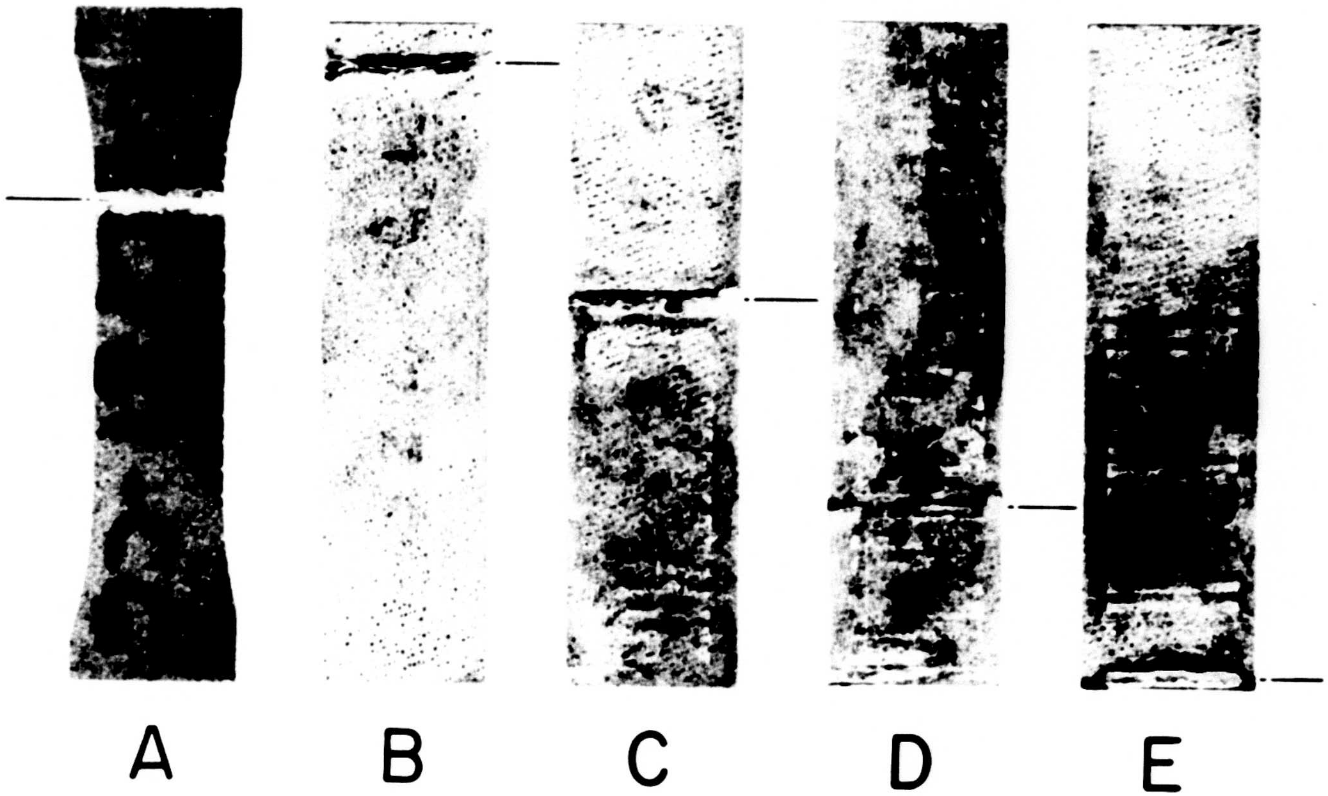


Figure 2. Laminate Compression Specimens: A, specimen shape initially evaluated; B,C,D,E, straight-sided specimens which were used throughout the test program showing various points of failure that occurred within the fixture grips.

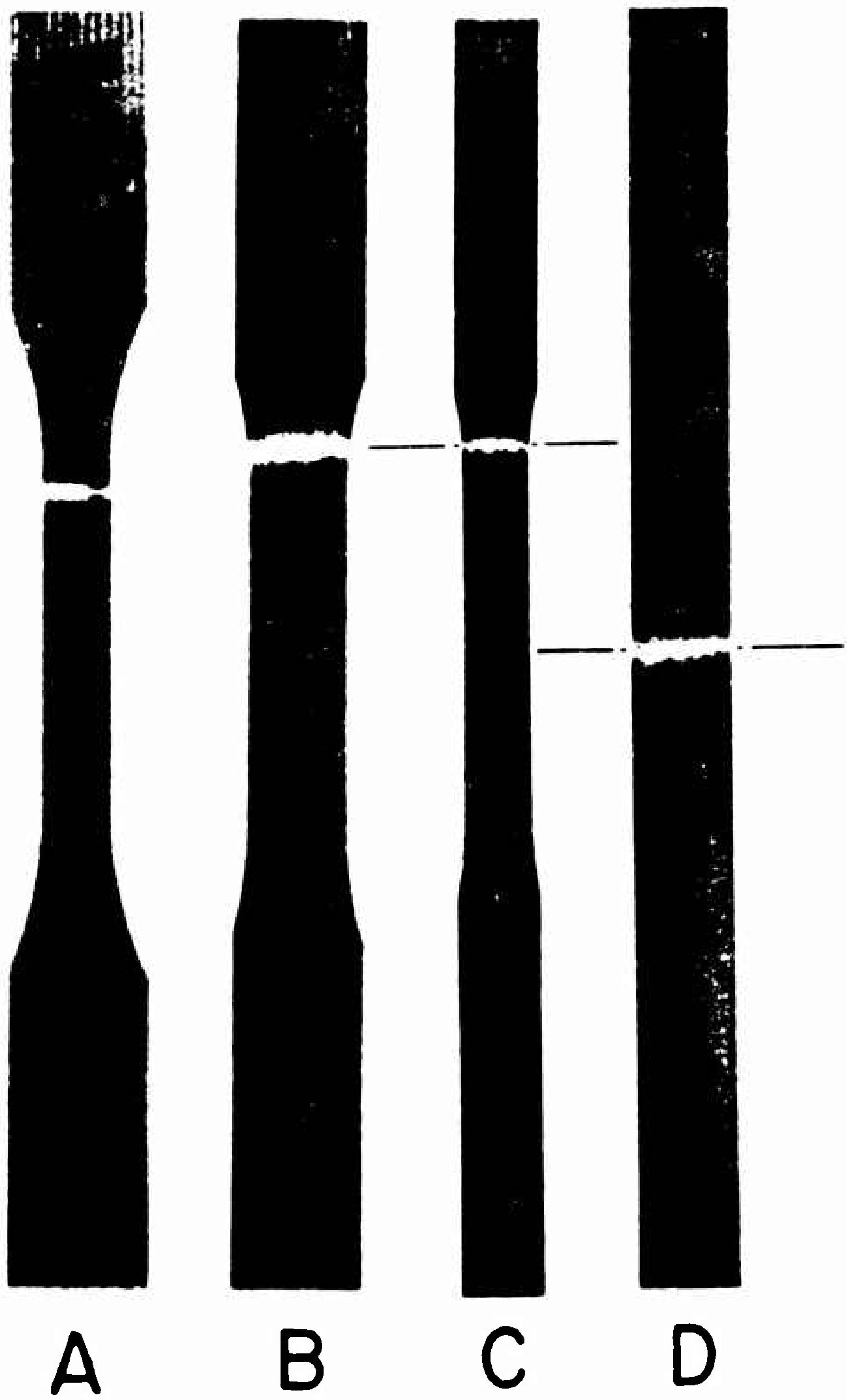


Figure 3. Laminate Tensile Test Specimens: A,B,C, various shaped specimens initially evaluated in the tensile testing program; D, straight-sided specimen with 0.007-inch side influences (see pointers) which was used throughout the test program.

EXPERIMENTAL PROCEDURE

The procedures used during the testing phase of the research program can best be presented under the four headings of resin content, single-step sandwich, bare laminates, and core-to-facing bond.

1. Resin Content

Though not of major concern during this research program, the resin content of the laminated facings for each fabrication condition was considered important. Samplings were made of both the bare laminates and the facings of the single-step sandwich. The ratio of the resin to the total weight of the specimen expressed in percent was the measurement used. For the case of the single-step sandwich facings this was modified as follows:

For resin content measurement a 2-inch square was cut from each of the 4-inch-square single-step sandwich specimens tested to failure as pictured in Figure 6. The facings were stripped from the cores of these small squares and the excess core remnants removed with a sharp knife. Each facing was then measured to the nearest 0.01 inch and weighed to the nearest 0.01 gram. The weight of the glass in the measured area, calculated from density, was subtracted from the total weight of the facing sample and the result divided by the total weight to obtain a resin content index. The term index is used because of the inaccuracy produced by the loss of resin that adhered to the end of the core. The values of each set of specimens were averaged to obtain the resin content index for each fabrication condition.

The resin content (RC) of the bare laminates under each fabrication condition was obtained using the following formula:

$$RC = \frac{(W - 3\,d\,w\,L)}{W} \times 100$$

where

- W is the average specimen weight
- d is the fabric density accurately determined by measurement
- w is the average specimen width
- L is the average specimen length

The specimen weight (W) was obtained by weighing the entire group of specimens (to 0.01 gram) for each fabrication condition and dividing by the number of specimens. Average specimen length and width measurements were obtained by measurement of a random sampling of each group of specimens with a caliper.

2. Single-Step Sandwich

Edgewise compression ultimate strength and modulus were taken as the criteria for evaluation of the single-step fabricated sandwich material. The specimens cut to a nominal 4- by 4-inch dimension were accurately measured to within 0.01 inch before testing. For the calculation of stress area the lengths (a) of the two loaded edges were averaged. Likewise, the specimen gage length used in the computation of strain was the average for both facings. The facing thicknesses (t) were taken as three times the average fabric thickness (0.01) and the stress area (A) calculated by $A = 2\ a\ t$.

The test procedure followed closely that recommended in MIL-STD-401A. The tests were made on a Tinius-Olsen testing machine of the balance-beam type having a capacity of 200 kips. Load was continuously applied to failure at a cross-head speed of 0.033 inch per minute. The beam was kept in balance by the operator who called out the load at selected intervals previously determined by the anticipated maximum load. The load registered at the instant the beam dropped was taken as the ultimate load, and the ultimate stress was then computed by dividing this load by the previously determined area.

The following particulars are significant in the test set-up. Mill-faced loading blocks were made and secured to the upper and lower loading platforms of the testing machine. To insure uniform distribution of the load across the edge of the specimen, the loading platforms were brought close together and the space between them checked with feeler gages and adjusted with shims until the faces were parallel throughout their surface areas Clamped loaded-edge condition was provided by means of a pair of accurately machined steel wedges at each loaded edge. The operator adjusted the wedges with reference to guide lines etched into the loading blocks (Figure 4) to center the specimen and to place the loaded axis perpendicular to the face of the blocks.

Stress-strain monitoring was done with a compressometer specially designed for this purpose (Figure 4). The compressometer calibration is discussed in detail in Appendix I. Readings were taken from Baldwin SR-4 strain gage reader console at the increments of load called out by the machine operator and later converted to strain by dividing by the compressometer constant. Stress-strain data were taken on one-half of the specimens tested.

Figure 6 illustrates the two basic failure modes encountered in these tests. The specimen on the left shows a clean fracture of

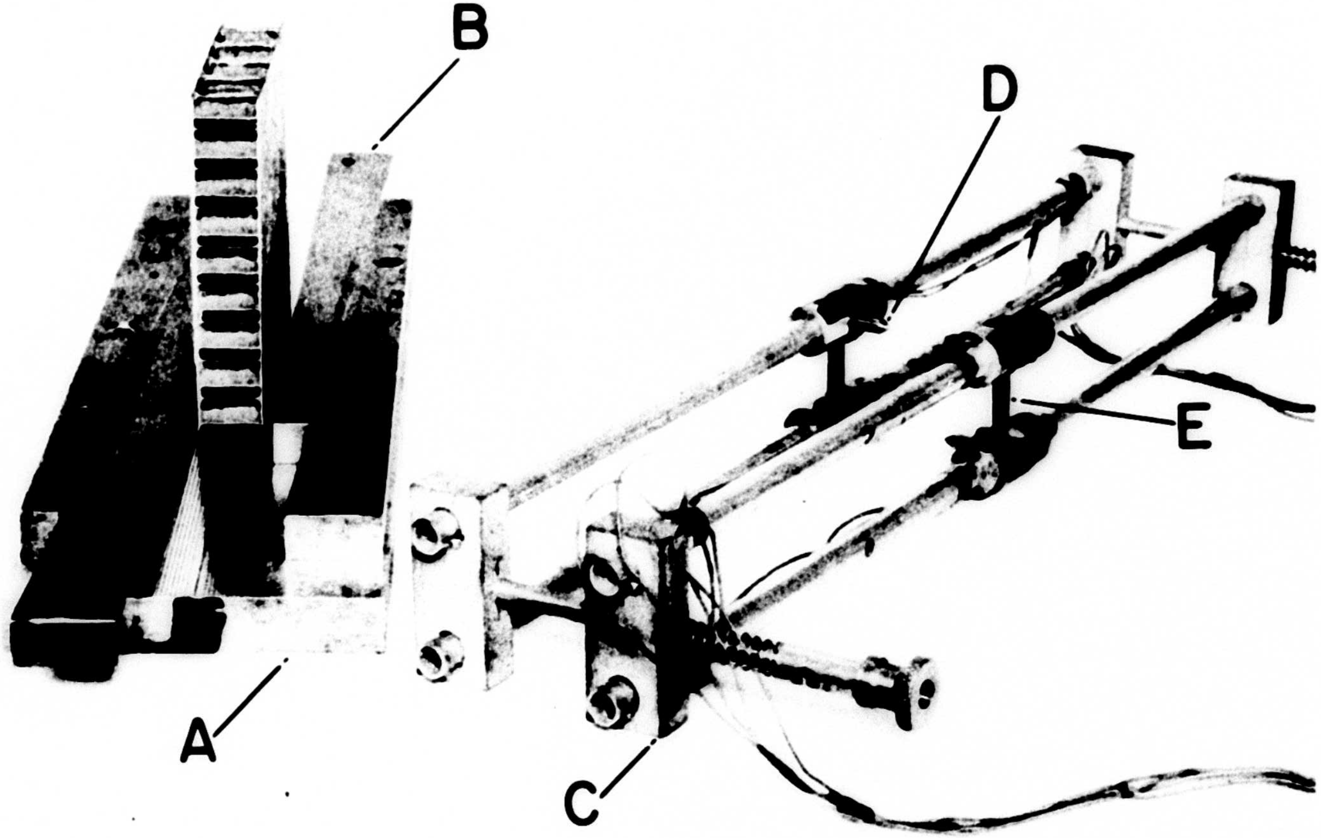


Figure 4. Sandwich Panel Edgewise Compression Test Apparatus: A, head plate showing guide lines for centering; B, sliding wedge grips; C, sandwich panel compressometer; D, needle points (2 per side) for following compression strain; E, strain gauge flexure strip.

FRAMES

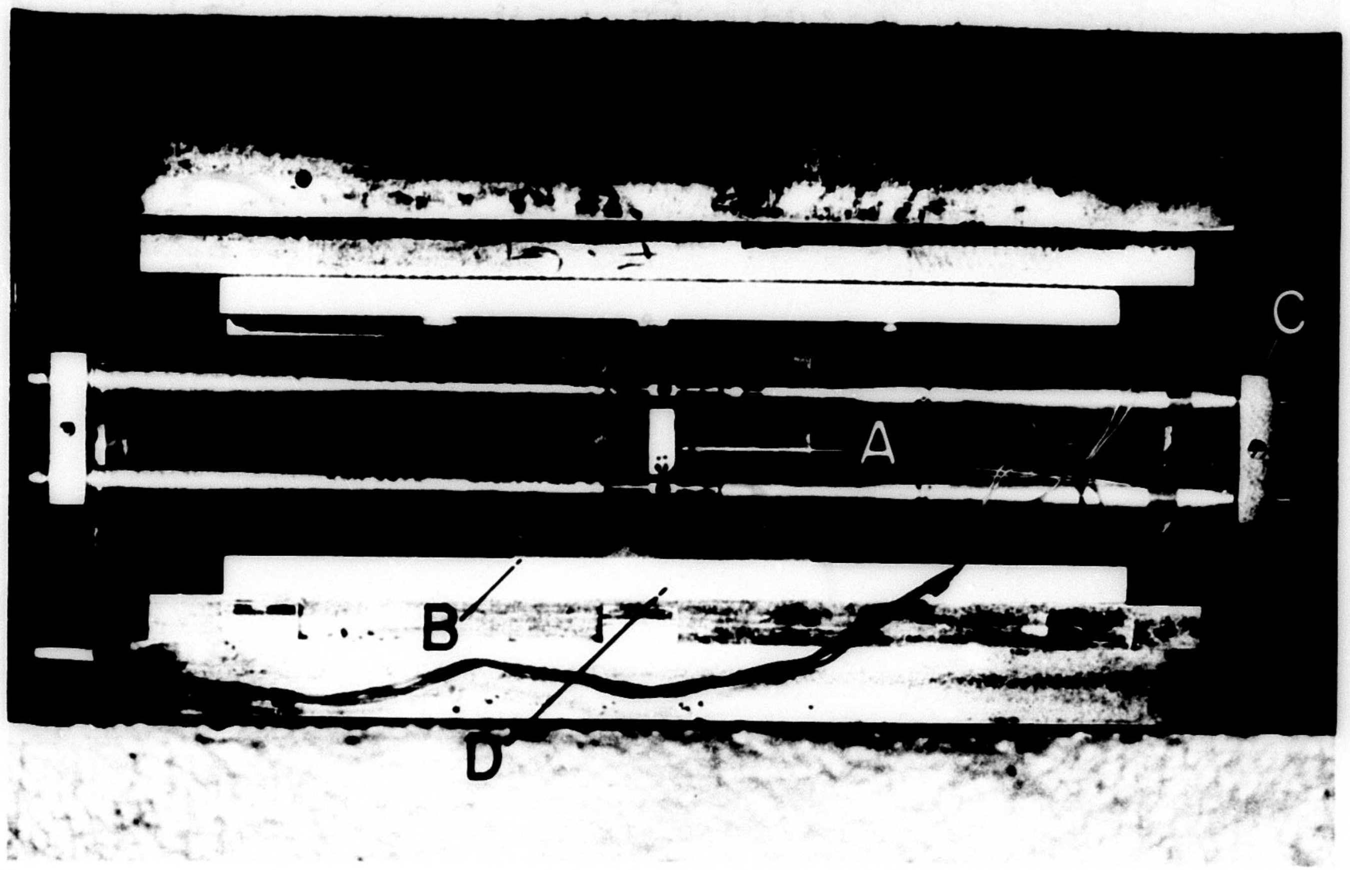


Figure 5. Typical Sandwich Panel Edgewise Compression Test Set-Up: A, strain gauge flexure strip; B, sandwich specimen; C, sandwich specimen compressometer; D, lower wedge grips.

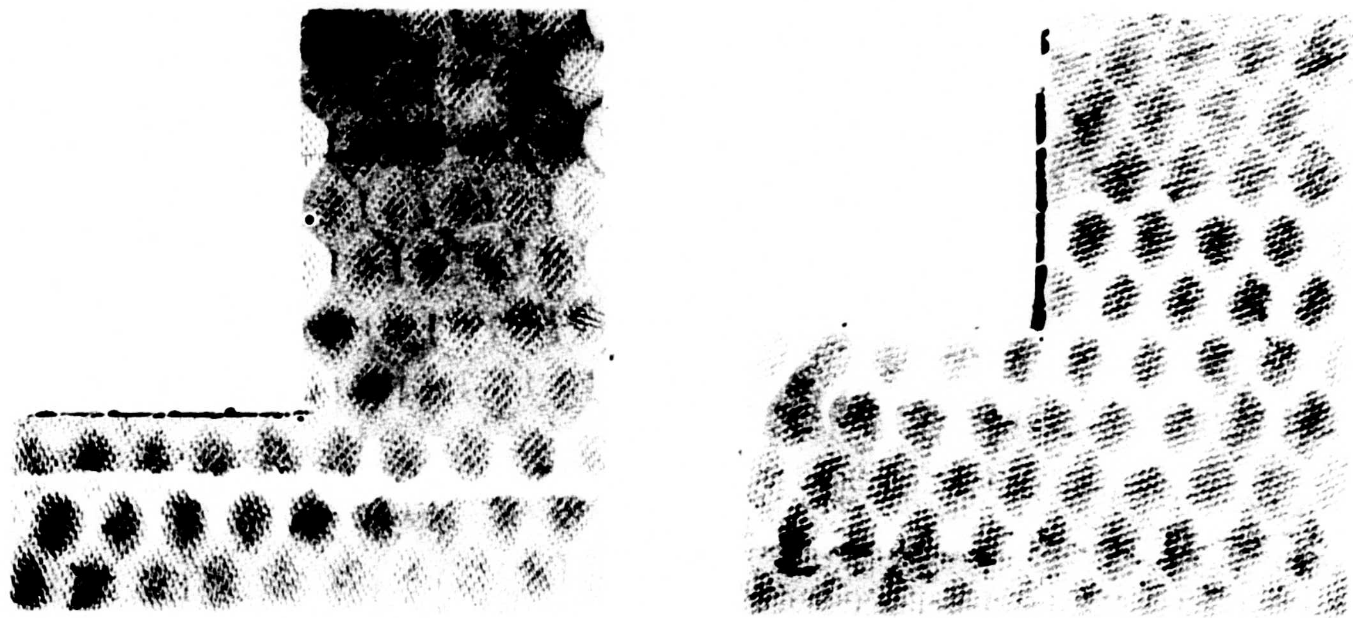


Figure 6. Typical Compression Failures of Single-Step Fabricated Panels: Left, face compression rupture; right, core-to-facing bond failure. The corners of specimens were removed for resin content measurement.

the facing occurring on one or both sides of the panel. The typical rupture path was along the cell walls rather than across the cell openings. The specimen on the right shows a partial rupture of the facing accompanied by core-to-facing bond separation--portion of facing.

Plate shear tests were also performed for the single-step sandwich panels. The sandwich modulus was the only property reported in that in the majority of cases the specimen broke free from the steel plates (Figure 7) before the ultimate strength of the sandwich was reached. The formulas given in MIL-STD-401A were used for computation of the moduli.

The nominally sized 2- by 6-inch test specimens were carefully measured to the nearest 0.01 inch with a steel scale. The thickness was measured with a micrometer.

The MIL-STD-401A test procedure was followed. An Ames dial indicator graduated in ten thousandths was attached to one of the steel plates of the test fixture so that the plunger was brought into perpendicular contact with an anvil mounted on the other steel plate (Figure 8). Readings taken from the dial gave a true measure of the relative motion of the two facings of the panel. The specimens were preloaded twice to 20 percent of their ultimate load to eliminate the initial and secondary moduli. The dial indicator was then set at zero while a load of 200 pounds was held momentarily on the specimen.

Part of the specimens were tested on a Model TEG Baldwin testing machine of capacity 100,000 pounds and cross-head speed of 0.050 inch per minute. On this machine one operator monitored the dial indicator and recorded the readings corresponding to the increments of load called out by the machine operator.

The remainder of the specimens was tested on an Instron testing machine model TTC M1-6 with a capacity of 10,000 pounds. The same test fixtures, preliminary loading technique, and loading speed were used as before. This machine was equipped with an X-Y chart recorder and was operated by one man. The curve plotted by the recorder was load versus cross-head movement, and a specific load could be marked or blipped by pressing a button on the machine console. Hence one man could mark the load and read the dial gage at the same time. Readings were taken at every 0.0010 inch of deformation.

Failure usually occurred at the facing-to-core bond when the specimen-to-steel plate bond strength was sufficient to allow development of the sandwich ultimate strength. In rare cases, failure was due to a catastrophic rupture of the core-cell walls.

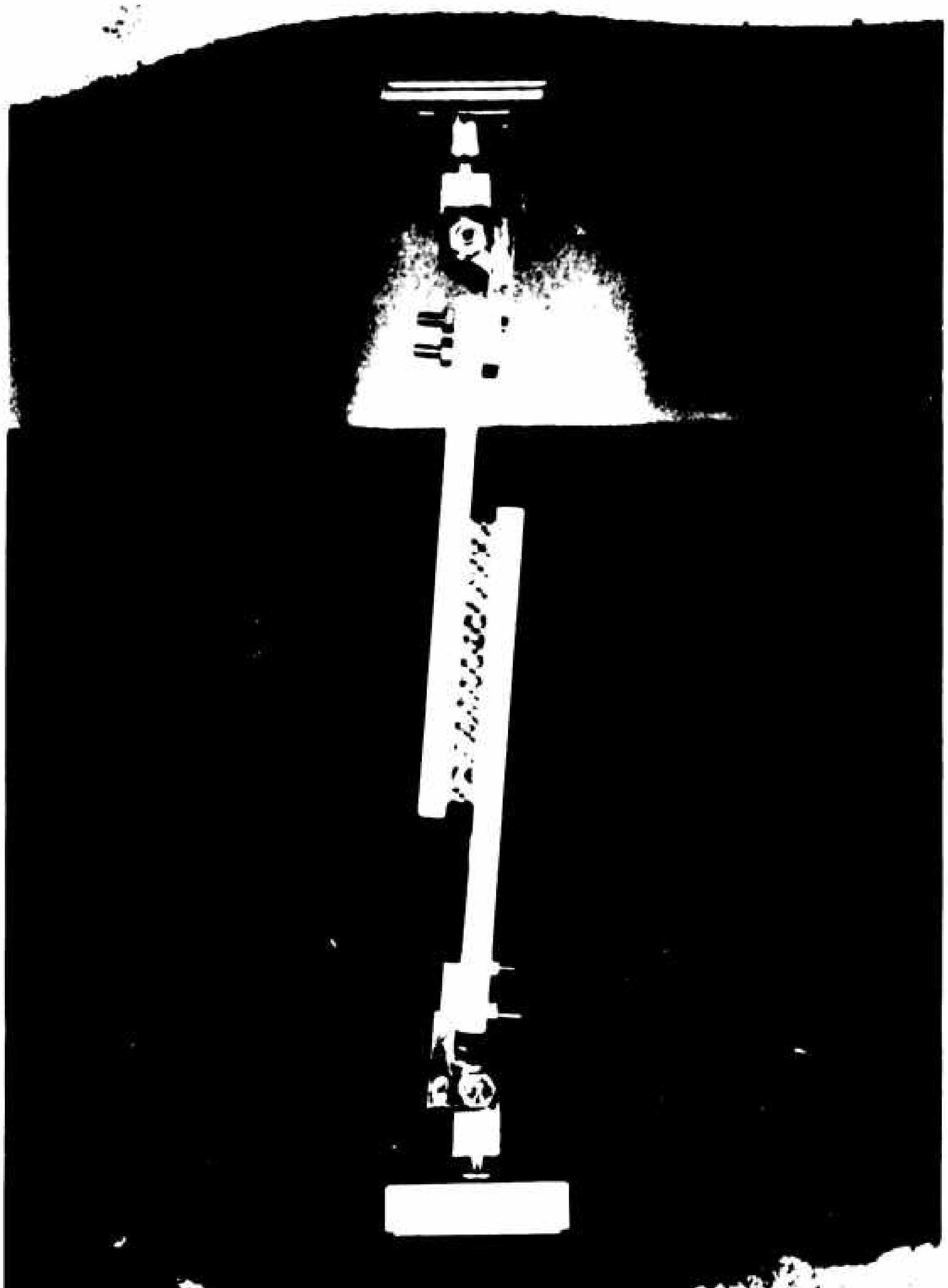


Figure 7. Test Set-Up for Sandwich Plate Shear Test Showing Specimen Installation.

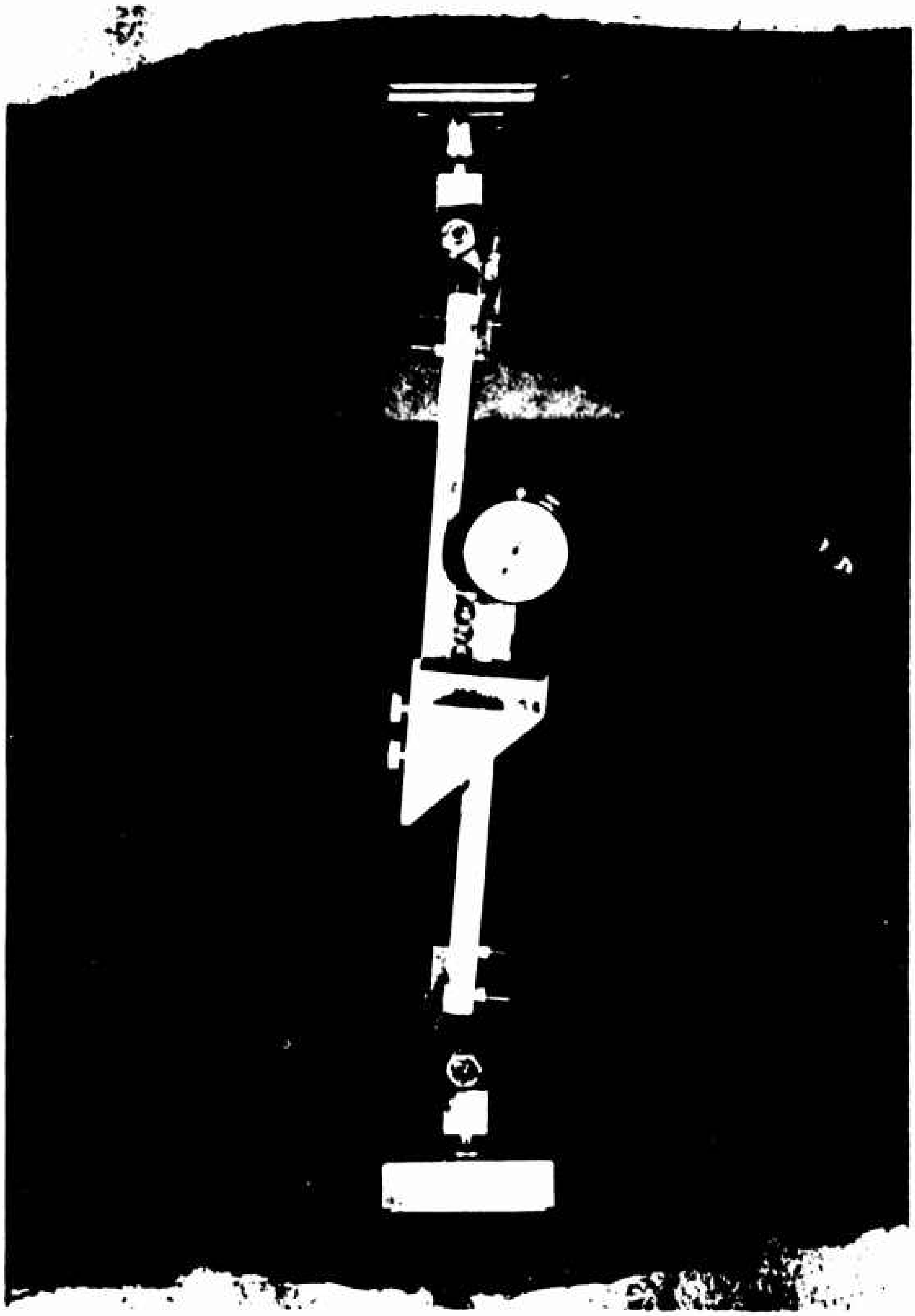


Figure 8. Test Set-Up for Plate Shear Test of Sandwich Shear Modulus Showing Test Specimen and Dial Gauge Arrangement for Measuring Deformation.

3. Bare Laminates

To perform the laminate compression tests, it was necessary to design a fixture to prevent buckling of the thin specimens. An excellent design was achieved possessing the following features: firm support of the specimens against buckling with freedom enough to permit uniform distribution of load throughout its length, jaw shape to permit compressometer installation for strain measurement, and quick loading and releasing action to accommodate large volume testing. Figures 9 and 10 show these essential details.

After grinding, the nominally sized compression and tension specimens were measured by a random sampling of the entire group fabricated under the same conditions. Length and width measurements were taken with a caliper calibrated in thousandths of an inch. Thickness measurements were made for each individual specimen (after testing) one-half inch on either side of the rupture, and the two readings averaged for use in the calculation of the failure cross-section area.

The test fixture was essentially a jig with two slotted jaws clamped about the specimen by the action of two cams. Horizontal slots 1/8 inch wide were cut into the jaws with 1/8-inch spacing between the slots; yet preliminary testing indicated the existence of an appreciable amount of friction between the jaws and the laminate. This indicated the need for a lubricant. Finely ground molybdenum disulphide prepared under the trade name of Molykote Z was found to be the best product for this purpose. Lubricant was applied by dipping each specimen into a container of Molykote and then rubbing the laminate by hand until uniformly coated. The specimen was then inserted between the fixture jaws, and the cams were turned down "finger tight". This developed a frictional force between the laminate and the jaws of about 5 pounds which was considered negligible.

The previously described Baldwin testing machine was also used for the laminate tests. The fixture with the test specimen installed was placed on the milled surface of the testing machine with the top of the specimen fitted into a tapered slot in the upper loading head. The specimen was then vertically aligned, and a wedge was inserted into the upper slot to provide a fixed-end condition during loading. The load was applied at the rate of 0.050 inch per minute to failure, and the stress was computed using the ultimate load. B, C, D, and E in Figure 2 typify the failures that occurred.

One fourth of the compression specimens in each group were tested for modulus. A Baldwin-Weidemann B-3M extensometer (Figure 11) was used as a compressometer to record load-deformation data.

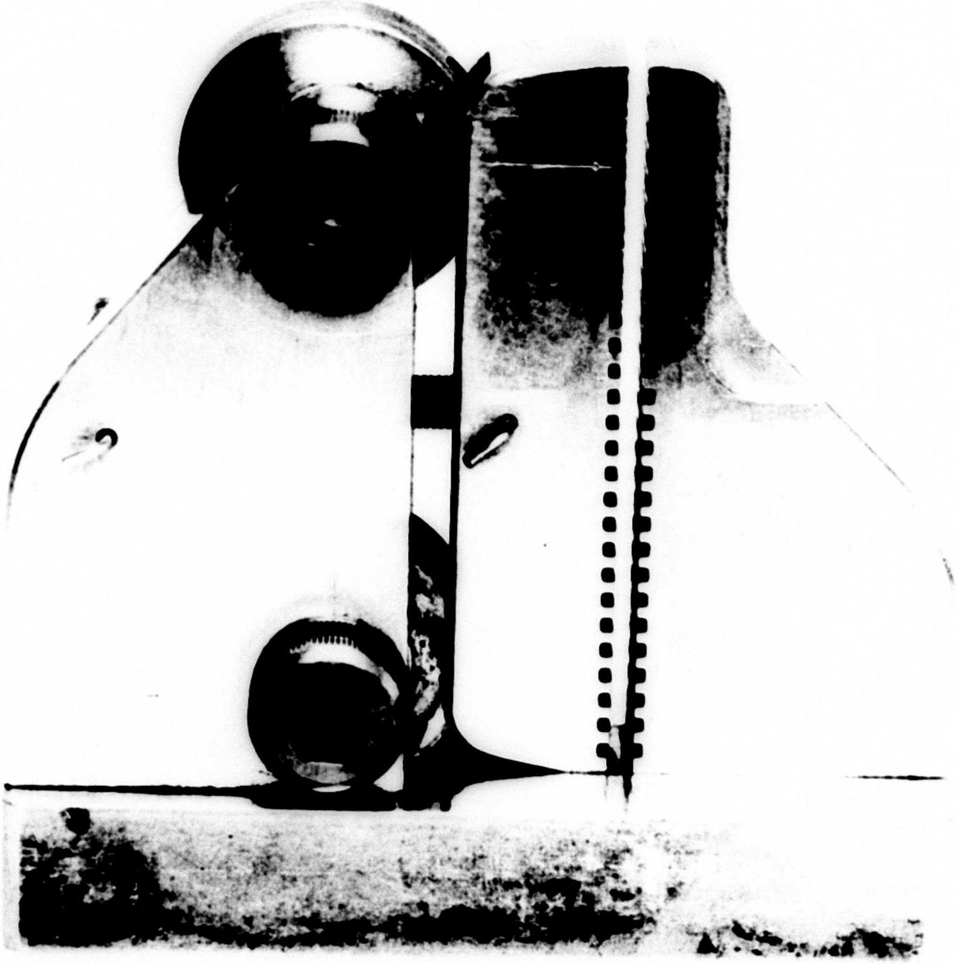


Figure 9. Thin-Laminate Compression Fixture Showing Quick-Release Cams.

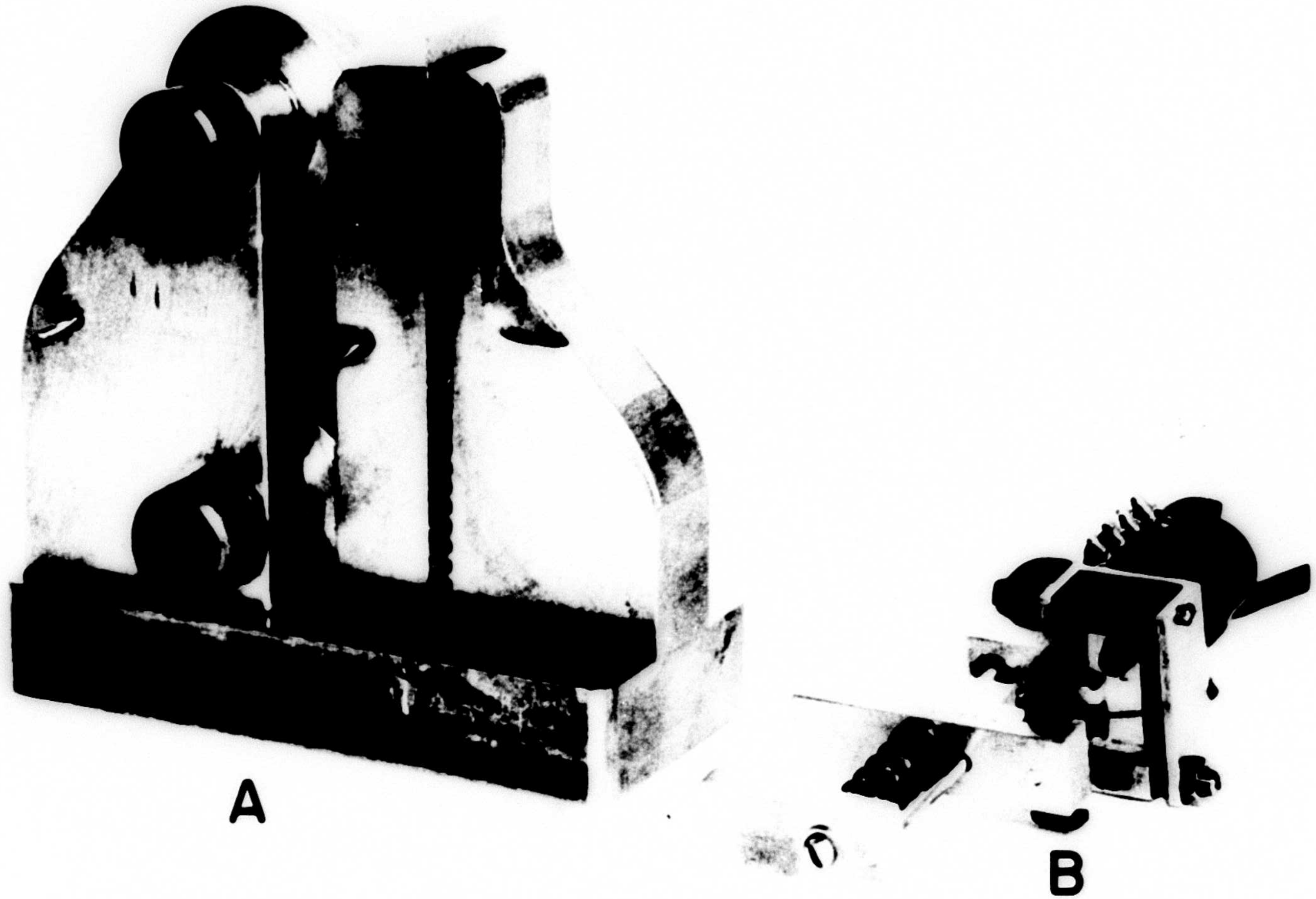


Figure 10. Thin-Laminate Compression Test Apparatus: A, compression fixture with specimen inserted; B, Baldwin-Wiedemann compressometer used to monitor strain during modulus testing.

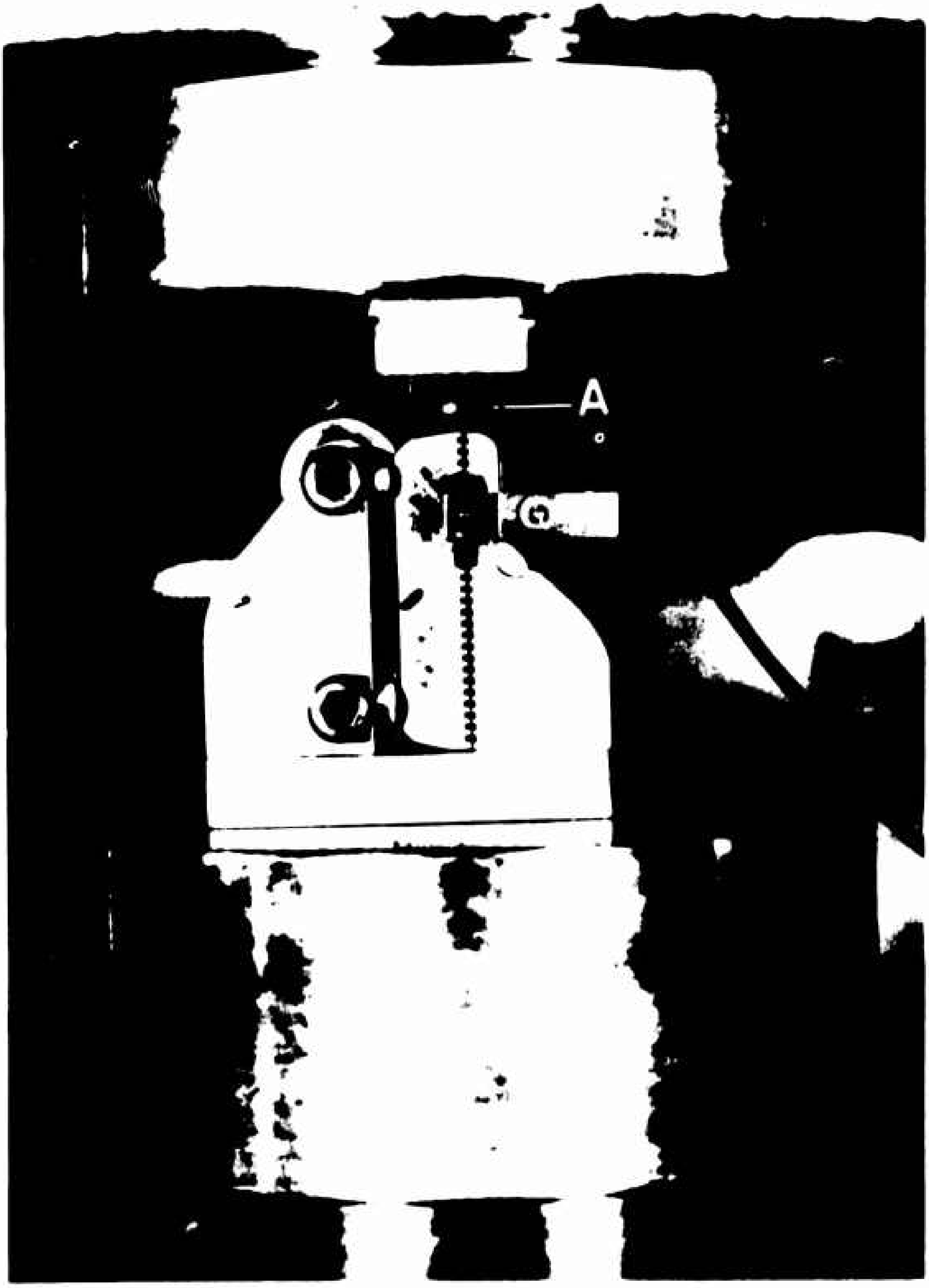


Figure 11. Test Set-Up for Compression Test of Thin Laminates Showing the Specimen and the Compressometer Installation. Pointer A identifies the wedge grip securing the specimen in a fixed-end condition during loading.

The knife edges on the extensometer were placed in contact with the edges of the modulus specimen that extended 1/8 inch beyond either side of the fixture--1/8 inch was the minimum required to clear the fixture. Thus with the deformation of the specimen controlling the chart speed of the X-Y recorder, and the load indicator of the testing machine controlling the recorder pen, a graph of load versus deformation was produced. Only a portion of the curve was obtained in that the instrument was removed at 75 percent load to prevent damage. The modulus was computed from the slope of this graph and the appropriate constants.

The tension ultimate strength and modulus for the laminates were obtained on the same Baldwin machine. The test coupons were placed in Templin grips with self-adjusting jaws (Figure 12), and the grips were attached to the loading heads with bolts resting on cylindrical seats to assure true alignment. The same extensometer used in the compression tests was clamped to the edges of the specimen with the knife edges being equidistant from the specimen notches. Again the load was only carried to 75 percent of ultimate and the load-deformation graph was used to obtain the modulus. D in Figure 3 shows the type of failure experienced.

4. Core-to-Facing Bond

Core-to-facing bond strength was obtained by testing 1- by 1-inch specimens of the sandwich in flatwise tension. The specimens were cut to size to within 0.01 inch so that the ultimate load was taken directly as the ultimate stress. The procedure outlined in MIL-STD-401A was followed in these tests. The bonded aluminum blocks and specimen were placed in the Instron testing machine as shown in Figure 14. The load was applied at the rate of 0.050 inch per minute to failure. Values were not recorded unless the desired core-to-facing bond failure occurred.

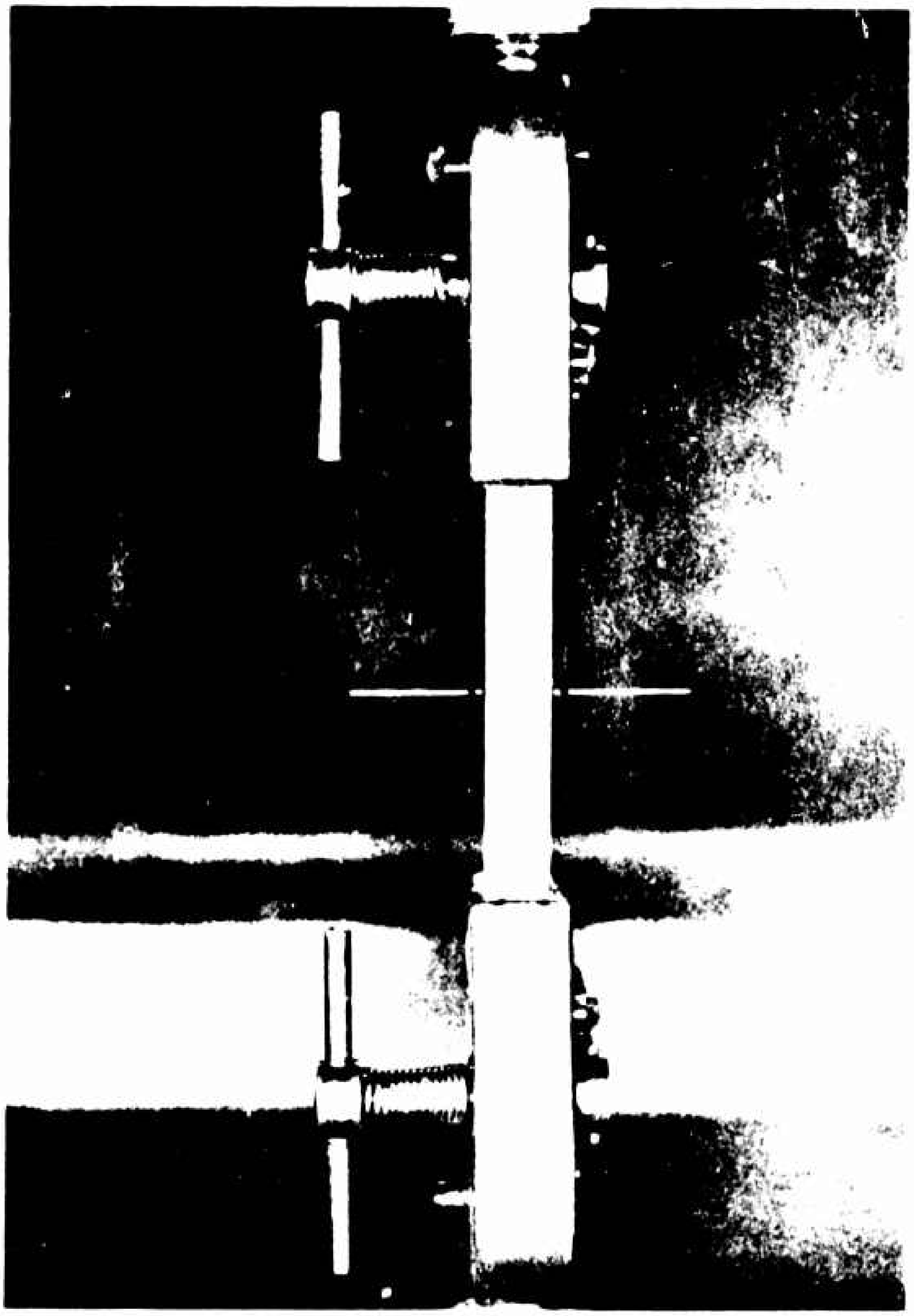


Figure 12. Test Set-Up for Tension Test of Thin Laminates Showing the Specimen Positioned in the Templin Grips. The pointers identify the influenced center section of the specimen.

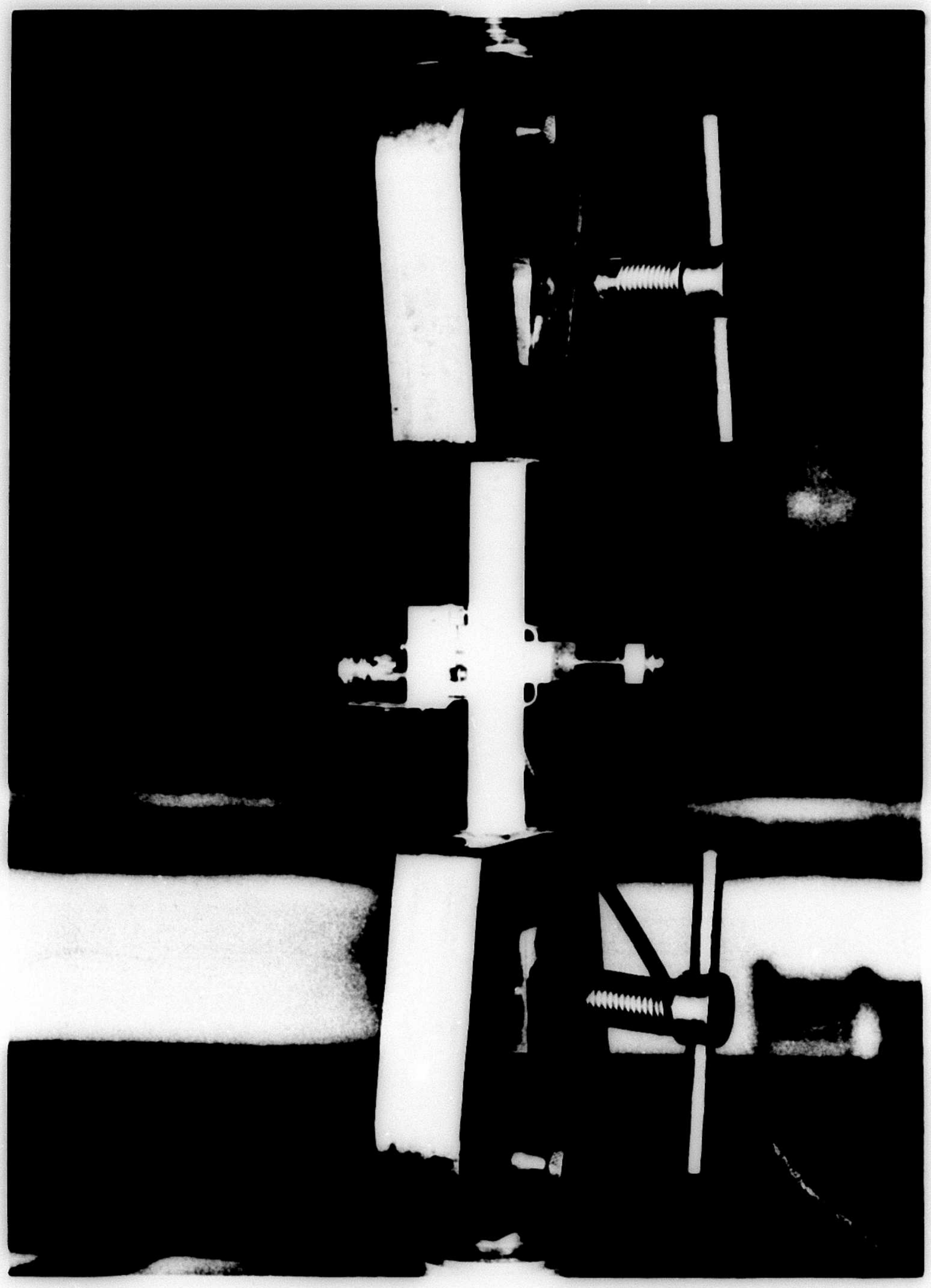


Figure 13. Test Set-Up for Tension Test of Thin Laminates Showing the Specimen and the Baldwin-Wiedemann Extensometer Installation.

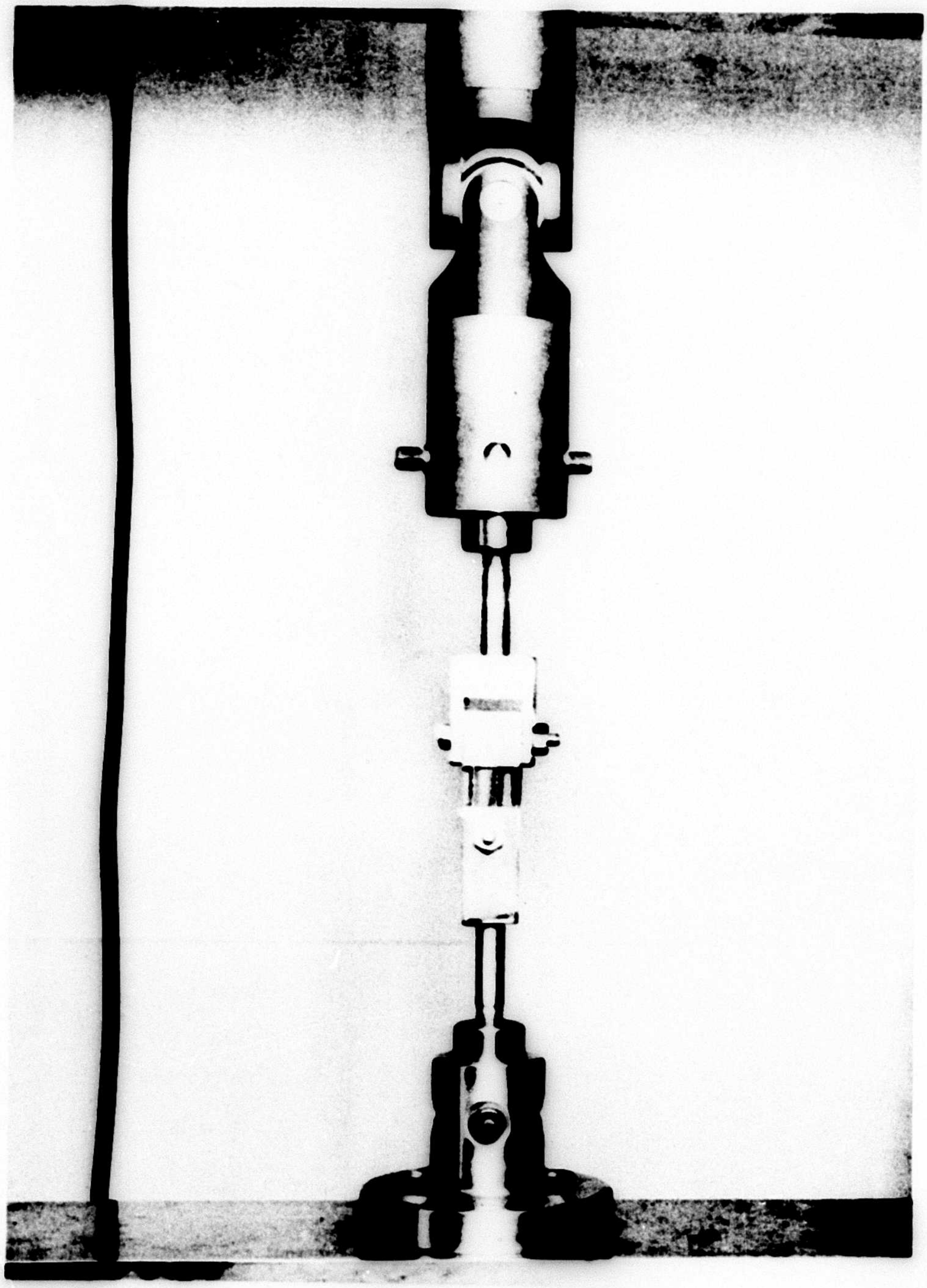


Figure 14. Test Set-Up for Flatwise Tension Test of Core-to-Facing Bond Strength.

EXPERIMENTAL RESULTS

The test results are tabulated in Tables 5 through 22 located in Appendix II. The calculated data and plotted data used in the evaluation of the results are also presented in this section.

TABLE 1

PLATE SHEAR MODULI

Direction of Loading	Average Sandwich Shear Modulus, psi	Core Shear Modulus, psi*
Perpendicular to core ribbon	9,500	10,200
Parallel to core ribbon	23,900	-

*As published by Douglas Aircraft Company, Inc.

TABLE 2
SINGLE-STEP SANDWICH
OPTIMUM STRENGTH PROPERTIES

Lay-Up	Optimum Molding	Strength Value (psi)
Wet	160°F 30 psi	32,400[1]
10-hr. B-stage	160°F 30 psi	34,300

[1]Data missing; this data (at 200°F) used in approximation.

TABLE 3
BARE LAMINATE
OPTIMUM STRENGTH PROPERTIES

Strength Property	Optimum Molding		Strength Value[1]	
	60 min.[2]	90 min.[3]	60 min.[2]	90 min.[3]
Compressive Ultimate	-	160°F 30 psi	-	44.4
	180°F 30 psi	160°F 13 psi	42.7	43.3[4]
Compressive Modulus	-	230°F 70 psi	-	4.17
	230°F 70 psi	230°F 70 psi	3.75	3.91
Tensile Ultimate	-	230°F 30 psi	-	58.7
	230°F 70 psi	200°F 70 psi	57.7	58.9
Tensile Modulus	-	230°F 13 psi	-	2.74
	230°F 70 psi	200°F 70 psi	2.68	2.79

[1]Stress in psi x 10^{-3} and modulus in psi x 10^{-6}. Upper value is for wet lay-up and lower for 10-hr. B-staged lay-up.
[2]Two hour post-cure data.
[3]Data averaged over post-cure times.
[4]Data missing, this data (at 200°F) used in approximation.

TABLE 4

ADHESIVE STUDY SUMMARY

Core Material and Size	Adhesive System: Facing Resin, 828-Z	Adhesive System: AF-110B	Adhesive System: EC-1595	Adhesive System: A-12
"Aircomb" Paper 125-35-20 0.42" cell 3/4" thick	Wet Lay-up Average: 300 psi Cure: 160 F, 30 psi 10 hr. B-staged Average: 460 psi Cure: 160 F, 30 psi	-	-	Peak: 800 psi[1] Cure: 200 F, 10 min.
HRP, GF-11 Fiberglass 3/16" cell 3/4" thick	Peak: 1000 psi Cure: 160 F, 90 min.	Peak: 1000 psi Cure: 325 F, 20 min.	Peak: 340 psi Cure: 325 F, 50 min.	Peak: 740 psi Cure: 250 F, 30 min.
5052 Aluminum 0.0025" foil 3/16" cell 0.40 thick	-	980 + psi[2]	Peak: 550 psi[3] Cure: 350 F, 60 min.	Peak: 420 psi[4] Cure: 200 F, 10 min.

[1] 1/2-inch-thick core.

[2] 0.0013-inch foil, core failed before bond. Average stress given. Cell size, $\frac{1}{4}$ inch.

[3] Data available from one cure condition only.

[4] 1/4-inch cell.

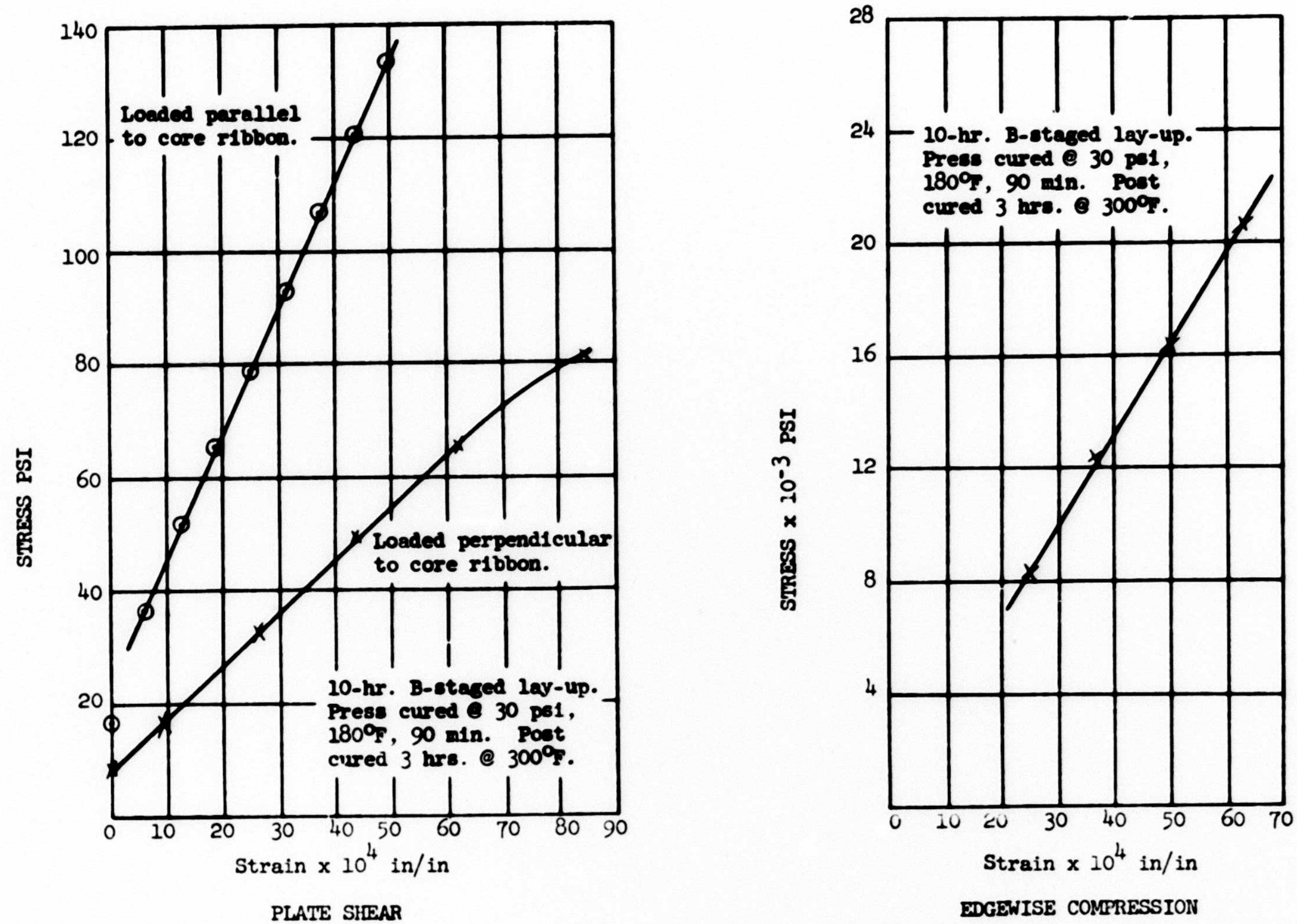
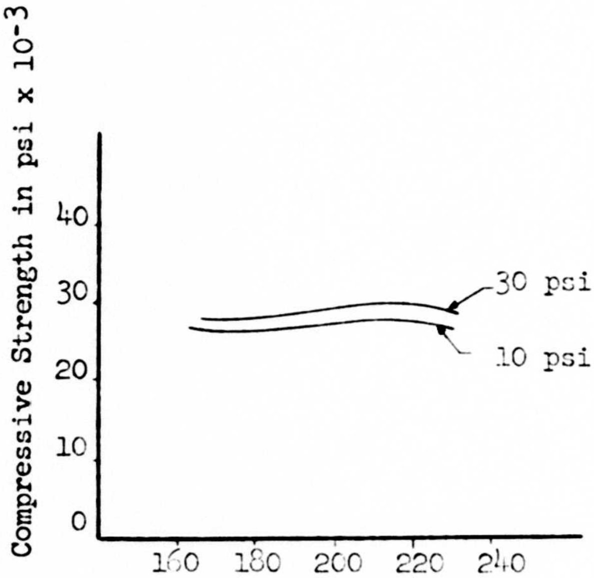
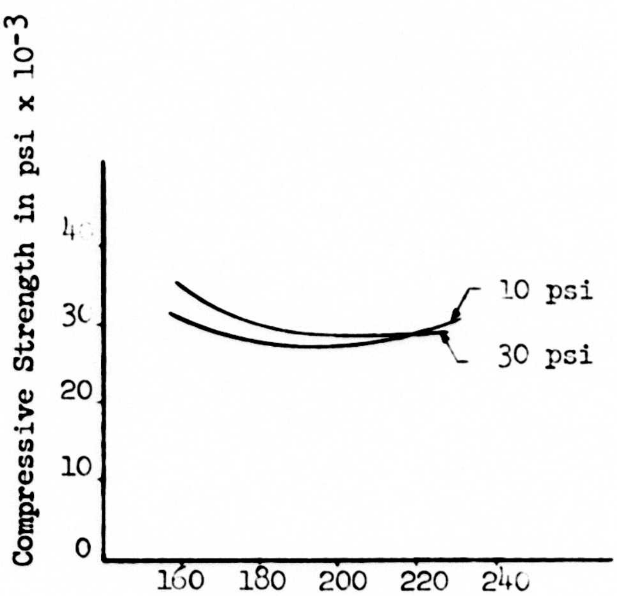


Figure 15. Typical Stress-Strain Curves for Single-Step Fabricated Sandwich panels.

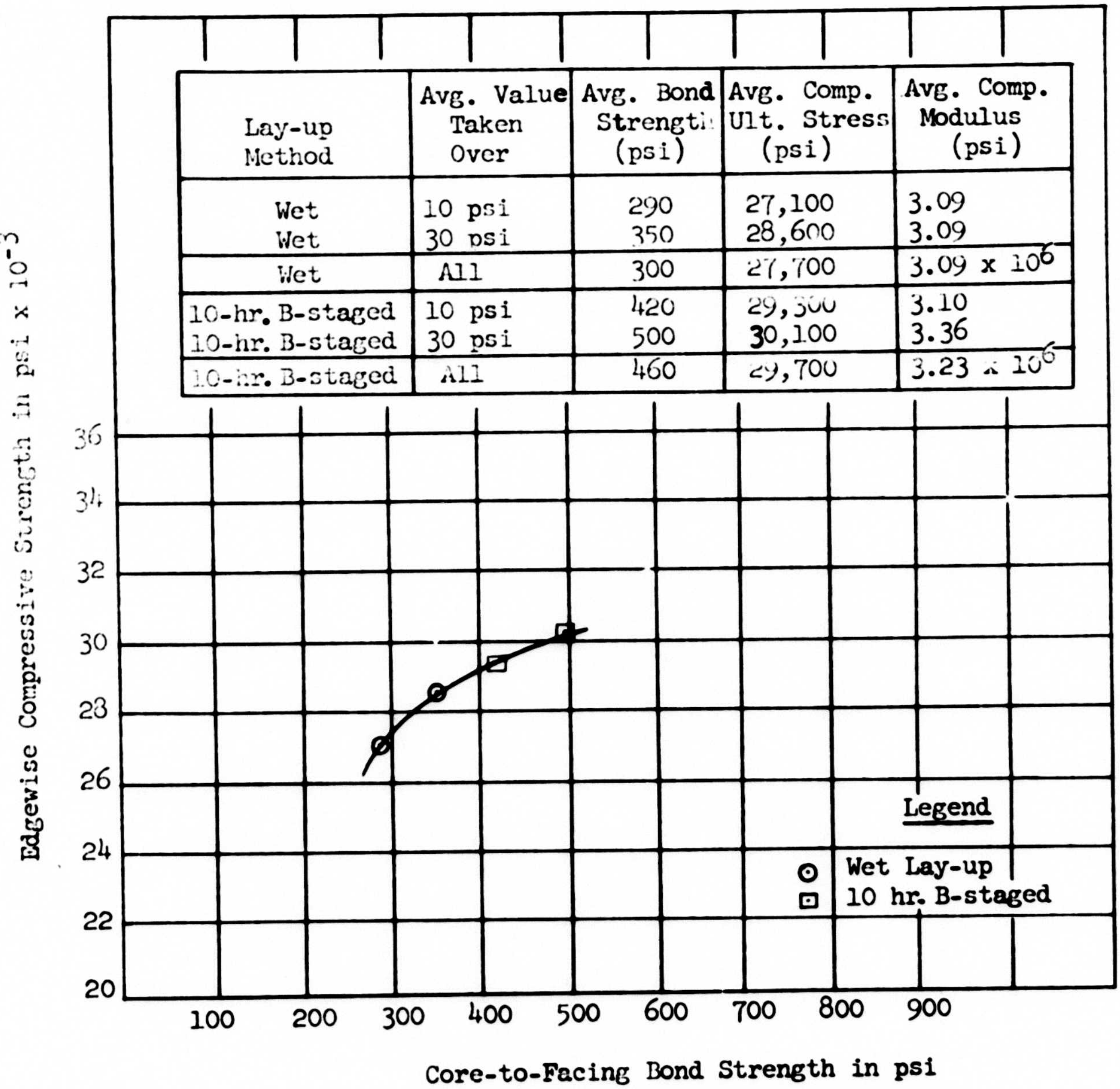


Temperature, Deg. F.
WET LAY-UP



Temperature, Deg. F.
10 HOUR B-STAGED LAY-UP

Figure 16. The Effect of Molding Conditions on the Edgewise Compressive Strength of FRP Single-Step Fabricated Sandwich Using the Wet Lay-Up Directly and the B-staged Lay-Up.



Lay-up Method	Avg. Value Taken Over	Avg. Bond Strength (psi)	Avg. Comp. Ult. Stress (psi)	Avg. Comp. Modulus (psi)
Wet	10 psi	290	27,100	3.09
Wet	30 psi	350	28,600	3.09
Wet	All	300	27,700	3.09 x 10^6
10-hr. B-staged	10 psi	420	29,300	3.10
10-hr. B-staged	30 psi	500	30,100	3.36
10-hr. B-staged	All	460	29,700	3.23 x 10^6

Figure 17. **Single-Step Fabricated Sandwich Strength Relationships.**

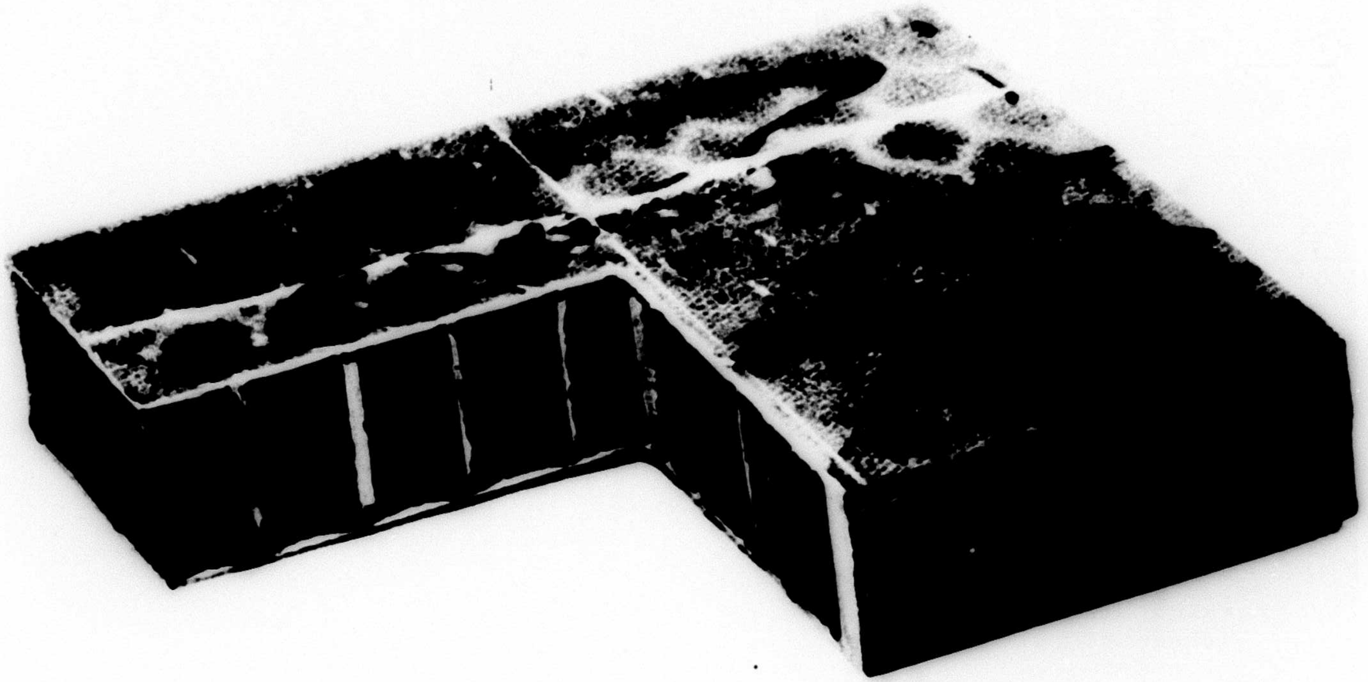


Figure 18. Typical Single-Step Fabricated Sandwich Panel in Which the B-Staged Lay-Up Was Used. The controlled resin flow qualities of the B-Staged facings produced good core-to-facing filleting action and bond strength.

1/2 FRAMES

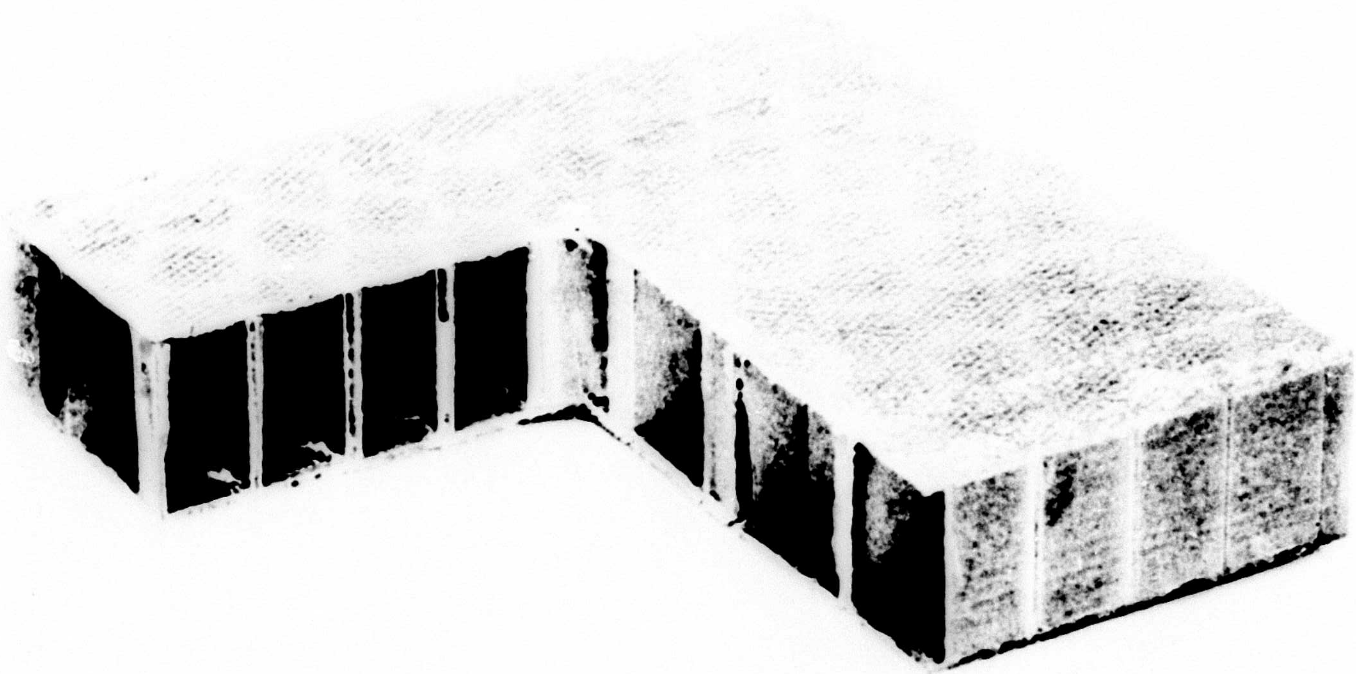


Figure 19. Typical Single-Step Fabricated Sandwich Panel in Which the Wet Lay-Up Was Used Directly. Low resin content facings with poor core-to-facing filleting was the result.

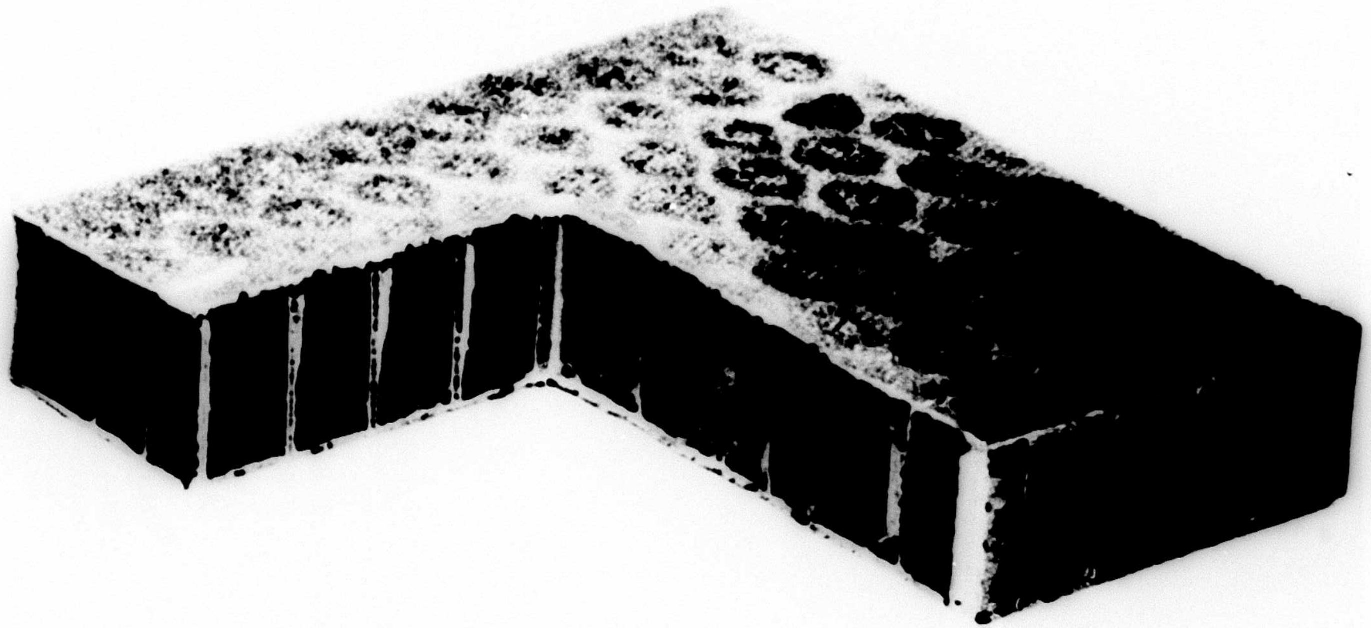


Figure 20. Single-Step Fabricated Sandwich Panel Showing the Hardened Resin Bubble Clusters Produced Within the Honeycomb Cells by Too High a Vacuum During Cure.

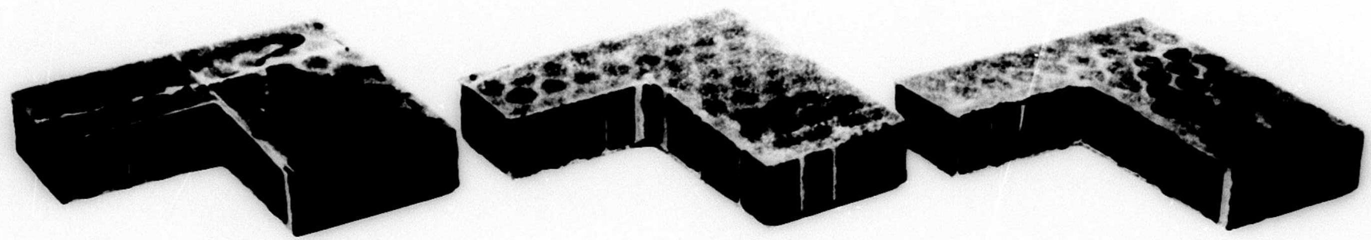
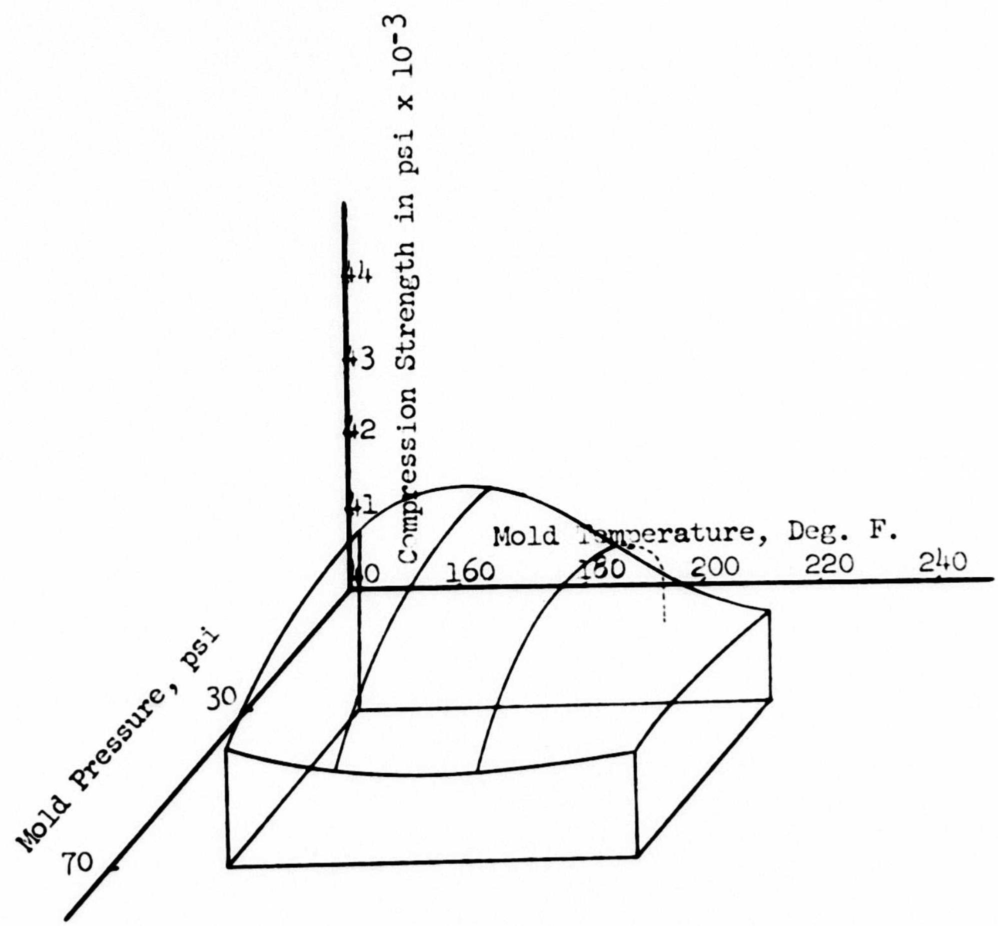
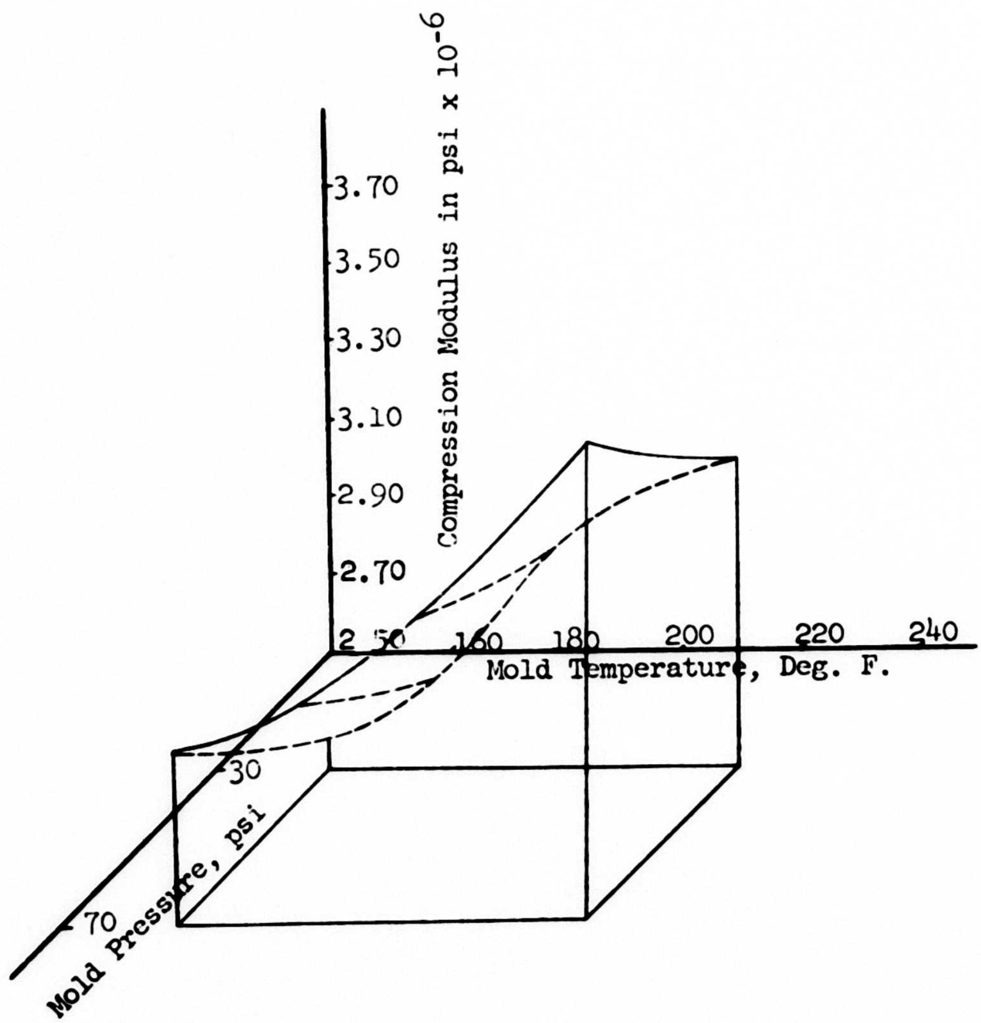


Figure 21. Typical Examples of the Three Types of Resin Flow Conditions Observed in the Single-Step Fabrication Study. From left to right: controlled resin flow produced by B-staged facings, resin starvation produced by direct use of wet facings, and resin bubble produced in the honeycomb cells by high vacuum.



10-HOUR B-STAGED LAY-UP
CURE TIME: 60 MINUTES
POST-CURE TIME: 2 HOURS

Figure 22. The Effects of Mold Pressure and Temperature on the Ultimate Compression Strength of FRP Laminates.



10-HOUR B-STAGED LAY-UP
CURE TIME: 60 MINUTES
POST-CURE TIME: 2 HOURS

Figure 23. **The Effects of Mold Pressure and Temperature on the Compression Modulus of FRP Laminates.**

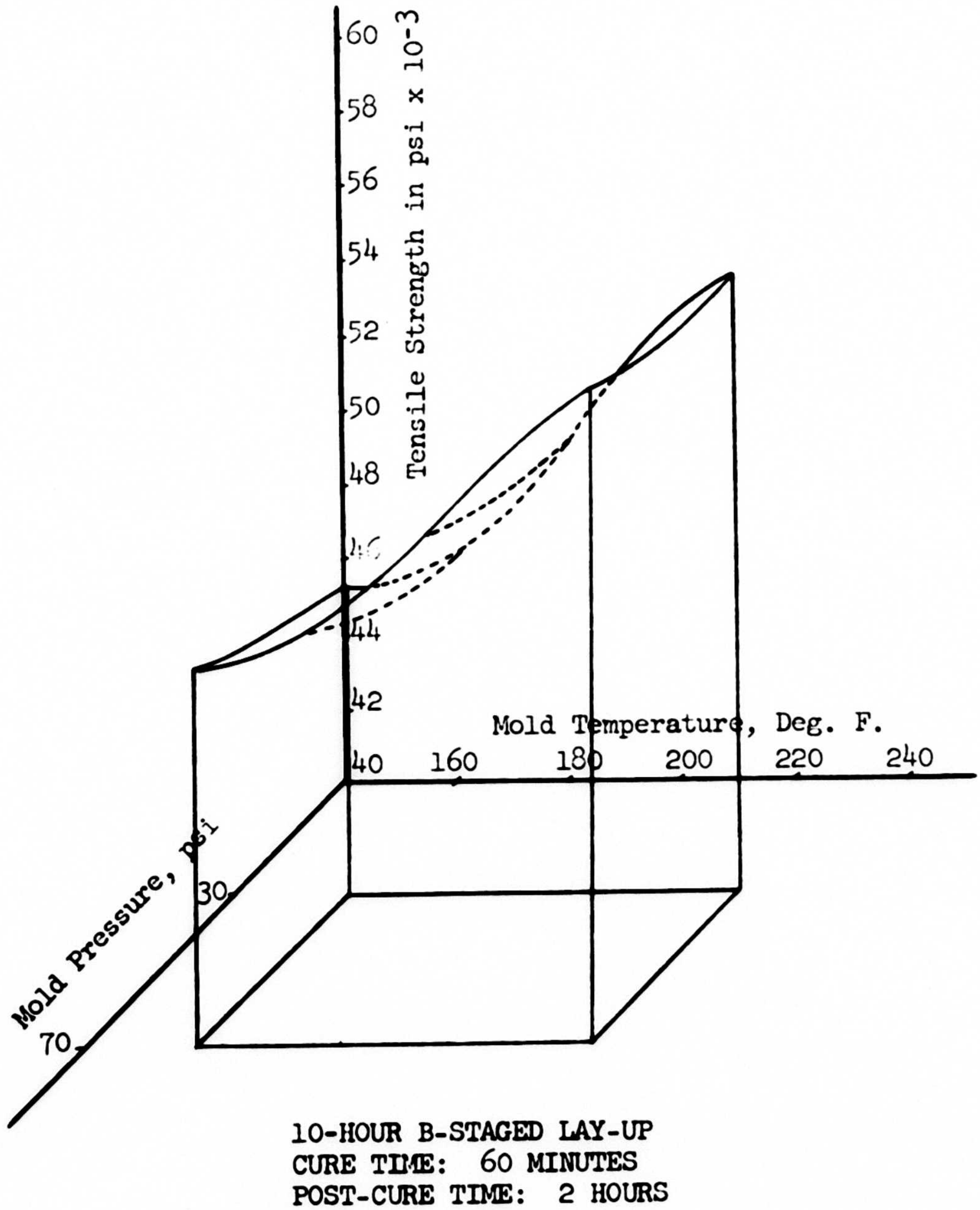
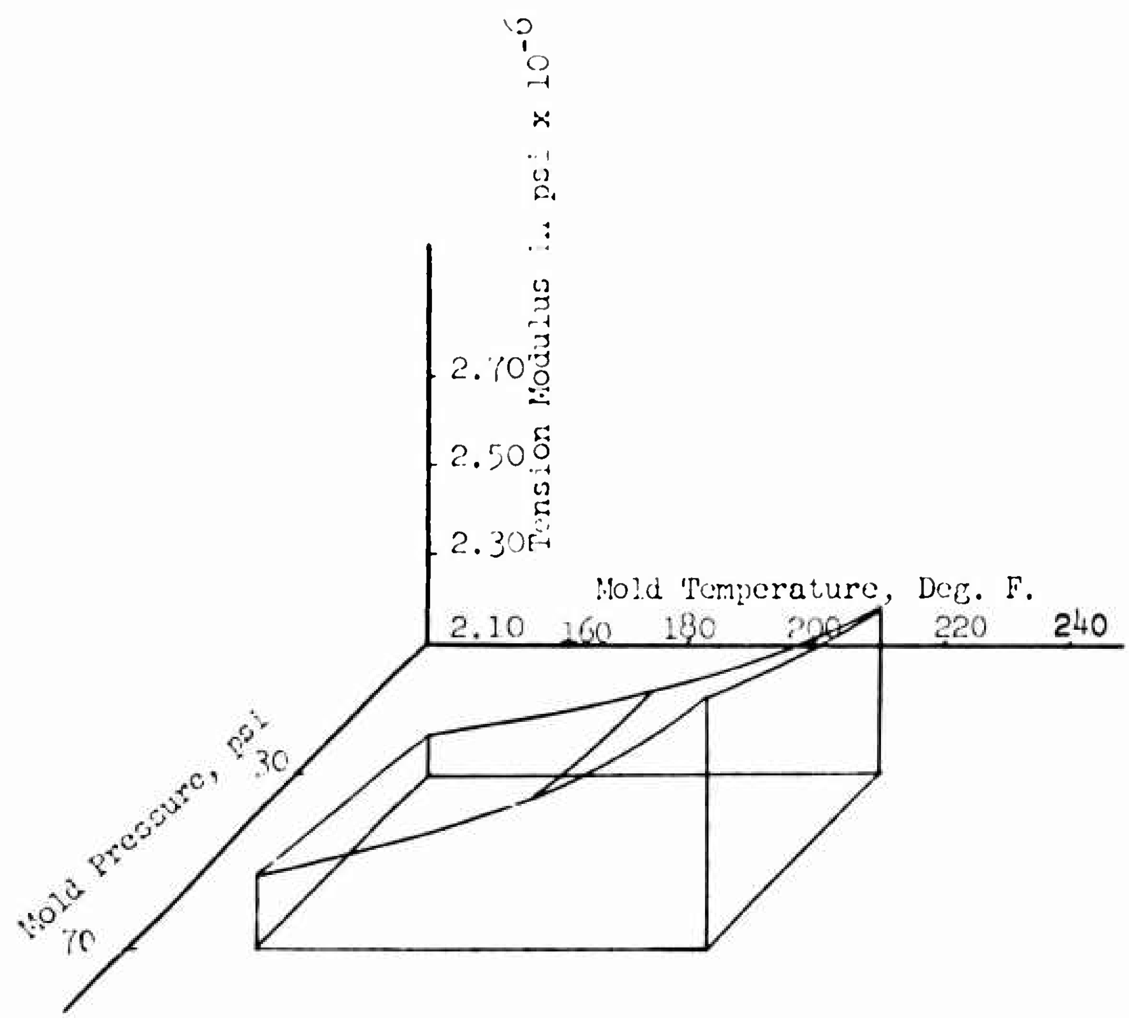
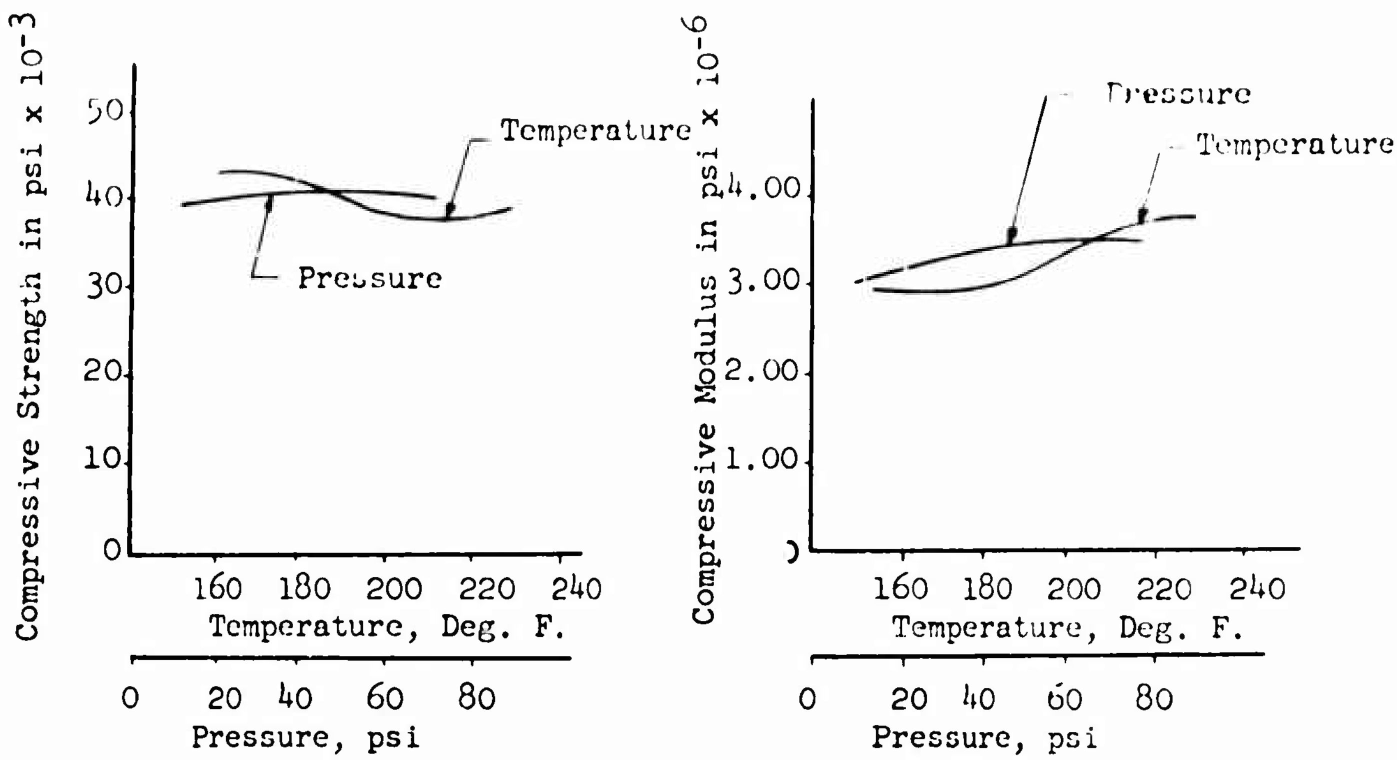


Figure 24. **The Effects of Mold Pressure and Temperature on the Ultimate Tensile Strength of FRP Laminates.**

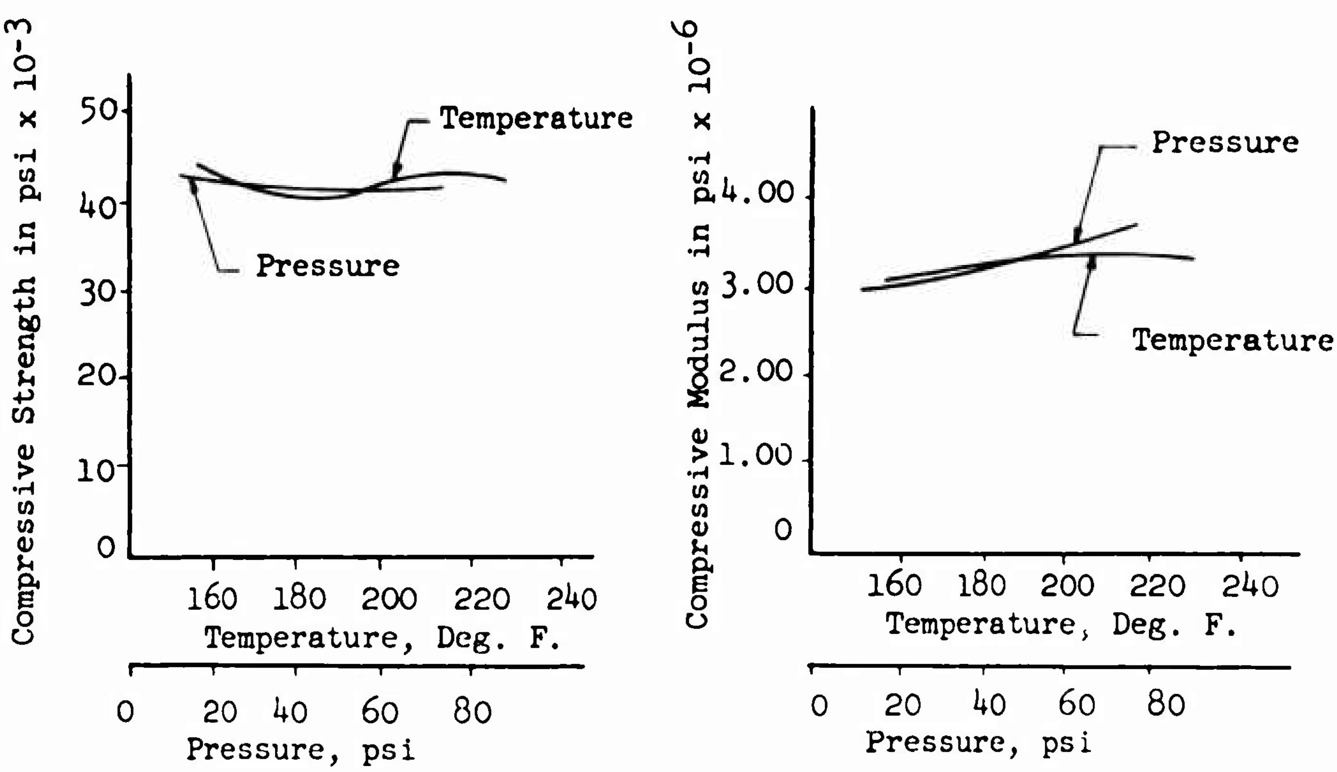


10-HOUR B-STAGED LAY-UP
CURE TIME: 60 MINUTES
POST-CURE TIME: 2 HOURS

Figure 25. The Effects of Mold Pressure and Temperature on the Tension Modulus of FRP Laminates.

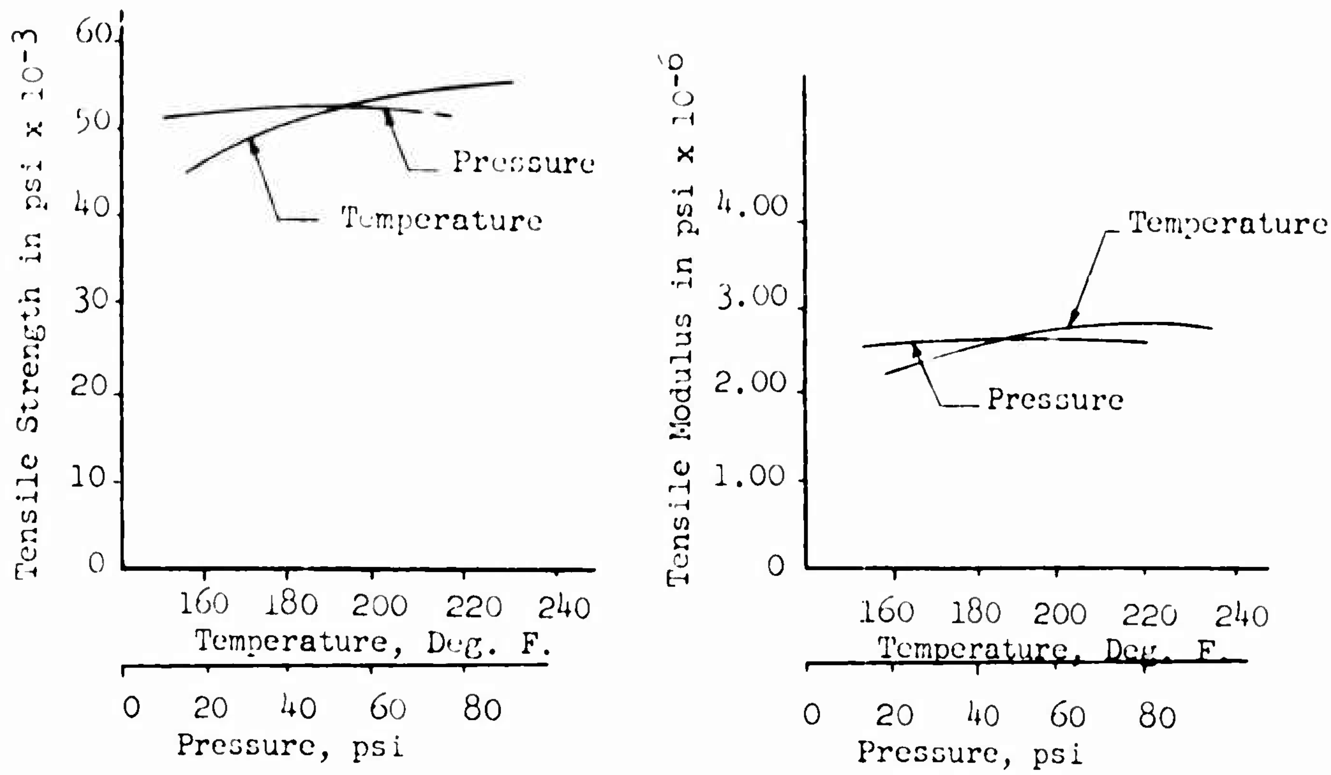


WET LAY-UP
CURE TIME: 90 MIN.

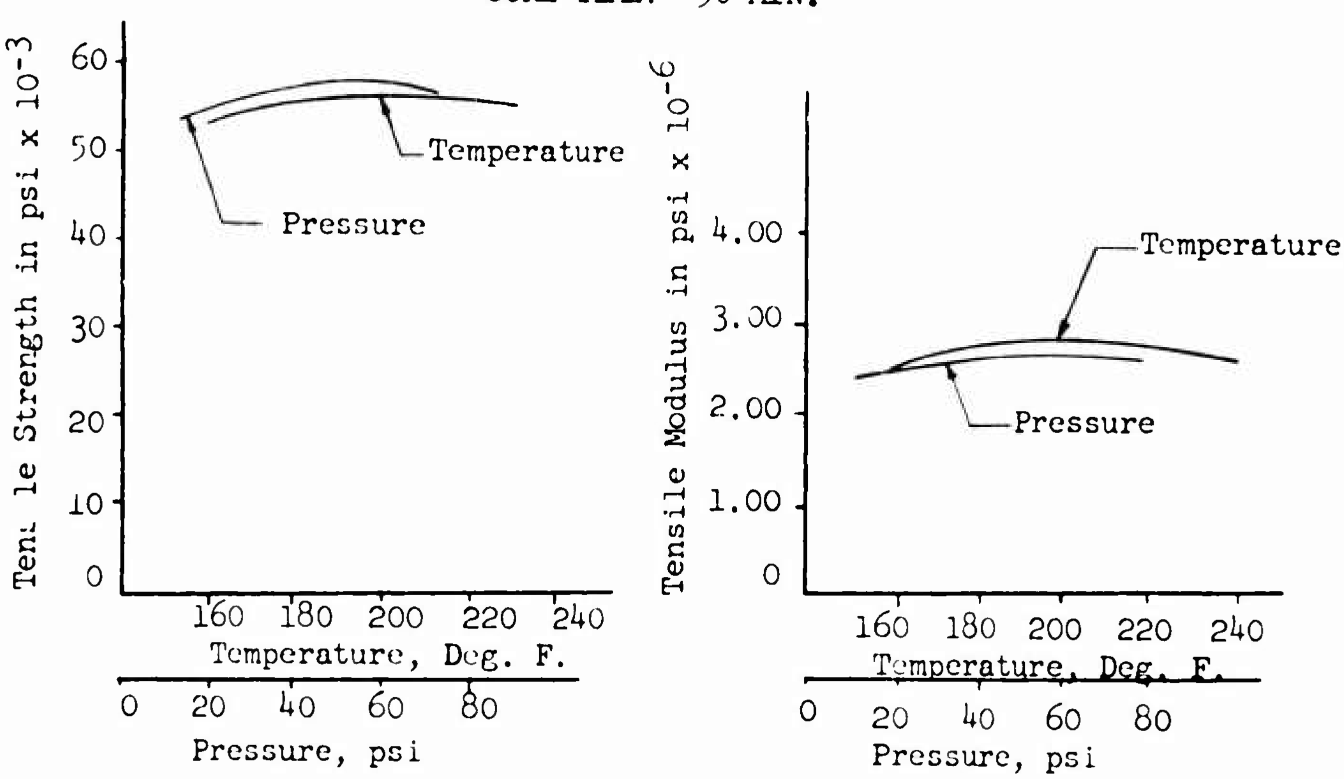


10 HOUR B-STAGED LAY-UP
CURE TIME: 90 MIN.

Figure 26. The Effect of Molding Conditions on the Compressive Strength of FRP Laminates.



WET LAY-UP
CURE TIME: 90 MIN.



10-HOUR B-STAGED LAY-UP
CURE TIME: 90 MIN.

Figure 27. **The Effect of Molding Conditions on the Tensile Strength of FRP Laminates.**

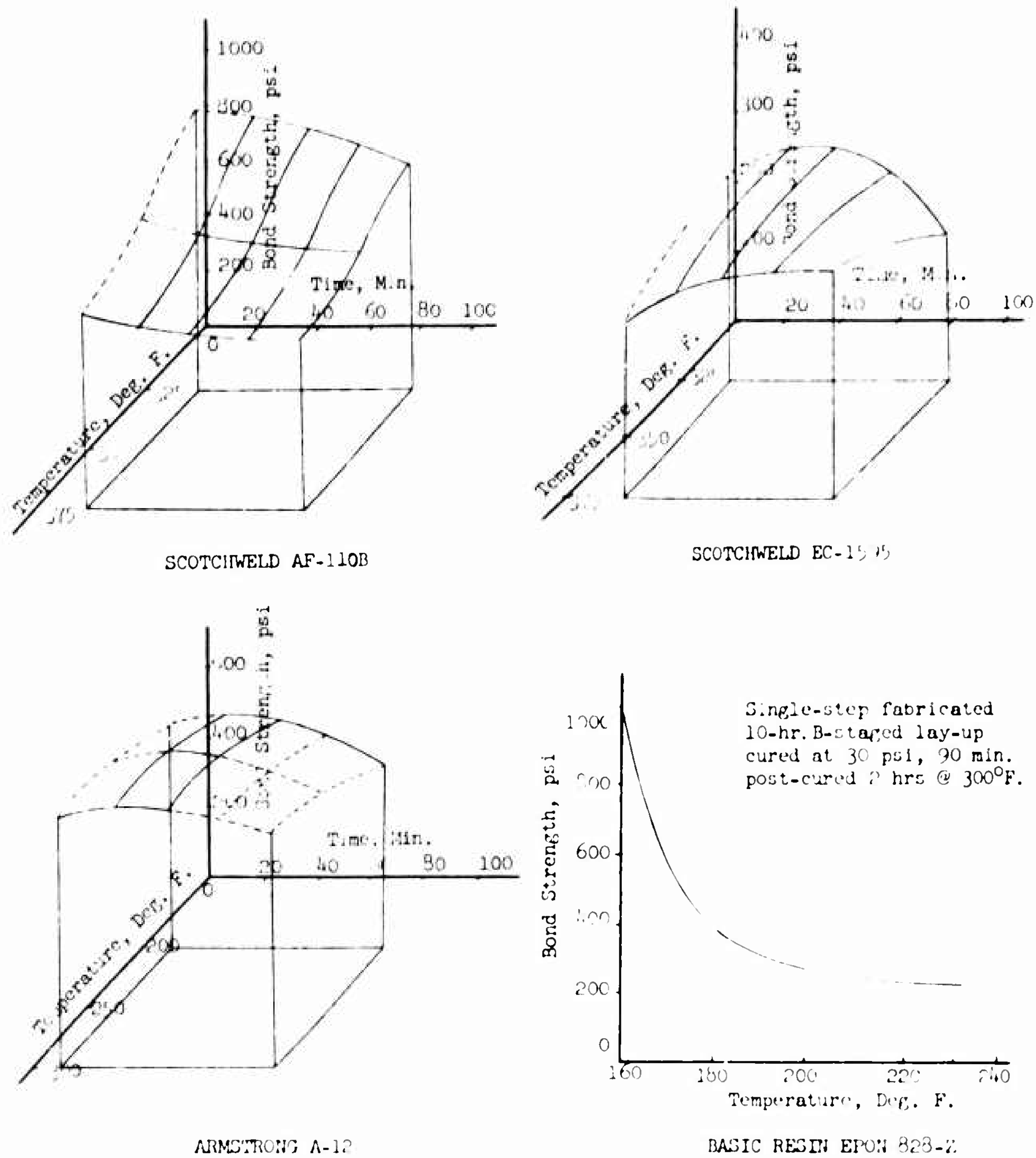
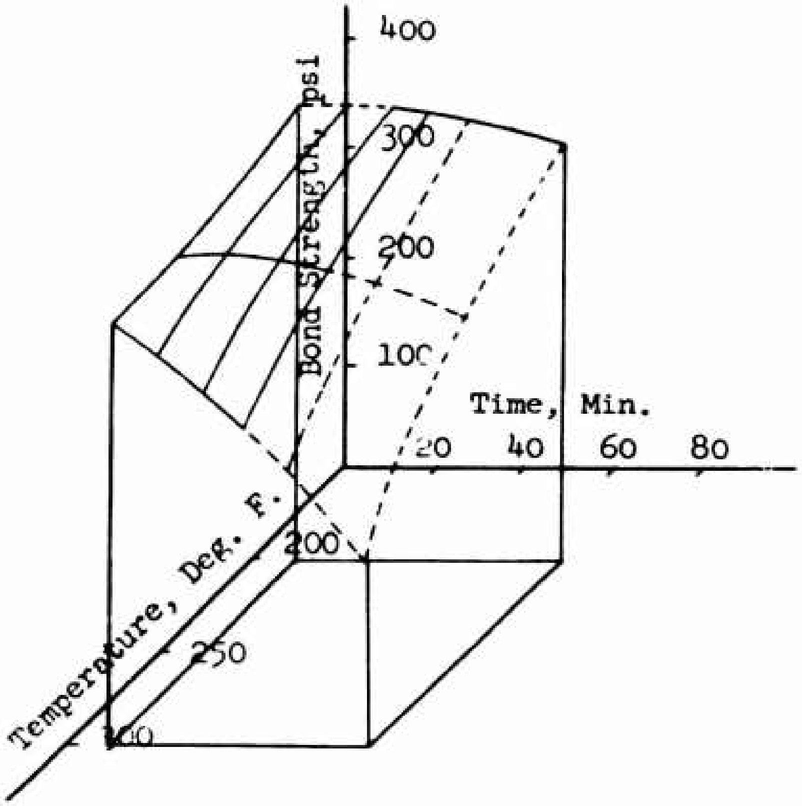
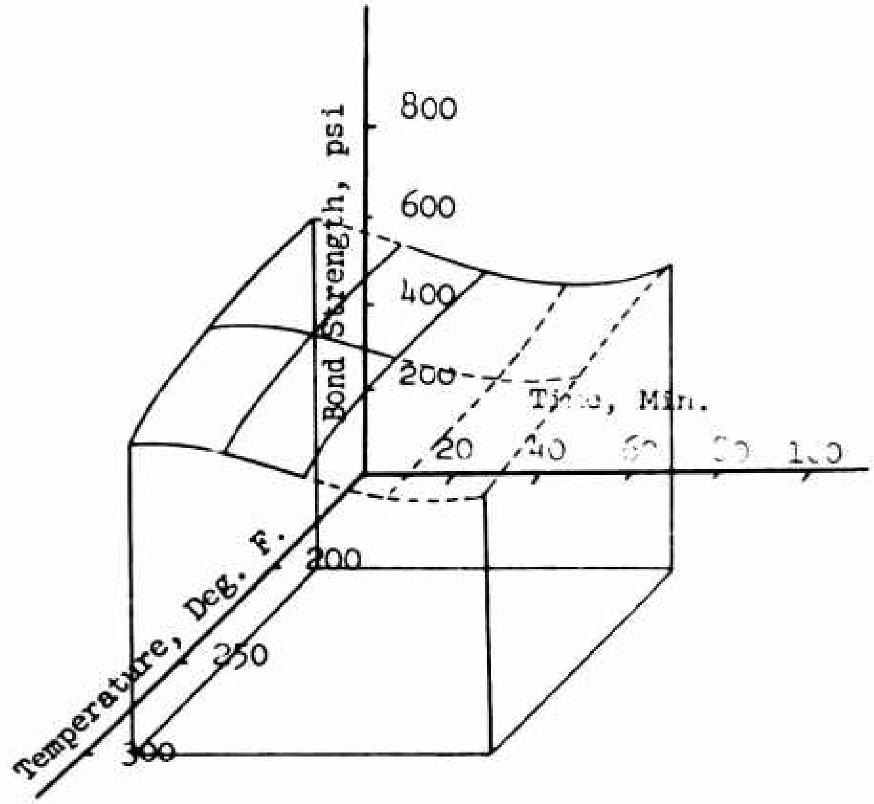


Figure 28. The Core-to-Facing Bonding Qualities of Four Adhesives on 3/16-Inch-Cell-Size Phenolic-Impregnated Fiberglass Honeycomb Core (HRP, GF-11) Under Various Conditions of Cure.



AIRCOMB PAPER
Type 125-35-20, 0.42-inch cell



5052 **ALUMINUM**
0.0025-inch foil, 3/16-inch cell

Figure 29. **The Core-to-Facing Bonding Qualities of Armstrong A-12 Adhesive on Paper and Aluminum Honeycomb Core Under Various Conditions cf Cure.**

EVALUATION

Single-Step Sandwich

Laboratory experience showed that the quantity of resin impregnated into the three ply facings during the lay-up phase of fabrication was rather difficult to control by the hand squeegee method; and for this reason a semiautomatic coating machine was developed. The single-step fabricated sandwich test results exhibit the variations present between the hand and the machine methods of impregnating thin facings. For example, at 200°F and 30 psi in the wet lay-up, the final resin content, as well as the corresponding compressive strength, was large in comparison to the other values in the experiment. These larger initial resin content specimens--or more precisely stated, the nonuniformity of the initial resin content of the facings--would, no doubt, tend to obscure or prevent detection of the effect of the fabrication variables on the final strength; hence as many panels as time would permit were replicated.

In the case of the wet lay-up, the statistical analysis showed a significant mold temperature and pressure main effect on the ultimate compressive strength of the sandwich with a high interaction. This is to say that both the temperature by itself and the pressure by itself brought about a change in the sandwich edgewise compressive strength, and the functional relationships were not the same at each level of the variable held constant. The interaction is mainly attributed to experimental error--to the aforementioned nonuniform initial resin content of the facings. These trends are presented graphically in Figure 16 by averaging together under each pressure the values for the replication and the values for the three post-cure times--since the statistical analysis indicated that the post-cure time, within the area investigated, had no significance. The extreme values previously discussed were excluded which resulted in the disappearance of the interaction as well as the temperature main effect.

In the case of th B-staged lay-up, the statistical analysis showed only a mold temperature main effect on the sandwich compressive strength. When the data were averaged over the replicate and the post-cure times as before, a pressure effect was shown to be present still (Figure 16).

Analysis of the modulus data, both the wet and the B-staged lay-up, revealed no significant variation. This was further confirmed by averaging the data for the replicate and the two post-cure times in each case and then plotting triordinate graphs of modulus versus mold temperature and pressure. The surfaces formed were essentially planes parallel to the temperature-pressure coordinate plane.

For the core-to-facing bond data, statistical analysis detected no effect of the fabrication variables on the bond strength due to a very high third-order interaction between the variables. Since higher order interactions seldom exist in nature, it is in this case attributed to experimental error. The cause of this error has not been isolated at the writing of this report. The facing bond strength can be expected to follow the compressive ultimate strength of the sandwich; and therefore in spite of the scatter in the data, effort was made to establish this trend. Since the compressive strength was found to be sensitive to mold pressure, the entirety of the bond data was averaged under the two pressures, for both the wet and the B-staged lay-ups, and plotted against the corresponding averages of the ultimate compressive stress. Figure 17 shows the relationship does exist; and thus it can be asserted that optimum compressive strength means optimum bond strength with the process variables important in establishing compressive strength also being important in establishing bond strength. Table 2 gives the optimum compressive strengths. The trend curves (Figure 16) were used to locate the optimums which were then calculated by averaging over the post-cure times and replicate for each condition.

Figure 17 is very revealing in another respect as shown by the table included as part of the graph. Not only was the B-staged lay-up easier to handle and work with in the laboratory, but the mechanical properties were high in every case. The superiority of the B-staged lay-up is further substantiated by the actual appearance of the sandwich. Figures 18 and 19 show the serious resin starving of the upper face and the resin richening of the lower face produced when the wet lay-up was used directly as compared to the more balanced condition produced when the B-staged lay-up was used.

An interesting comparison is made in Figure 21 between the three resin conditions encountered in the research. The two specimens on the left have just been discussed. The third specimen shown reveals an important limitation to the vacuum blanket technique of developing mold pressure; i.e., resin vaporization. Efforts to use high vacuum molding of the single-step sandwich were thwarted by this condition. Figure 20 gives a close-up view of the hardened resin bubbles produced on the inner side of the sandwich facings. Laboratory experience indicates 20 inches of mercury to be the safe lower vacuum limit to prevent this phenomenon.

The shear modulus of the sandwich was expected to be near in value to that of the core and for this reason was monitored as an index of the core condition after experiencing the conditions of sandwich fabrication. The plate shear data showed only one anomaly, two low values arising from mislabeling of the specimens, and the averages compared favorably with the manufacturer's published core data, as shown in Table 1.

Bare Laminates

Preliminary examination of the experimental data for the 60- and 90-minute cure times in the mold phase of fabrication showed that at the 60-minute time there were great differences in the data in comparison to those present at the 90-minute time (only B-staged data are available for the 60-minute time). However, within the 1- to 3-hour post-cure times the differences did not indicate a pronounced post-cure trend. Hence, to expedite the data analysis the central value of 2 hours was chosen and the 60-minute data were plotted on triordinate graphs, with pressure and temperature as coordinates (Figures 22 through 25) in order to detect trends and locate peak values. From the graphs it can be seen that in every case but one, the ultimate compressive strength, there is an increase in strength with temperature and pressure, the temperature main effect being the strongest. The ultimate compressive strength actually showed a maximum value. This value and the peak values for the other properties are tabulated in Table 3. The trends for the 90-minute cure time were much more subtle; therefore, statistical analysis was employed here as initially planned.

As mentioned in the description of the design of the program, one reason why the 60-minute mold time was included in the bare laminate study was to obtain an indication of the time required to complete resin cure during the mold phase, as this time was apparently used in reference 2 to uncouple the mold and the post-cure phases so that they could be examined separately. Thus, it was anticipated that the near-completion time of the cure in the mold phase would permit clearer detection of a post-cure influence on strength, should it be significant. The consistently lower values of resin content in the case of the 90-minute mold time was taken as an indication that this time was closer to the desired value; however, the expected results did not follow.

The statistical analysis showed a significant post-cure main effect for one strength property, compression modulus in the wet lay-up. Post-cure time was found in interaction with the mold variables for two properties: compressive ultimate strength for the wet and the B-staged lay-ups. In the light of these findings it is difficult to positively assert that there is no post-cure effect though its presence is only slightly detected in comparison to the effects of the mold variables cure temperature and pressure (Appendix III). Apparently there is some post-cure effect on the room temperature measured strength properties of the laminate, but it is obscured by the coupling still present between the mold and the post-cure phases of the cure cycle or possibly by experimental error. Hence, a post-cure of 1, 2, or 3 hours would be acceptable within the range of conditions investigated in this program.

The results of the statistical analysis of the laminate data are given by the statistical summary tables in Appendix III Figures 26 and 27 are plots of the data for each laminate showing the trends observed. The curves were established by averaging the post-cure data and the data for the mold variable being held constant.

With the exception of the tensile ultimate strength for the wet lay-up, the mold variables temperature and pressure are seen to have very little influence on the laminate ultimate strength in tension or compression for the range of the conditions of fabrication investigated at the 90-minute cure time. The trend curves do show that the cure of the resin affects the compression modulus slightly more than the tension modulus as evidenced by the somewhat steeper curves.

Even though the variations are small, the optimum fabrication conditions were obtained from the trend curves and then the corresponding strength properties were calculated from the actual data by averaging over the post-cure times in each case. Table 3 contains these data. This compilation of data shows that the optimum condition for compressive properties is not necessarily the optimum for tensile properties. Should a balance of these properties be desired, as in the case of flexural strength, further testing would be required. For the 90-minute cure time the B-staged lay-up is seen to have no consistent strength advantage. The 60-minute cure time, at the 2-hour post-cure, gave slightly lower strength properties than did the 90-minute cure.

Near the end of the work program, advantage was taken of the opportunity to obtain data on 3-ply laminates of S994-glass HTS-finished 181 fiberglass fabric. These data are tabulated in Table 19. The tensile strength is seen to be approximately double that for the Volan A finished fabric with the modulus only slightly higher. The tensile specimens were noticed to fail in an unusual manner. Instead of failing across the influenced section, the laminate failed by splintering in the length direction, the length of the splinters extending over the entire exposed portion of the test coupon.

Core-to-Facing Bond

The results of the flatwise tension tests were plotted on triordinate graphs and the average surfaces drawn in order that trends could easily be seen and peak values located. These plots are contained in Figures 28 and 29. Though in most cases the exact optimum values were on the edge or slightly off the surface, the gradient of the surfaces in this area is shallow enough for the peak values found within the experimental region to be good estimates of the actual optimum values. The experimental peak values are summarized in Table 4.

The experimental data indicates that the A-12 adhesive gave better results in core-to-facing bond when used with paper core than when used with fiberglass core or aluminum core. The EC-1595 adhesive gave better results with aluminum core when compared with HRP core. AF-110B adhesive gave the best results when used with aluminum core when compared with fiberglass core. The latter was by inferrence, however, since the aluminum core-to-facing bond had not failed when the core foil failed at approximately the same stress as the fiberglass core-to-facing bond. This occurred in spite of the fact that there was a lesser bonding area on the aluminum core because of the larger cell size used in this series of tests. The basic resin system, 828-Z, functioned best as an adhesive on fiberglass core than on paper core.

These data can be summarized from another point of view. Within the limits of these tests, it appears that:

1. A-12 adhesive will give the strongest bond on paper core.

2. AF-110B adhesive and the facing resin 828-Z will give the best results on the HRP core; and

3. EC-1595 adhesive, the best results on the aluminum core.

Summary

Comparison of the influence of resin cure on the single-step sandwich and on the bare laminate compression strength shows the laminate strength to be about 30 percent higher. No doubt, the reduction in strength for the single-step sandwich is influenced by the nonuniform application of pressure on the facing by the ends of core during the mold phase of fabrication when the lamination of the facings is effected. The properties were more sensitive to fabrication than the single-step sandwich, especially in view of the fewer number of specimens used in the single-step sandwich program.

Tables 21 and 22 show the data recorded for the cold storage of the resin impregnated fabric. As the table shows, the maximum time between impregnation and use of any one lay-up was 12 days. Though the detail effect of the cold storage time is obscured in the experiment, it can be stated that the effect of low-time cold storage (5°F) of 828 Z-181 Volan A lay-ups is not pronounced.

The major conclusions drawn from the research are as follows:

1. The initial resin content of the facings of sandwich material and the uniformity and extent of voids in the impregnation have an important effect on its final strength properties. This is especially true when the facings are thin. The effect is also associated with the flow that takes place during the resin cure cycle.

2. The mechanical coating process produces more controllable and uniform resin impregnations of fiberglass fabric laminations than the hand squeegee method.

3. For the vacuum blanket technique of applying pressure to EPON 828-Z epoxy resin impregnations, 20 inches of mercury is a safe lower cacuum pressure to prevent resin's bubbling within the 160- to 200-degree Fahrenheit temperature range.

4. Room temperature B-staged lay-ups of 828Z-181 Volan A laminations are more convenient to work with and can be expected, in most cases, to produce slightly higher strengths.

5. Post-cure time between 1 and 3 hours at 300 degrees Fahrenheit, for the pre-cure and mold (cure) conditions investigated, does not have a major influence on the strength properties developed from resin cure.

6. Within the levels of cure pressure, temperature, and time examined in this project (10-70 psi, 160-230°F, and 60-90 minutes), the optimum strength properties and their specific cure conditions are as given in Tables 2 and 3.

7. For the 60-minute cure time, within the range of post-cure times investigated (1 to 3 hours), higher molding pressures and

temperatures are required to develop strength properties comparable to those obtained for 90-minute cure during the mold phase of fabrication

8. A serious condition of resin starvation on the upper facing can be expected when the wet lay-up of the facings is used directly in the fabrication of sandwich by the single-step method This condition is not nearly so severe when the 10-hour room temperature B-staged lay-up is used.

9. Of the three adhesives studied, the Armstrong A-12 produces the strongest core-to-facing bond on 20 percent phenolic-impregnated kraft paper honeycomb core; the EPON 828-Z epoxy resin and the Scotchweld AF-100B produce the strongest bond on 20 percent phenolic-impregnated HRP fiberglass honeycomb core; and the AF-110B produces the strongest bond on aluminum honeycomb core.

10. The bonded-type sandwich material investigated can be expected to develop a maximum of 30 percent higher compressive strength than the single-step-type sandwich

11. The optimum conditions of fabrication for tensile and compressive properties are not the same; hence, further testing is required to establish flexural optimum strength properties

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APPENDIX I

FABRICATION AND TEST EQUIPMENT

Laminating Presses

Two laminating presses were used in this research program: a 38- by 24-inch platen vacuum press (Figure 30) and a 22- by 28-inch platen hydraulic press (Figure 31). Both presses utilize machined aluminum upper and lower platens heated by "Chromalox" heating strips bolted to the back surfaces. The heaters are 6.5 inches apart on the vacuum press and 7.5 inches apart on the hydraulic press. Nine thermocouples are located on the vacuum press platens and 6 on the hydraulic press. Thermocouple stations were located at the heaters and between heaters both in the center and on the edges of the platens Electric power is supplied by a 220-volt, 3-phase circuit controlled by a Barber-Colman regulating pyrometer. This instrument has a calibrated range of zero to 600 degrees Fahrenheit at 5 degree increments and produced an observed regulating tolerance of 5 degrees Fahrenheit. A 5-degree temperature variation was observed on the platens after the transient period following heat-up.

Both presses were designed and built at the University of Oklahoma Research Institute specifically for the FRP laminating. The vacuum press features an air-activated upper bed which carries the upper platen and the fiberglass-reinforced silicone rubber vacuum blanket. When this bed is lowered, it drops the vacuum blanket around the piece being molded and seals it against the surface of the lower platen The air is then evacuated from under the blanket by a 3-cylinder vacuum pump which is self-regulating at any preset vacuum level between 5 inches Hg and 29 inches Hg.

The hydraulic press is operated by an 11-inch diameter hydraulic cylinder. Hydraulic pressure is developed by a pump powered by a vari-drive electric motor contained in the press console (Figure 31). There are two automatic speed control positions on the console for high-speed opening and closing of the press and low-speed adjustment of the final platen pressure. The 60-ton-capacity press is presently calibrated to approximately half capacity, or 100-psi platen pressure Laminating pressure is set by reference to the indicated ram pressure displayed on the control gage (A in Figure 31). An Amsler mercury compression head was used to calibrate the press. The ratio of the control gage pressure to the platen pressure applied to the 22- by 28-inch area and the 20- by 26-inch area are 6.5 and 4.69 respectively.

Figure 30. Vacuum Press. The fiberglass-reinforced silicone rubber vacuum blanket is shown resting on the lower platen.

Figure 31. High Pressure Hydraulic Press: A, control gauge for setting the desired curing pressure; B, control console for monitoring and regulating the temperature of the heated press platens.

Multi-Ply Coating Machine

The requirement for a machine that could simultaneously impregnate a number of plies of fiberglass fabric and perform this operation with a uniform, controllable, and reproducible resin content free of air pockets was realized early in the single-step sandwich fabrication. The machine subsequently developed experimentally, adequately fulfills these requirements.

As conceived in its present form (Figures 32, 33, and 34), the machine utilizes several feed rolls (F in Figure 33) wound with dry fabric equal in number to the number of plies to be simultaneously impregnated. The ends of the fabric thread through the small guide rolls (A in Figure 33) across the resin feed tubes (B in Figure 33), and up between the zero-pressure rolls (E in Figure 33), and finally through the large pressure rolls (A in Figure 34). Just before entering the pressure rolls, a poly ethylene film (B in Figure 34) is applied to both sides of the wet fabric. This film aids even resin squeeze-out at the pressure rolls and provides a means of easily handling the very sticky wet impregnate.

The impregnated fabric is drawn through the machine by a motor-driven take-up roll (B in Figure 32). Preheated resin is poured into the resin reservoirs (A in Figure 32) which are then air pressurized, forcing the resin through the heated perforated feed tubes (B in Figure 33). These tubes are heated by a low-voltage high-amperage spot-welding transformer which is connected to them in series (power leads are marked D in Figure 33). The heating is necessary to provide uniform, uninterrupted flow of the viscous resin through the relatively small holes which perforate the feed tubes. The pressure cutoff switch and resin flow controls are shown by pointer C in Figure 34. A fluorescent lamp light panel is located at D in Figure 34 for inspection of the freshly impregnated fabric as it is being wound on the take-up roll.

The resin content of the fabric is determined by the spacing between the upper and the lower pressure rolls (A in Figure 34). This spacing is adjusted by turning the adjustment screws marked E in Figure 34 and setting the desired opening with feeler gages. Though the machine is quite versatile, all of the impregnations made during this program were 3 ply of 180-inch length and 44-inch width. The results of these runs are summarized by Figure 35, showing the excellent resin content control achieved.

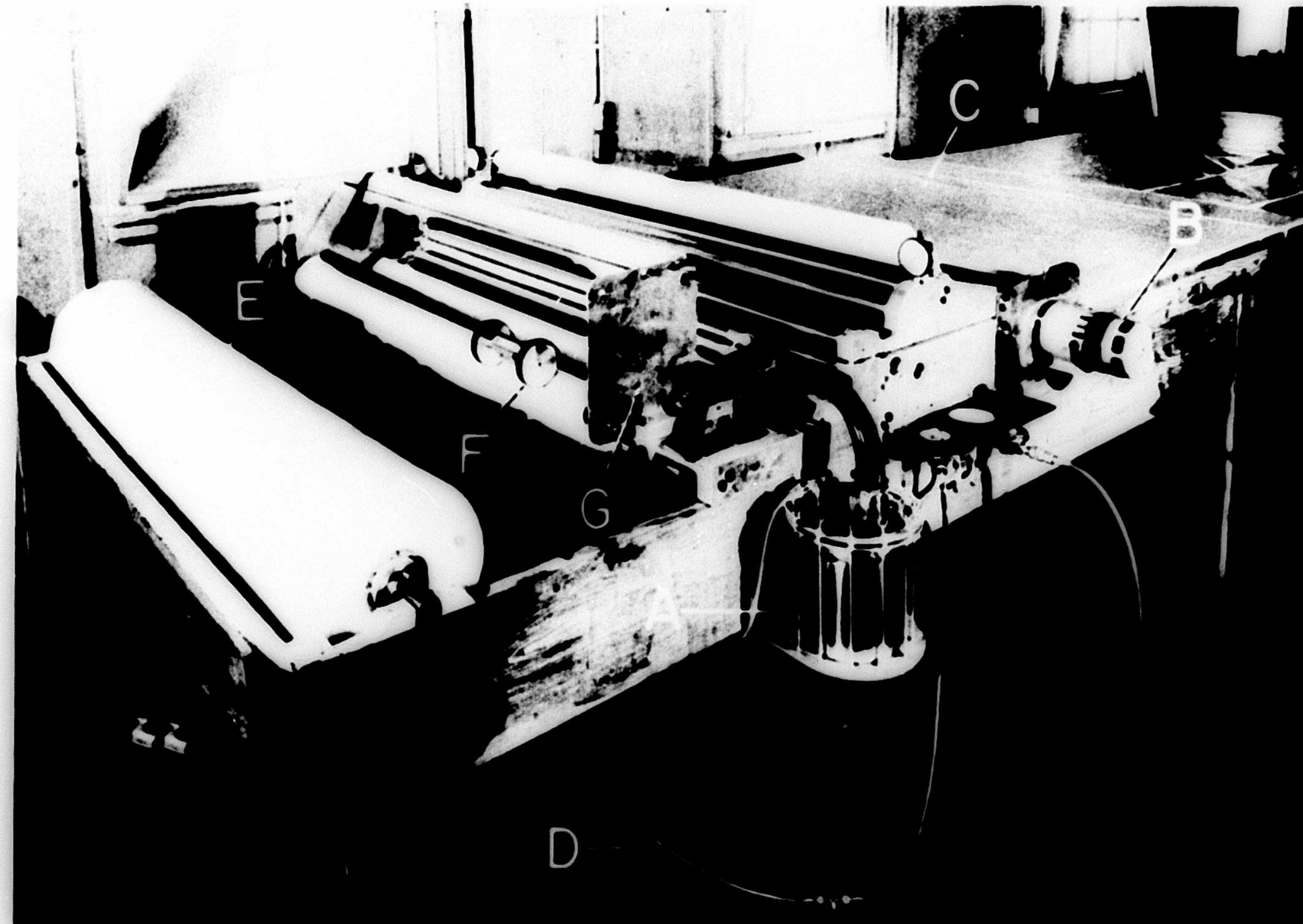

Figure 32. Overall View of Multi-Ply Coating Machine: A, pressurized resin reservoir (one other located on opposite side of table); B, reduction drive motor which draws fabric through machine onto take-up roll; C, cutting table; D, air lines to pressurize the resin reservoirs; E, large supply roll of polyethylene film (stored in this position); F, fabric length measuring counter; G, mounting rack which carries the dry fabric feed rolls (3 ply as shown).

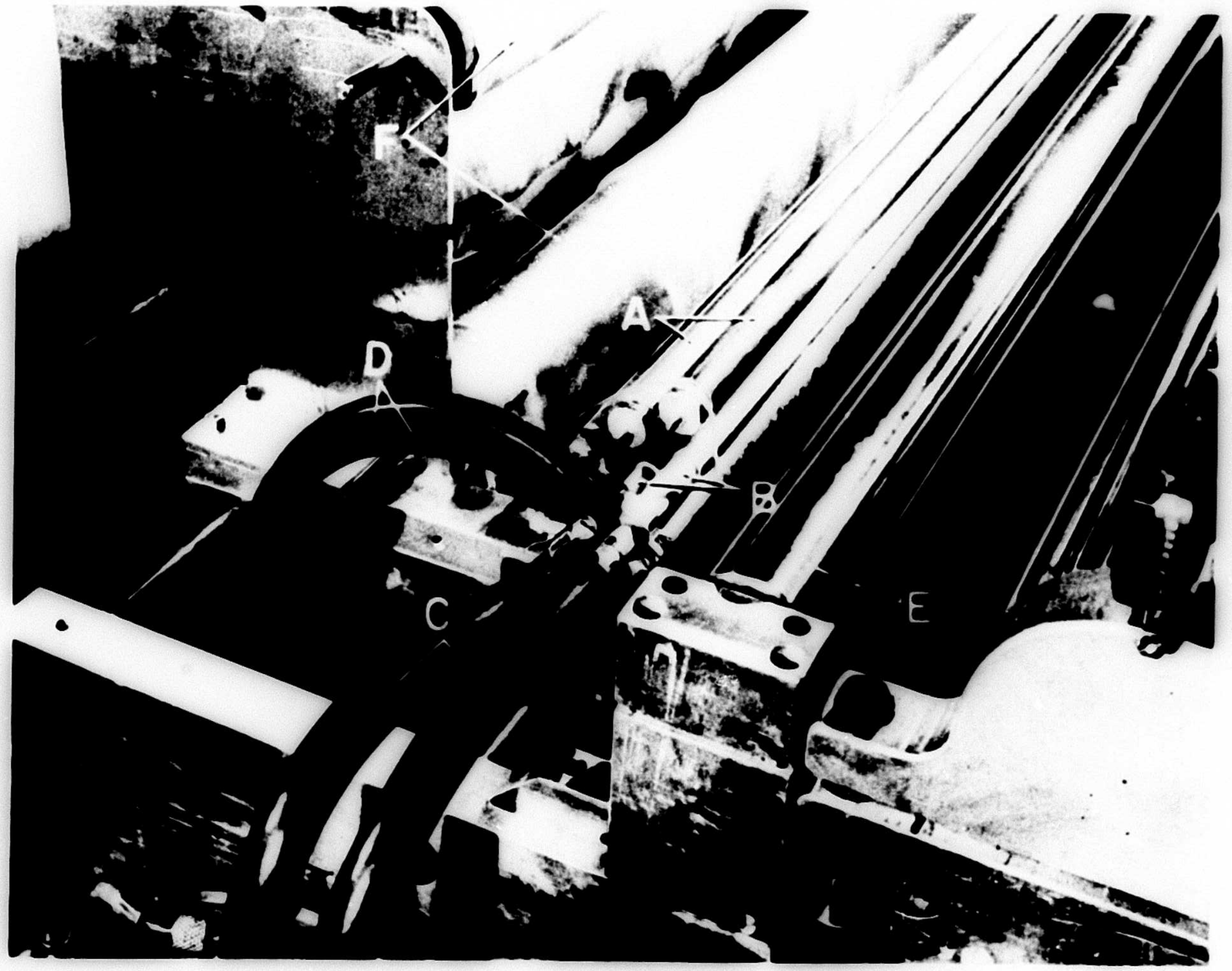

Figure 33. Detail View of Coating Machine: A. fabric guide rolls; B, perforated resin feed tubes; C, flexible connection lines between feed tubes and resin reservoir; D, power leads from feed tubes heating transformer; E, zero-pressure rolls; F, feed rolls carrying dry fiberglass fabric.

1/2 FRAMES

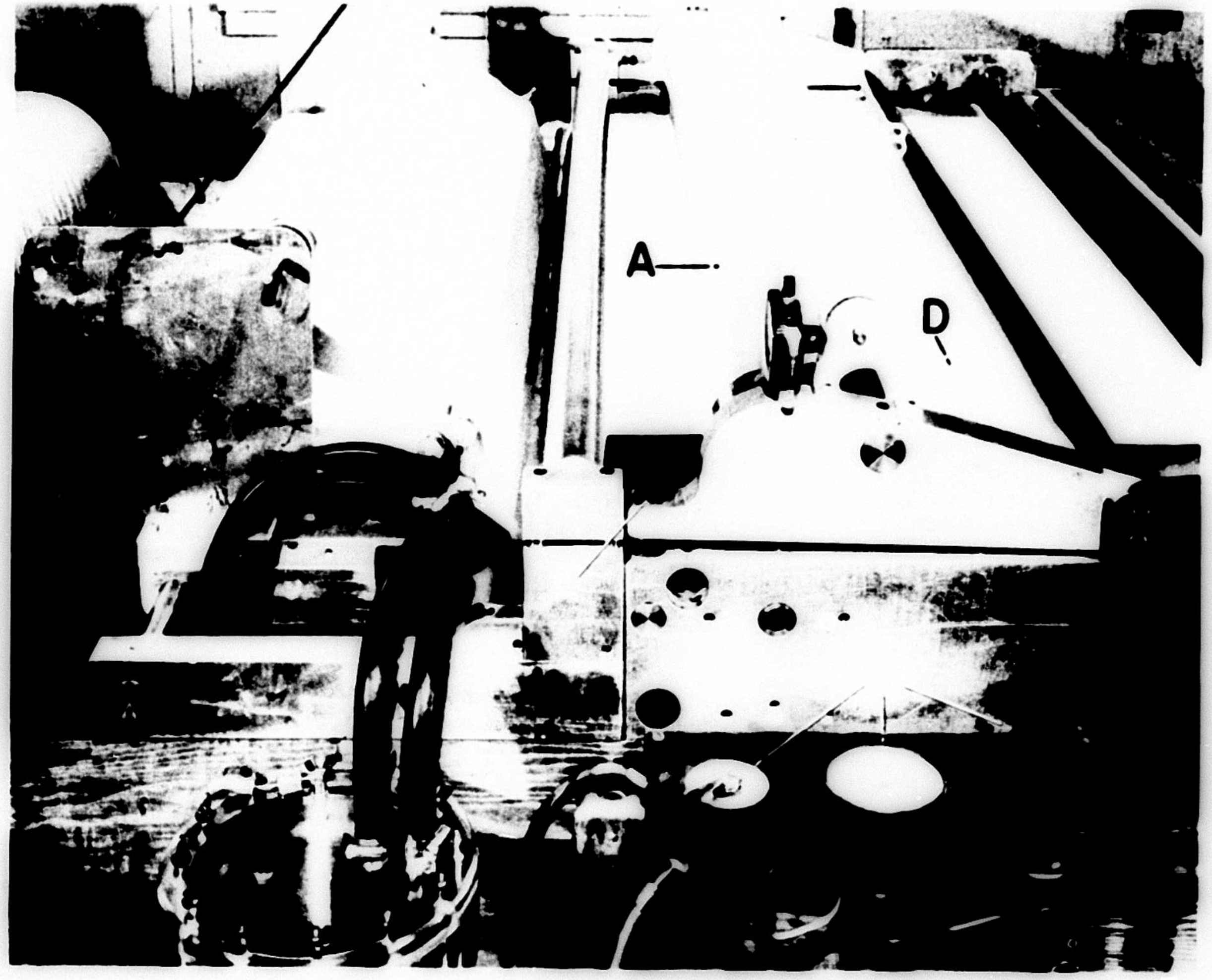

Figure 34. Lateral View of Coating Machine. A, large pressure rolls; B, feed roll for polyethylene film (one other located under table); C, control console for pressurization of resin reservoirs; D, fluorescent light inspection panel under fabric at this location; E, adjustment screws for setting spacing between large pressure rolls.

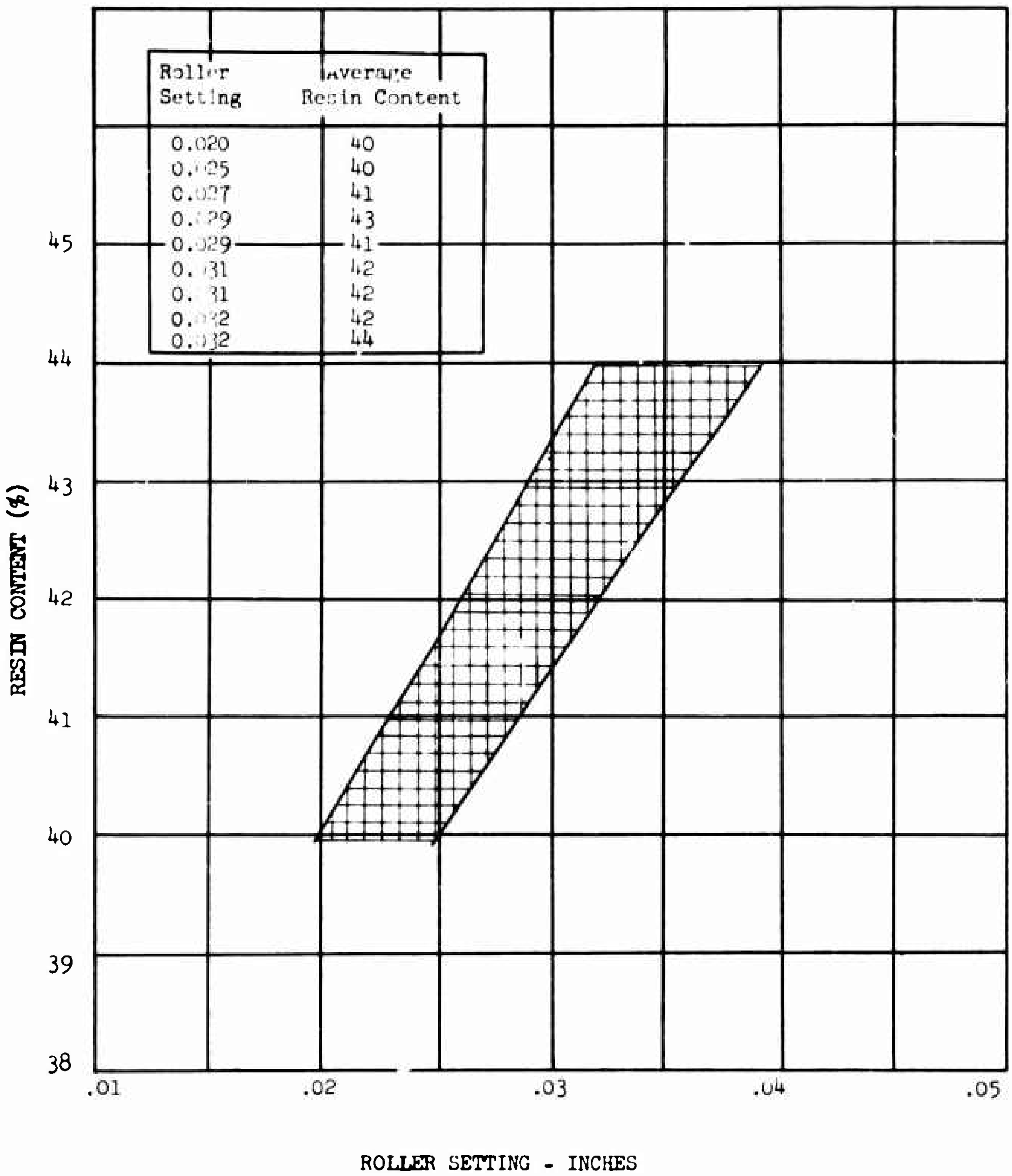

Figure 35. The Effect of Coating Machine Roller Spacing on Resin Content for 3-Ply 181 Volan A Glass Fabric Impregnations. The resin content was controlled to within ± 1%.

Sandwich Compressometer

To measure strain on the 4- by 4-inch sandwich panels over the gauge length called for in MIL-STD-401A, it was necessary to design and construct a large compressometer. The completed item is pictured in Figures 4 and 5. The circuitry and the mounting details are given in Figure 36.

The compressometer was calibrated by comparing the measured strain and the calculated strain for a circular 7075-T aluminum test cylinder. Readings were taken for gages AB, DC, and AD (Figure 36) at every 2000 pounds for loads from 0 to 22,000 pounds. The actual strain was calculated by the usual formula (P/AE) and plotted against the measured strain to obtain the best straight line. The slope of this line was taken as the constant for the compressometer.

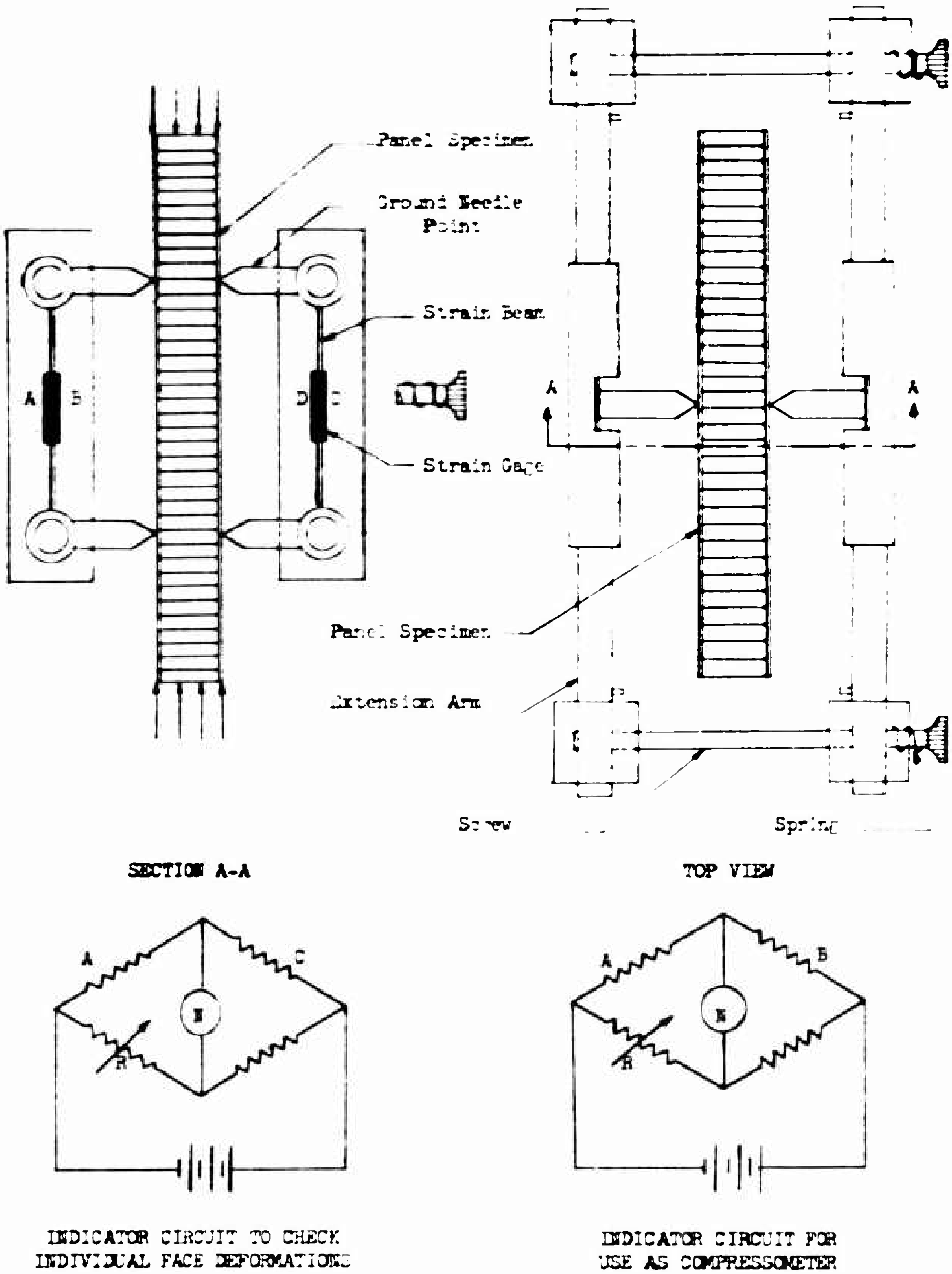

Figure 36. Panel Compressometer.

APPENDIX II

TABULATIONS OF TEST RESULTS

TABLE 5

SINGLE-STEP SANDWICH EDGEWISE COMPRESSION STRENGTH

Lay-Up	Cure Pressure and Time	Post Cure	160 Original	160 Replicate	180 Original	180 Replicate	200 Original	200 Replicate	230 Original[2]
			Cure Temperature (°F) and Panel Identification						
Wet	10 psi	2 hr. @ 300°F	27.8[1,4]	-	24.1	25.2	26.2[4]	25.8	24.3
	(20.4 in. Hg		30.7	-	25.8	27.7	28.0	27.9	26.1
	under vacuum)		34.0	-	28.6	30.6	29.5	29.6	29.6
	90 min.	3 hr. @ 300°F	31.7[4]	23.0[3]	24.9	24.1	23.2[4]	24.8	20.6
			33.6	27.2	25.9	27.3	25.6	27.6	27.4
			35.4	28.7	27.7	30.0	29.2	29.5	29.8
	30 psi	2 hr. @ 300°F	26.8[4]	-	26.4[4]	26.1	33.9[4]	25.8	24.9
	90 min.		29.3	-	27.6	29.1	35.2	28.6	27.4
			31.5	-	28.3	33.6	36.4	30.8	30.5
		3 hr. @ 300°F	25.2[4]	-	24.9[4]	25.8	33.2[4]	23.5	26.2
			27.7	-	27.5	28.6	36.5	29.4	29.9
			29.9	-	31.4	32.3	39.8	33.9	33.8
10-hour B-staged	10 psi	2 hr. @ 300°F	28.7[4]	-	-	24.8	25.8[4]	-	27.2
	(20.4 in. Hg		32.4	-	-	27.5	29.3	-	29.9
	under vacuum)		34.5	-	-	29.4	32.4	-	32.2
	90 min.	3 hr. @ 300°F	28.2[4]	-	-	25.4	22.4[4]	-	28.2
			31.3	-	-	28.9	24.9	-	30.4
			33.2	-	-	31.3	27.0	-	31.6
	30 psi	2 hr. @ 300°F	32.4[4]	-	25.0[4]	-	27.9[4]	24.8	26.1
	90 min.		34.8	-	29.1	-	28.9	28.3	28.7
			38.2	-	31.7	-	29.5	30.0	30.8
		3 hr. @ 300°F	22.6[4]	-	26.5[4]	-	27.6[4]	27.5	-
			33.8	-	28.3	-	29.3	29.3	-
			34.8	-	29.6	-	31.7	31.4	-

[1] Stress in psi x 10^{-3} tabulated in the following order: low, average, and high.

[2] Core thickness was changed from 3/4 to 1/2 inch.

[3] Underlined values indicate machine-coated lay-ups.

[4] One panel was cut in half for post cure at 2 and 3 hours rather than a single panel being fabricated for each post cure time.

TABLE 6

**SINGLE-STEP SANDWICH
EDGEWISE COMPRESSION MODULUS**

Lay-Up	Cure Pressure and Time	Post-Cure	Cure Temperature (°F) and Panel Identification						
			160 Original	160 Replicate	180 Original	180 Replicate	200 Original	200 Replicate	230 Original
Wet	10 psi (20.4 in. Hg under vacuum) 90 min.	2 hr. @ 300°F	3.33[1,4]	2.87	2.89[2]	3.19	3.21[4]	3.09	2.87
		3 hr. @ 300°F	3.12[4]	2.70	3.61	2.94	3.30[4]	3.14	2.96
	30 psi 90 min.	2 hr. @ 300°F	3.09[4]	-	3.28[4]	2.89	3.95[4]	2.96	2.71
		3 hr. @ 300°F	3.02[4]	-	3.34[4]	3.01	2.96[4]	2.89	3.04
10-hour B-stage	10 psi (20.4 in. Hg under vacuum) 90 min.	2 hr. @ 300°F	3.47[4]	-	-	3.02	3.24[4]	-	2.90
		3 hr. @ 300°F	3.43[4]	-	-	3.00	3.09[4]	-	2.69
	30 psi 90 min.	2 hr. @ 300°F	3.21[4]	-	3.43[4]	-	3.15[4]	2.99	3.01
		3 hr. @ 300°F	3.89[4]	-	3.30[4]	-	4.09[4]	3.14	-

[1] Average modulus in psi x 10^{-6}.

[2] Underlined values indicate machine-coated lay-ups.

[3] Core thickness was changed from 3/4 to 1/2 inch.

[4] One panel was cut in half for post cure at 2 and 3 hours rather than a single panel being fabricated for each post-cure.

TABLE 7

SINGLE-STEP SANDWICH FACING
RESIN CONTENT INDEX

			Cure Temperature (^oF) and Panel Identification						
			160		180		200		230
Lay-Up	Cure Pressure and Time	Post-Cure	Original	Replicate	Original	Replicate	Original	Replicate	Original
Wet	10 psi (20.4 in. Hg under vacuum) 90 min.	2 hr. @ 300^oF	44[1,3]	36[2]	37	35	29[3]	32	32
		3 hr. @ 300^oF	44[3]	36	37	34	29[3]	30	32
	30 psi 90 min.	2 hr. @ 300^oF	39[3]	-	38[3]	31	43[3]	36	32
		3 hr. @ 300^oF	39[3]	-	38[3]	33	43[3]	35	38
10-hour B-staged	10 psi (20.4 in. Hg under vacuum) 90 min.	2 hr. @ 300^oF	38[3]	-	-	32	37[3]	-	33
		3 hr. @ 300^oF	38[3]	-	-	30	37[3]	-	31
	30 psi 90 min.	2 hr. @ 300^oF	33[3]	-	37[3]	-	34[3]	33	35
		3 hr. @ 300^oF	33[3]	-	37[3]	-	34[3]	33	-

[1] Resin content index in percent $\left[\frac{\text{Total Wt.} - \text{Glass Wt.}}{\text{Total Wt.}}\right]$, where total Wt. was determined after facing had been stripped from core.

[2] Underlined values indicate machine-coated lay-ups.

[3] One panel was cut in half for post-cure at 2 and 3 hours rather than a single panel being fabricated for each post-cure time.

TABLE 8

SINGLE-STEP SANDWICH
CORE-TO-FACING BOND STRENGTH

Lay-Up	Cure Pressure and Time	Post-Cure	160 Original	160 Replicate	180 Original	180 Replicate	200 Original	200 Replicate
Wet	10 psi (20.4 in. Hg under vacuum)	2 hr. @ 300°F	330[1,3]	90[2]	190	-	170[3]	380
			400	160	260	-	290	320
			470	290	310	-	350	420
	90 min.	3 hr. @ 300°F	260[3]	180	150	-	140[3]	-
			310	270	250	-	280	-
			380	360	300	-	350	-
	30 psi 90 min.	2 hr. @ 300°F	300[3]	-	120[3]	-	100[3]	170
			390	-	250	-	150	230
			450	-	420	-	200	340
		3 hr. @ 300°F	210[3]	-	210[3]	450	140[3]	360
			390	-	260	520	200	440
			510	-	300	620	260	600
10-hour B-staged	10 psi (20.4 in. Hg under vacuum)	2 hr. @ 300°F	400[3]	-	-	410	290[3]	-
			500	-	-	60	360	-
			580	-	-	530	410	-
	90 min.	3 hr. @ 300°F	210[3]	-	-	-	240[3]	-
			470	-	-	-	290	-
			570	-	-	-	360	-
	30 psi 90 min.	2 hr. @ 300°F	390[3]	-	330[3]	-	100[3]	500
			490	-	470	-	460	560
			570	-	510	-	570	650
		3 hr. @ 300°F	370[3]	-	250[3]	-	410[3]	560
			530	-	310	-	480	660
			710	-	360	-	570	740

Cure Temperature (°F) and Panel Identification applies to the last six columns.

[1]Stress in psi tabulated in the following order: low, average, and high.
[2]Underlined values indicate machine-coated lay-ups.
[3]One panel was cut in half for post-cure at 2 and 3 hours rather than a single panel being fabricated for each post-cure.

SINGLE-STEP SANDWICH
PLATE SHEAR MODULUS

Lay-Up	Cure Pressure and Time	Post-Cure	160 Original +R[1]	160 Original =R[1]	180 Original +R	180 Original =R	180 Replicate +R	180 Replicate =R	200 Original +R	200 Original =R	200 Replicate +R	200 Replicate =R	230 Original[3] +R	230 Original[3] =R
			Cure Temperature (°F), Panel Identification, and Load Orientation											
Wet	10 psi (20.4 in. Hg under vacuum) 90 min.	2 hr. @ 300°F	9.8[2]	-	-	25.1[4]	-	-	8.5	17.2	-	-	9.5	2[illegible].5
		3 hr. @ 300°F	8.8	23.5	-	22.2	-	-	10.2	22.9	-	-	10.3	32.2
	30 psi 90 min.	2 hr. @ 300°F	9.2	25.6	-	21.8	-	25.7	6.6	17.6	8.8	27.1	-	-
		3 hr. @ 300°F	9.7	22.9	-	-	9.4	24.7	8.1	13.2	11.0	27.1	9.0	28.6
10-hour B-staged	10 psi (20.4 in. Hg under vacuum) 90 min.	2 hr. @ 300°F	11.1	23.9	-	-	-	-	7.5	14.5	-	-	10.6	25.[illegible]
		3 hr. @ 300°F	8.9	13.8	-	-	-	-	9.0	11.7	-	-	5.8 [illegible] [illegible]	24.8
	30 psi 90 min.	2 hr. @ 300°F	10.8	27.2	9.2	21.0 25.0 31.9	-	-	9.2	21.7	10.8 12.2 12.9	25.1 32.7 42.3	9.5	27.4
		3 hr. @ 300°F	9.6	27.0	10.2	21.3 23.5 26.6	-	-	9.5	24.7	10.7	27.1	-	-

[1] Load orientation is indicated as follows: +R is perpendicular to core ribbon and =R is parallel to core ribbon.
[2] Average modulus in psi x 10^{-3}. Where the number of specimens exceeds 4, the low and high values are tabulated above and below the average.
[3] Core thickness was changed from 3/4 to 1/2 inch.
[4] Underlined values indicate machine-coated lay-ups.

TABLE 10

LAMINATE COMPRESSION ULTIMATE STRENGTH,
WET LAY-UP USED DIRECTLY

Cure Pressure	Post-Cure	Cure Temperature and Time							
		160°F 60 min.	160°F 90 min.	180°F 60 min.	180°F 90 min.	200°F 60 min.	200°F 90 min.	230°F 60 min.	230°F 90 min.
	1 hr. @ 300°F	-	36.0*	-	40.5	33.0	35.5	-	34.0
		-	38.2	-	43.8	42.2	39.8	-	38.4
		-	40.2	-	49.4	46.4	42.6	-	41.1
13 psi	2 hr. @ 300°F	-	35.4	-	36.8	37.6	31.8	-	35.1
		-	38.2	-	40.0	42.1	39.6	-	38.1
		-	41.2	-	44.1	47.2	55.0	-	42.0
	3 hr. @ 300°F	-	36.9	-	35.8	42.4	32.6	-	29.3
		-	38.8	-	41.7	44.3	39.8	-	38.8
		-	41.9	-	47.2	46.2	45.3	-	48.6
	1 hr. @ 300°F	-	33.7	-	-	-	31.5	-	30.5
		-	43.7	-	-	-	40.5	-	39.9
		-	49.9	-	-	-	44.3	-	43.8
30 psi	2 hr. @ 300°F	-	37.6	-	-	-	34.3	-	35.0
		-	44.5	-	-	-	40.1	-	39.0
		-	48.2	-	-	-	49.3	-	42.6
	3 hr. @ 300°F	-	39.6	-	-	-	32.5	-	35.4
		-	45.0	-	-	-	39.7	-	39.0
		-	49.0	-	-	-	43.4	-	43.4
	1 hr. @ 300°F	-	39.2	-	36.7	25.2	30.5	-	33.2
		-	45.6	-	43.5	33.7	35.0	-	40.5
		-	48.9	-	49.5	37.6	39.6	-	45.7
70 psi	2 hr. @ 300°F	-	37.5	-	34.4	33.3	30.3	-	28.7
		-	47.1	-	43.8	36.2	35.8	-	40.7
		-	51.3	-	51.6	40.0	41.9	-	48.9
	3 hr. @ 300°F	-	42.1	-	36.9	29.6	29.2	-	26.4
		-	44.5	-	42.5	34.4	34.6	-	39.5
		-	47.3	-	49.0	37.4	41.0	-	43.4

*Stress in psi x 10^{-3} tabulated in the following order: low, average, and high.

TABLE 11

LAMINATE COMPRESSION MODULUS,
WET LAY-UP USED DIRECTLY

Cure Pressure	Post-Cure	Cure Temperature and Time 160°F 60 min.	160°F 90 min.	180°F 60 min.	180°F 90 min.	200°F 60 min.	200°F 90 min.	230°F 60 min.	230°F 90 min.
	1 hr. @ 300°F	–	2.72*	–	–	2.65	2.81	–	3.12
		–	3.15	–	–	2.68	3.14	–	3.15
		–	3.46	–	–	2.73	4.44	–	3.19
	2 hr. @ 300°F	–	2.54	–	2.68	2.60	2.38	–	3.12
13 psi		–	2.87	–	2.77	2.69	2.89	–	3.27
		–	3.24	–	2.91	2.76	3.16	–	3.54
	3 hr. @ 300°F	–	2.78	–	2.68	2.65	2.78	–	2.82
		–	3.23	–	3.21	2.71	2.97	–	3.15
		–	3.57	–	4.00	2.78	3.13	–	3.43
	1 hr. @ 300°F	–	–	–	–	–	2.86	–	3.45
		–	–	–	–	–	3.38	–	3.98
		–	–	–	–	–	3.61	–	4.73
	2 hr. @ 300°F	–	2.61	–	–	–	2.98	–	3.58
30 psi		–	2.82	–	–	–	3.23	–	4.00
		–	2.95	–	–	–	3.61	–	4.71
	3 hr. @ 300°F	–	2.81	–	–	–	2.98	–	3.53
		–	2.89	–	–	–	3.14	–	3.81
		–	2.98	–	–	–	4.11	–	4.33
	1 hr. @ 300°F	–	2.69	–	2.93	3.30	3.79	–	3.93
		–	2.81	–	3.26	3.67	4.18	–	4.35
		–	2.94	–	3.55	3.95	4.54	–	4.82
	2 hr. @ 300°F	–	2.54	–	2.60	3.36	3.81	–	3.87
70 psi		–	2.72	–	2.80	3.[illegible]1	4.17	–	4.14
		–	2.88	–	3.08	3.82	4.56	–	4.91
	3 hr. @ 300°F	–	2.64	–	2.59	3.56	–	–	3.51
		–	2.77	–	2.78	3.85	–	–	4.03
		–	2.90	–	3.04	4.4[illegible]	–	–	4.60

* Test values in psi x 10^{-6} tabulated in the following order: low, average, and high.

TABLE 12

LAMINATE COMPRESSION ULTIMATE STRENGTH,
10-HOUR B-STAGED LAY-UP USED

		Cure Temperature and Time							
Cure Pressure	Post-Cure	160°F 60 min.	160°F 90 min.	180°F 60 min.	180°F 90 min.	200°F 60 min.	200°F 90 min.	230°F 60 min.	230°F 90 min.
	1 hr. @ 300°F	-	-	-	35.3*	37.1	38.6	-	36.9
		-	-	-	39.6	39.3	43.7	-	44.9
		-	-	-	45.6	43.3	49.0	-	50.8
13 psi	2 hr. @ 300°F	-	-	-	32.1	38.3	37.9	-	39.2
		-	-	-	39.1	40.8	44.0	-	48.6
		-	-	-	44.2	43.8	47.1	-	47.0
	3 hr. @ 300°F	-	-	-	36.4	39.2	34.9	-	39.5
		-	-	-	41.4	42.4	42.3	-	42.5
		-	-	-	44.8	45.0	48.7	-	47.3
	1 hr. @ 300°F	33.6	31.1	40.0	35.0	34.6	36.6	35.2	40.6
		39.5	40.6	43.4	42.1	40.8	42.1	40.4	44.4
		44.1	46.3	46.8	47.3	44.4	45.6	43.8	46.7
30 psi	2 hr. @ 300°F	37.8	34.9	39.0	33.6	37.8	34.1	37.0	39.9
		42.2	44.0	42.9	38.6	41.8	42.2	41.2	42.1
		45.6	48.4	47.0	42.1	43.2	46.7	46.7	45.2
	3 hr. @ 300°F	39.9	42.7	37.2	31.6	33.7	37.2	35.4	36.2
		43.3	45.2	43.4	37.0	40.4	40.8	42.0	42.1
		48.4	47.9	48.4	42.5	44.8	45.0	47.6	48.1
	1 hr. @ 300°F	40.4	33.7	37.6	34.0	36.6	37.1	35.3	40.6
		43.1	41.2	42.3	40.0	41.1	43.5	42.6	41.8
		47.6	46.5	46.6	42.9	45.3	47.9	46.2	44.1
70 psi	2 hr. @ 300°F	34.9	39.2	36.3	38.8	36.0	37.9	37.2	31.1
		41.5	44.4	41.4	41.0	40.9	42.3	41.8	38.5
		46.4	49.0	44.1	44.4	46.9	45.6	45.7	42.4
	3 hr. @ 300°F	34.2	39.6	36.6	36.9	34.8	38.2	34.1	34.2
		40.8	45.2	42.0	40.1	39.8	41.1	38.7	39.5
		47.6	51.8	45.8	44.0	46.2	43.8	41.7	43.3

*Stress in psi x 10^{-3} tabulated in the following order: low, average, and high.

TABLE 13

LAMINATE COMPRESSION MODULUS,
10 HOUR B-STAGED LAY-UP USED

Cure Pressure	Post-Cure	160°F 60 min.	160°F 90 min.	180°F 60 min.	180°F 90 min.	200°F 60 min.	200°F 90 min.	230°F 60 min.	230°F 90 min.
		Cure Temperature and Time							
	1 hr. @ 300°F	-	-	-	2.69*	2.60	2.19	-	2.78
		-	-	-	2.87	2.81	2.94	-	3.01
		-	-	-	3.09	2.99	4.00	-	3.46
13 psi	2 hr. @ 300°F	-	-	-	2.59	2.79	2.68	-	2.93
		-	-	-	3.05	2.92	2.91	-	3.13
		-	-	-	3.84	3.11	3.36	-	3.28
	3 hr. @ 300°F	-	-	-	2.65	2.73	2.76	-	2.88
		-	-	-	2.92	2.93	3.12	-	2.99
		-	-	-	3.14	3.09	3.70	-	3.12
	1 hr. @ 300°F	2.60	2.75	2.59	3.88	2.85	2.95	3.07	2.79
		2.67	2.96	2.86	4.15	3.09	3.22	3.20	3.02
		2.81	3.09	3.10	4.62	3.29	3.69	3.38	3.26
30 psi	2 hr. @ 300°F	2.42	2.67	2.64	3.71	2.66	2.75	3.00	2.95
		2.59	3.04	2.71	3.85	3.13	3.20	3.29	3.25
		2.77	3.39	2.76	4.04	3.60	3.59	3.62	3.58
	3 hr. @ 300°F	2.39	2.96	2.60	3.62	2.67	2.79	2.99	2.91
		2.47	3.16	2.92	4.03	2.90	3.15	3.18	3.22
		2.57	3.32	3.36	4.69	3.10	3.55	3.49	3.37
	1 hr. @ 300°F	2.84	2.84	2.84	3.32	2.85	3.18	3.52	3.18
		3.07	3.59	3.36	3.73	3.28	3.49	3.65	3.81
		3.30	4.21	3.82	3.93	3.78	3.62	3.95	4.60
70 psi	2 hr. @ 300°F	2.51	2.68	2.76	3.45	2.51	3.31	3.36	3.33
		2.95	3.07	3.07	3.75	2.79	3.66	3.75	3.84
		3.38	3.38	3.56	4.17	3.51	4.13	4.05	4.14
	3 hr. @ 300°F	2.75	2.94	2.81	3.48	2.44	2.91	3.32	3.64
		3.22	3.18	3.20	3.82	2.91	3.35	4.09	4.09
		3.70	3.40	3.49	4.17	3.44	3.59	5.52	4.56

*Test values in psi x 10^{-6} tabulated in the following order: low, average, and high.

TABLE 14

LAMINATE TENSION ULTIMATE STRENGTH,
WET LAY-UP USED DIRECTLY

Cure Pressure	Post-Cure	160°F 60 min.	160°F 90 min.	180°F 60 min.	180°F 90 min.	200°F 60 min.	200°F 90 min.	230°F 60 min.	230°F 90 min.
		Cure Temperature and Time							
	1 hr. @ 300°F	-	43.8*	-	29.1	34.3	48.7	-	51.4
		-	48.5	-	31.8	40.7	50.6	-	54.5
		-	51.8	-	34.3	45.7	51.4	-	56.4
13 psi	2 hr. @ 300°F	-	42.0	-	-	-	46.6	-	49.0
		-	47.5	-	-	-	51.4	-	53.6
		-	52.5	-	-	-	54.1	-	58.4
	3 hr. @ 300°F	-	50.6	-	-	-	48.5	-	49.5
		-	51.6	-	-	-	52.2	-	53.8
		-	52.4	-	-	-	56.8	-	60.3
	1 hr. @ 300°F	-	49.6	-	-	-	50.2	-	54.8
		-	52.7	-	-	-	56.8	-	59.5
		-	56.8	-	-	-	60.8	-	61.9
30 psi	2 hr. @ 300°F	-	34.5	-	-	-	49.3	-	57.0
		-	39.7	-	-	-	53.8	-	59.2
		-	46.8	-	-	-	60.6	-	61.2
	3 hr. @ 300°F	-	29.4	-	-	-	52.9	-	54.1
		-	35.0	-	-	-	55.0	-	57.4
		-	42.9	-	-	-	59.2	-	61.6
	1 hr. @ 300°F	-	47.2	-	49.8	-	37.8	-	54.4
		-	49.1	-	52.7	-	43.9	-	59.4
		-	52.0	-	56.8	-	51.1	-	62.0
70 psi	2 hr. @ 300°F	-	45.1	-	47.8	59.0	36.9	-	53.9
		-	46.8	-	50.1	63.8	41.1	-	57.6
		-	48.4	-	52.2	68.2	44.1	-	62.8
	3 hr. @ 300°F	-	47.0	-	-	59.7	60.7	-	56.5
		-	48.8	-	-	62.2	63.5	-	59.5
		-	54.6	-	-	64.9	70.4	-	62.9

*Stress in psi x 10^{-3} tabulated in the following order: low, average, and high.

TABLE 15

LAMINATE TENSION MODULUS, WET LAY-UP USED DIRECTLY

Cure Pressure	Post-Cure	160°F 60 min.	160°F 90 min.	180°F 60 min.	180°F 90 min.	200°F 60 min.	200°F 90 min.	230°F 60 min.	230°F 90 min.
		Cure Temperature and Time							
	1 hr. @ 300°F	-	2.23*	-	2.04	-	2.32	-	2.54
		-	2.35	-	2.15	-	2.40	-	2.70
		-	2.46	-	2.25	-	2.60	-	2.83
13 psi	2 hr. @ 300°F	-	2.08	-	-	1.62	2.40	-	2.56
		-	2.31	-	-	1.67	2.49	-	2.83
		-	2.41	-	-	1.70	2.62	-	3.17
	3 hr. @ 300°F	-	2.32	-	-	1.50	2.45	-	2.53
		-	2.44	-	-	1.59	2.54	-	2.69
		-	2.63	-	-	1.68	2.70	-	2.97
	1 hr. @ 300°F	-	2.44	-	-	-	1.97	-	2.70
		-	2.57	-	-	-	2.69	-	2.86
		-	2.70	-	-	-	3.25	-	3.15
30 psi	2 hr. @ 300°F	-	1.99	-	-	-	2.37	-	2.53
		-	2.14	-	-	-	2.52	-	2.60
		-	2.41	-	-	-	2.67	-	2.79
	3 hr. @ 300°F	-	2.13	-	-	-	2.29	-	2.56
		-	2.24	-	-	-	2.49	-	2.80
		-	2.37	-	-	-	2.62	-	3.04
	1 hr. @ 300°F	-	2.08	-	2.36	2.92	2.50	-	2.48
		-	2.15	-	2.46	3.02	2.95	-	2.70
		-	2.22	-	2.57	3.09	3.11	-	2.84
70 psi	2 hr. @ 300°F	-	1.95	-	2.39	2.88	2.95	-	2.69
		-	2.09	-	2.43	3.06	3.10	-	2.85
		-	2.28	-	2.46	3.19	3.36	-	3.15
	3 hr. @ 300°F	-	2.08	-	-	2.85	3.14	-	2.70
		-	2.21	-	-	3.04	3.26	-	3.01
		-	2.32	-	-	3.28	3.36	-	3.47

*Test values in psi x 10^{-6} tabulated in the following order: low, average, and high.

TABLE 16

LAMINATE TENSION ULTIMATE STRENGTH,
10-HOUR B-STAGED LAY-UP USED

Cure Pressure	Post-Cure	160°F 60 min.	160°F 90 min.	180°F 60 min.	180°F 90 min.	200°F 60 min.	200°F 90 min.	230°F 60 min.	230°F 90 min.
		Cure Temperature and Time							
	1 hr. @ 300°F	-	-	-	46.8*	49.8	48.4	-	50.0
		-	-	-	48.1	50.5	52.2	-	52.3
		-	-	-	50.0	51.1	56.3	-	54.5
13 psi	2 hr. @ 300°F	-	-	-	-	51.8	47.0	-	48.1
		-	-	-	41.2	53.8	50.7	-	53.3
		-	-	-	-	56.9	56.1	-	60.1
	3 hr. @ 300°F	-	-	-	43.8	51.8	51.2	-	47.9
		-	-	-	45.5	53.1	53.8	-	51.5
		-	-	-	47.2	54.6	56.1	-	56.0
	1 hr. @ 300°F	51.3	51.0	51.5	55.0	52.1	53.8	52.7	51.5
		52.7	54.5	53.9	58.4	54.2	55.8	54.6	55.7
		54.8	57.3	60.1	63.3	57.1	58.1	56.0	59.8
30 psi	2 hr. @ 300°F	44.0	51.6	47.7	55.5	46.0	52.0	53.3	54.6
		48.2	53.4	49.1	60.3	52.1	53.5	56.3	57.5
		51.2	55.0	49.6	61.5	55.4	56.4	60.2	60.8
	3 hr. @ 300°F	46.2	50.9	51.8	55.9	48.6	48.5	52.2	52.9
		48.6	56.4	53.3	58.8	53.3	51.9	58.6	56.0
		51.2	59.5	56.7	60.9	57.1	55.3	63.0	59.1
	1 hr. @ 300°F	48.5	-	55.6	59.9	50.7	54.3	54.9	54.3
		53.1	-	58.4	61.4	58.4	60.7	59.1	56.3
		58.8	-	60.5	63.4	70.6	63.7	60.8	59.1
70 psi	2 hr. @ 300°F	47.1	50.5	46.8	55.6	50.7	56.4	54.2	54.0
		50.1	53.0	50.9	60.2	53.7	58.8	57.7	56.8
		51.9	58.0	55.5	63.9	56.0	60.8	60.5	60.2
	3 hr. @ 300°F	48.1	46.4	48.7	55.6	49.5	56.1	58.1	53.8
		50.7	50.0	52.5	60.4	54.3	57.3	59.9	57.2
		52.7	52.9	58.0	62.2	60.2	58.9	62.3	62.3

*Stress in psi x 10^{-3} tabulated in the following order: low, average, and high.

TABLE 17

LAMINATE TENSION MODULUS, 10-HOUR B-STAGED LAY-UP USED

Cure Pressure	Post-Cure	Cure Temperature and Time: 160°F 60 min.	160°F 90 min.	180°F 60 min.	180°F 90 min.	200°F 60 min.	200°F 90 min.	230°F 60 min.	230°F 90 min.
	1 hr. @ 300°F	-	-	-	2.10*	2.45	2.40	-	2.42
		-	-	-	2.67	2.54	2.46	-	2.59
		-	-	-	2.41	2.66	2.50	-	2.92
13 psi	2 hr. @ 300°F	-	-	-	-	2.40	2.19	-	2.33
		-	-	-	2.45	2.53	2.42	-	2.37
		-	-	-	-	2.68	2.56	-	2.40
	3 hr. @ 300°F	-	-	-	2.13	2.44	2.29	-	2.45
		-	-	-	2.22	2.61	2.43	-	2.67
		-	-	-	2.33	2.89	2.53	-	2.96
	1 hr. @ 300°F	2.07	2.38	-	2.85	2.33	2.46	2.50	2.44
		2.23	2.53	2.32	3.20	2.37	2.54	2.56	2.56
		2.41	2.62	-	3.58	2.45	2.65	2.64	2.72
30 psi	2 hr. @ 300°F	2.11	2.43	-	2.98	2.29	2.32	2.38	2.52
		2.19	2.53	2.20	3.26	2.35	2.36	2.43	2.58
		2.26	2.61	-	3.81	2.47	2.42	2.56	2.64
	3 hr. @ 300°F	2.08	2.48	2.37	2.83	2.28	2.38	2.54	2.55
		2.12	2.62	2.51	2.97	2.30	2.48	2.55	2.62
		2.17	2.77	2.65	3.10	2.34	2.58	2.55	2.74
	1 hr. @ 300°F	2.19	-	2.46	2.92	2.49	2.53	2.69	2.69
		2.33	-	2.54	2.96	2.63	2.75	2.89	2.99
		2.44	-	2.63	2.98	2.88	2.96	3.07	3.34
70 psi	2 hr. @ 300°F	2.13	2.36	2.25	2.85	2.25	2.56	2.51	2.73
		2.22	2.48	2.38	2.94	2.35	2.70	2.68	2.85
		2.34	2.67	2.48	3.00	2.46	2.99	2.77	3.01
	3 hr. @ 300°F	2.23	2.20	2.23	2.47	2.40	2.88	2.66	2.64
		2.35	2.26	2.42	2.78	2.60	2.94	2.70	2.77
		2.44	2.34	2.70	3.02	2.77	3.00	2.73	2.84

*Test values in psi x 10^{-6} tabulated in the following order: low, average, and high.

TABLE 18

LAMINATE RESIN CONTENT

Cure Pressure	Post-Cure	Cure Temperature and Time 160°F 60 min.	160°F 90 min.	180°F 60 min.	180°F 90 min.	200°F 60 min.	200°F 90 min.	230°F 60 min.	230°F 90 min.
	1 hr. @ 300°F	- -	- 38.2	- -	38.8* 38.5	37.6 46.0	28.5 37.7	- -	36.4 34.6
13 psi	2 hr. @ 300°F	- -	- 40.2	- -	40.1 39.7	38.9 41.3	37.3 34.6	- -	36.0 35.4
	3 hr. @ 300°F	- -	- 39.3	- -	40.2 39.4	37.6 42.7	36.0 38.6	- -	34.9 34.2
	1 hr. @ 300°F	39.1 -	34.1 38.0	37.4 -	26.7 -	38.8 -	35.2 35.9	33.8 -	33.8 29.0
30 psi	2 hr. @ 300°F	41.1 -	35.4 40.4	40.1 -	28.3 -	38.5 -	35.9 38.1	35.0 -	34.3 29.4
	3 hr. @ 300°F	42.0 -	34.7 39.9	37.0 -	26.6 -	36.0 -	33.8 36.3	34.1 -	32.1 28.1
	1 hr. @ 300°F	38.7 -	33.7 39.9	35.0 -	26.4 37.9	36.0 23.6	29.0 24.8	29.9 -	27.0 28.1
70 psi	2 hr. @ 300°F	41.2 -	36.5 40.5	39.7 -	27.7 40.9	38.4 24.2	30.0 22.5	31.8 -	27.1 30.2
	3 hr. @ 300°F	37.7 -	34.7 38.7	37.5 -	26.9 38.6	34.8 22.8	26.2 22.7	28.5 -	27.6 28.5

*Resin content in percent $\left[\frac{\text{Total Wt.} - \text{Glass Wt.}}{\text{Total Wt.}}\right]$ associated with specimens tested in both tension and compression.

Tabulations are in the following order: 1st value is for 10-hour B-staged lay-up, 2nd value is for wet lay-up used directly.

TABLE 19

181 HTS LAMINATE PROPERTIES

Test Condition	Post-Cure	Cure Temperature* (°F) and Strength Property: 180 Ultimate	180 Modulus	200 Ultimate	200 Modulus	230 Ultimate	230 Modulus
Tension	1 hr. @ 300°F	93.4**	2.73**	93.2	2.97	107.8	3.00
		98.3	2.95	95.2	3.15	110.9	3.36
		106.8	3.11	99.1	3.40	114.1	3.72
	2 hr. @ 300°F	86.3	2.64	86.8	2.77	101.0	3.05
		91.3	2.77	93.5	2.90	107.5	3.34
		93.8	2.99	97.4	3.14	114.3	3.61
	3 hr. @ 300°F	86.6	2.80	95.1	2.87	106.7	3.41
		92.7	3.04	97.3	3.06	109.8	3.70
		97.7	3.31	100.5	3.37	114.0	4.07
Compression	1 hr. @ 300°F	34.7	3.75	43.7	3.65	41.3	4.41
		48.6	4.24	50.6	3.94	50.6	4.56
		50.7	4.81	59.0	4.79	57.0	4.73
	2 hr. @ 300°F	44.2	3.31	44.6	3.31	38.5	3.52
		48.1	3.49	50.8	3.53	50.3	3.90
		55.7	3.86	57.7	3.85	57.3	4.24
	3 hr. @ 300°F	41.3	3.65	43.1	3.10	37.8	3.03
		50.7	4.09	51.9	4.02	49.2	4.20
		51.2	4.79	58.5	4.73	57.8	4.65

*Cure pressure = 70 psi; cure time = 90 minutes.

**Stress in psi x 10^{-3} and modulus in psi x 10^{-6} are tabulated in the following order: low, average, and high.

TABLE 20

ADHESIVE SYSTEM STUDY,
CORE-TO-FACING BOND STRENGTH

Core Material	Core Cell (in)	Core Thickness (in)	Adhesive System	Bonding Temperature (°F)	Bonding Time (min) 10	20	30	40	50	60	70	80	90	100
HRP	3/16	3/4	Scotchweld	375	-	710[1]	-	650	-	750	-	630	-	-
Fiberglass	3/16	3/4	AF-110B	350	-	-	-	780	-	740	-	720	-	720
GF-11	3/16	3/4	10 psi cure	325	-	-	-	1000	-	940	-	900	-	820
	3/16	3/4	Scotchweld	375	-	230	-	320	-	330	-	340	-	-
	3/16	3/4	EC-1595	350	-	-	-	260	-	340	-	300	-	290
	3/16	3/4	10 psi cure	325	-	-	-	320	-	360	-	290	-	200
	3/16	3/4	Armstrong	300	730	680	750	750	-	-	-	-	-	-
	3/16	3/4	A-12	250	-	700	750	620	600	-	-	-	-	-
	3/16	3/4	10 psi cure	200	-	-	660	-	670	-	630	-	520	-
	3/16	3/4	EPON[2]	230	-	-	-	-	-	-	-	-	230	-
	3/8	3/4	828 Z	230	-	-	-	-	-	-	-	-	400	-
	3/16	3/4	30 psi cure	180	-	-	-	-	-	-	-	-	360	-
	3/8	3/4	2 hr. @ 300°F	180	-	-	-	-	-	-	-	-	900	-
	3/16	3/4	post cure	160	-	-	-	-	-	-	-	-	1080	-
	3/16	3/4		160	-	-	-	-	-	-	-	-	920	-
5052	1/4	0.40	Scotchweld[3]	375	-	940	-	1020	-	890	-	870	-	-
Aluminum	1/4	0.40	AF-110B	350	-	-	-	1010	-	1010	-	1020	-	920
0.0013 foil	1/4	0.40	10 psi cure	325	-	-	-	1020	-	1040	-	1010	-	1050
	3/16	0.40	Scotchweld EC-1595 10 psi cure	350	-	-	-	-	-	550	-	-	-	-
	3/16	0.40	Armstrong[4]	300	710	670	690	680	-	-	-	-	-	-
	3/16	0.40	A-12	250	-	800	690	730	680	-	-	-	-	-
	3/16	0.40	10 psi cure	200	-	-	760	-	700	-	680	-	720	-
Aircomb	0.42	1/2	Armstrong	300	400	360	290	290	-	-	-	-	-	-
Paper	0.42	1/2	A-12	250	-	370	370	360	390	-	-	-	-	-
125-35-20	0.42	1/2	10 psi cure	200	-	-	420	-	410	-	410	-	-	-

[1]Stress tabulated in psi.
[2]Panels fabricated by single-step process.
[3]Aluminum core foil thickness was increased to 0.0025 inch to prevent core failure.
[4]Core failed before bond in all cases.

TABLE 21

SINGLE-STEP PANEL, RESIN-IMPREGNATED FABRIC COLD-STORAGE HISTORY

Lay-Up	Cure Pressure and Time	Post-Cure	Cure Temperature (°F) and Panel Identification						
			160 Original	160 Replicate	180 Original	180 Replicate	200 Original	200 Replicate	230 Original
Wet	10 psi (20.4 in. Hg under vacuum) 90 min.	2 hr. @ 300°F	0*	0	-	1	0	1	0
		3 hr. @ 300°F	0	0	-	1	0	1	0
	30 psi 90 min.	2 hr. @ 300°F	0	-	-	0	0	-	0
		3 hr. @ 300°F	0	-	-	0	0	-	4
10 hour B-stage	10 psi (20.4 in. Hg under vacuum) 90 min.	2 hr. @ 300°F	0	-	-	1	0	-	1
		3 hr. @ 300°F	0	-	-	1	0	-	1
	30 psi 90 min.	2 hr. @ 300°F	0	-	-	-	0	0	1
		3 hr. @ 300°F	0	-	-	-	0	-	-

*Storage time expressed in days.

TABLE 22

BARE LAMINATE.
RESIN IMPREGNATED FABRIC
COLD STORAGE HISTORY

Cure Pressure	Post Cure	160°F 60 min.	160°F 90 min.	180°F 60 min.	180°F 90 min.	200°F 60 min.	200°F 90 min.	230°F 60 min.	230°F 90 min.
		Cure Temperature and Time							
13 psi	1 hr. @ 300°F	-	0[1]	-	0 2	7	0 1	-	1 1
	2 hr. @ 300°F	-	0	-	0 2	7	0 1	-	1 1
	3 hr. @ 300°F	-	0	-	0 2	7	0 1	-	1 1
30 psi	1 hr. @ 300°F	-	4[2]	-	-	9	1 7	-	1 2
	2 hr. @ 300°F	-	4	-	-	9	1 7	-	1 2
	3 hr. @ 300°F	-	4	-	-	9	1 7	-	1 2
70 psi	1 hr. @ 300°F	12	4	2	0	0 9	0	2	1 1
	2 hr. @ 300°F	12	4	2	0	0 9	0	2	1 1
	3 hr. @ 300°F	12	4	2	0	0 9	0	2	1 1

[1] Storage time expressed in days.

[2] Underlined values refer to 10-hour B-stage lay-ups; other values refer to wet lay-ups used directly.

APPENDIX III

ANALYSIS OF VARIANCE

As previously stated, a large factorial design was employed in the research program. For the single-step sandwich, three factors were considered: mold pressure at two levels, 13 and 30 psi; mold temperature at four levels, 160, 180, 200, and 230 degrees Fahrenheit; and post-cure time at two levels, 2 and 3 hours. For the bare laminate, four factors were considered: mold pressure at three levels, 13, 30 and 70 psi; mold time at two levels, 60 and 90 minutes; mold temperature at four levels, 160, 180, 200, and 230 degrees Fahrenheit; and post-cure at three levels, 1, 2, and 3 hours.

The correspondence between the fabrication variables and the mechanical properties of these materials was determined according to the common statistical method, analysis of variance.[1] Significance of the variance at the 90-minute cure time was determined for ultimate compression strength, compressive modulus, core-to-facing bond strength, and resin content index in the case of the single-step sandwich; and for tension ultimate strength and modulus, compression ultimate strength and modulus, and resin content in the case of the bare laminate. The complete analysis for the single-step sandwich compression ultimate strength is included in this section as a sample calculation, and for the other cases only the summary tables with a description of the conditions of analysis are presented. The latter includes the handling of missing data, the cross section of the experiment used, etc.

1. Single-step sandwich, ultimate compressive strength, wet lay-up used directly.

    a. Experimental data used in the analysis: average values from Table 5.

TABLE 23
SINGLE-STEP SANDWICH COMPRESSIVE STRENGTH,
DATA USED IN THE STATISTICAL ANALYSIS

Cure Pressure	Post Cure Time @ 300°F	Cure Temperature				
		160°F	180°F	200°F	230°F	Sum
10 psi	2 hours	28.8*	26.7	28.0	26.1	108.8
	3 hours	27.2	26.6	26.6	27.4	107.8
30 psi	2 hours	29.3	28.3	28.6	27.4	113.6
	3 hours	27 7	28.1	29.4	29.9	115.1
	Sum	112.2	109.7	112.6	110.8	445.3

*Estimated value: data from panels which exceeded 40% resin content have been excluded from this analysis. Replicate used in other cases.

[1]References 1 and 4.

b. Analysis tables.

Correction to mean squares $= \frac{(445.3)^2}{16} = 12,393.26$

Overall sum of squares = 17.93

TABLE 24
SINGLE-STEP SANDWICH ULTIMATE COMPRESSIVE STRENGTH,
TWO-WAY TABLE OF SUMS FOR THE FACTORS TEMPERATURE AND PRESSURE

Cure Pressure	Cure Temperature				
	160°F	180°F	200°F	230°F	Sum
10 psi	55.2	53.3	54.6	53.5	216.6
30 psi	57.0	56.4	58.0	57.3	228.7
Sum	112.2	109.7	112.6	110.8	445.3

TABLE 25
SINGLE-STEP SANDWICH ULTIMATE COMPRESSIVE STRENGTH,
ANALYSIS OF VARIANCE TABLE FOR THE FACTORS TEMPERATURE AND PRESSURE

Source of Variation	Sum of Squares	Degrees Freedom	Mean Square
Temp. - Main Effect	1.32	3	0.44
Press. - Main Effect	9.14	1	9.14
Temp. x Press. Interaction	0.57	3	0.19
Total	11.03		

TABLE 26
SINGLE-STEP SANDWICH ULTIMATE COMPRESSIVE STRENGTH,
TWO-WAY TABLE OF SUMS FOR THE FACTORS TEMPERATURE AND POST-CURE TIME

	Cure Temperature				
Post Cure	160°F	180°F	200°F	230°F	Sum
2 hours	57.3	55.0	56.6	53.5	222.4
3 hours	54.9	54.7	56 0	57.3	222.9
Sum	112.2	109 7	112.6	110.8	445.3

TABLE 27
SINGLE-STEP SANDWICH ULTIMATE COMPRESSIVE STRENGTH,
ANALYSIS OF VARIANCE TABLE FOR THE FACTORS TEMPERATURE AND POST-CURE TIME

Source of Variation	Sum of Squares	Degrees Freedom	Mean Square
Temp. - Main Effect	1.32	3	0.44
Post-Cure - Main Effect	0.01	1	0.01
Temp. x Post-Cure Interaction	5.15	3	1.72
Total	6.48		

TABLE 28

SINGLE-STEP SANDWICH ULTIMATE COMPRESSIVE STRENGTH,
TWO-WAY TABLE OF SUMS FOR THE FACTORS PRESSURE AND POST-CURE TIME

	Cure Time		
Cure Pressure	2 hours	3 hours	Sum
10 psi	108.8	107.8	216.6
30 psi	113.6	115.1	228.7
Sum	222.4	222.9	

TABLE 29

SINGLE-STEP SANDWICH ULTIMATE COMPRESSIVE STRENGTH,
ANALYSIS OF VARIANCE TABLE FOR PRESSURE AND POST-CURE TIME

Source of Variation	Sum of Squares	Degrees Freedom	Mean Square
Press. - Main Effect	9.14	1	9.14
Post-Cure - Main Effect	0.01	1	0.01
Press. x Post-Cure Interaction	0.40	1	0.40
Total	9.55		

TABLE 30
SINGLE-STEP SANDWICH ULTIMATE COMPRESSIVE STRENGTH,
ANALYSIS OF VARIANCE SUMMARY FOR WET LAY-UP

Source of Variation	Sum of Squares	Degrees Freedom	Mean Square	Variance Ratio
Temp. Main Effect	1.32	3	0.44	-
Press. Main Effect	9.14	1	9.14	20.3*
Post-Cure Main Effect	0.01	1	0.01	-
Temp. x Press. Interaction	0.57	3	0.19	-
Temp. x Post-Cure Interaction	5.15	3	1.72	3.82
Press. x Post-Cure Interaction	0.40	1	0.40	-
Error	1.34	3		
Total	17.93			

*Significant at the 95% level.

2. Single-step sandwich ultimate compressive strength, 10-hour B-staged lay-up used.

   a. Experimental data used in the analysis: average values from Table 5.

   b. Value for 30 psi, 3-hour post-cure, and 230°F estimated to be 29.0.

   c. Pressure post-cure interaction assumed to be nonexistent and, therefore, included in estimate of experimental error.

TABLE 31
SINGLE-STEP SANDWICH ULTIMATE COMPRESSIVE STRENGTH,
ANALYSIS OF VARIANCE SUMMARY FOR 10-HOUR B-STAGED LAY-UP

Source of Variation	Sum of Squares	Degrees Freedom	Mean Square	Variance Ratio
Temp. - Main Effect	63.13	3	21.04	10.90*
Press. - Main Effect	3.06	1	3.06	1.59
Post-Cure Main Effect	1.21	1	1.21	-
Temp. x Press. Interaction	8.31	3	2.10	1.09
Temp. x Post-Cure Interaction	3.57	3	1.19	-
Error	7.72	4	1.93	
Total	87.00			

*Significant at the 95% level.

3. Laminate ultimate compression strength, wet lay-up used directly.

   a. Experimental data used in the analysis: average values from Table 10.

   b. 180°F temperature level not included in this analysis.

TABLE 32
LAMINATE COMPRESSION ULTIMATE STRENGTH,
ANALYSIS OF VARIANCE SUMMARY FOR WET LAY-UP

Source of Variation	Sum of Squares	Degrees Freedom	Mean Square	Variance Ratio
Temp. - Main Effect	998,854	2	499,427	222.66*
Press. - Main Effect	258,503	2	129,252	57.62*
Post-Cure - Main Effect	9,294	2	4,647	2.07
Temp. x Press. Interaction	1,195,072	4	597,536	226.40*
Temp. x Post-Cure Interaction	10,870	4	2,718	1.21
Press. x Post-Cure Interaction	34,902	4	8,725	3.89+
Error	17,940	8	2,243	

*Significant at the 99% level.
+Significant at the 95% level.

4. Laminate compression modulus, wet lay-up used directly.

   a. Experimental data in the analysis: average values from Table 11.

   b. 180°F temperature level not included in this analysis.

   c. Pressure post-cure interaction assumed to be nonexistent and, therefore, included in estimate of experimental error.

   d. Value for 30 psi, 160°F, and 1 hour of post-cure estimated to be 3.05.

TABLE 33
LAMINATE COMPRESSION MODULUS,
ANALYSIS OF VARIANCE SUMMARY FOR WET LAY-UP

Source of Variation	Sum of Squares	Degrees Freedom	Mean Square	Variance Ratio
Temp. - Main Effect	32,340	2	16,170	161.70*
Press. - Main Effect	14,857	2	7,429	74.29*
Post-Cure - Main Effect	1,171	2	586	5.86+
Temp. x Press. Interaction	20,683	4	5,171	51.71*
Temp. x Post-Cure Interaction	959	4	240	2.40
Error	1,207	12	100	
Total	71,217			

*Significant at the 99% level.
+Significant at the 95% level.

5. Laminate compression ultimate strength, 10-hour B-staged lay-up used.

a. Experimental data in the analysis: average values from Table 12.

b. 10-psi pressure level not included in this analysis.

c. Pressure post-cure interaction included in estimate of experimental error.

TABLE 34
LAMINATE COMPRESSION ULTIMATE STRENGTH,
ANALYSIS OF VARIANCE SUMMARY FOR 10-HOUR B-STAGE LAY-UP

Source of Variation	Sum of Squares	Degrees Freedom	Mean Square	Variance Ratio
Temp. - Main Effect	382,623	3	127,541	10.65*
Press. - Main Effect	693	1	693	-
Post-Cure - Main Effect	13,586	2	6,793	-
Temp. x Press. Interaction	162,222	3	54,074	4.51+
Temp. x Post-Cure Interaction	376,681	6	62,784	5.24+
Error	95,827	8	11,978	
Total	1,031,632			

*Significant at the 99% level.
+Significant at the 95% level.

6. Laminate compression modulus, 10-hour B-staged lay-up used.

a. Experimental data in the analysis: average values from Table 13.

b. 10-psi pressure level not included in this analysis.

TABLE 35
LAMINATE COMPRESSION MODULUS,
ANALYSIS OF VARIANCE SUMMARY FOR 10-HOUR B-STAGED LAY-UP

Source of Variation	Sum of Squares	Degrees Freedom	Mean Square	Variance Ratio
Temp. - Main Effect	17,187	3	5,729	19.42*
Press. - Main Effect	4,082	1	4,082	13.84*
Post-Cure - Main Effect	88	2	44	-
Temp. x Press. Interaction	7,456	3	2,485	8.42+
Temp. x Post-Cure Interaction	1,537	6	256	-
Press. x Post-Cure Interaction	103	2	52	-
Error	1,771	6	295	
Total	32,224			

*Significant at the 99% level.
+Significant at the 95% level.

7. **Laminate tension ultimate strength, wet lay-up used directly.**

a. **Experimental data in the analysis: average values from Table 14.**

b. **180°F temperature level not included in this analysis.**

c. **Pressure post-cure interaction assumed nonexistent and, therefore, included in estimate of experimental error.**

TABLE 36
LAMINATE TENSION ULTIMATE STRENGTH
ANALYSIS OF VARIANCE SUMMARY FOR WET LAY-UP

Source of Variation	Sum of Squares	Degrees Freedom	Mean Square	Variance Ratio
Temp. - Main Effect	499.39	2	249.69	9.29*
Press. - Main Effect	2.43	2	1.21	-
Post-Cure - Main Effect	47.22	2	23.41	-
Temp. x Press. Interaction	173.74	4	43.43	1.62
Temp. x Post-Cure Interaction	119.75	4	29.94	1.31
Error	322.50	12		
Total	1,165.03			

*Significant at the 95% level.

8. **Laminate tension modulus, wet lay-up used directly.**

a. **Experimental data in the analysis: average values from Table 15.**

b. **180°F temperature level not included in this analysis.**

c. **Pressure post-cure interaction assumed nonexistent and, therefore, included in estimate of experimental error.**

TABLE 37
LAMINATE TENSION MODULUS,
ANALYSIS OF VARIANCE SUMMARY FOR WET LAY-UP

Source of Variation	Sum of Squares	Degrees Freedom	Mean Square	Variance Ratio
Temp. - Main Effect	9,263	2	4,632	22.49*
Press. - Main Effect	1,106	2	553	2.68
Post-Cure - Main Effect	155	2	78	-
Temp. x Press. Interaction	9,166	4	2,292	11.13*
Temp. x Post-Cure Interaction	699	4	175	-
Error	2,467	12	206	
Total	22,856			

*Significant at the 99% level.

9. Laminate tension ultimate strength, 10-hour B-staged lay-up used.

a. Experimental data in the analysis: average values from Table 16.

b. 160°F temperature level not included in this analysis.

c. Pressure post-cure interaction included in estimate of experimental error.

TABLE 38
LAMINATE TENSION ULTIMATE STRENGTH,
ANALYSIS OF VARIANCE SUMMARY FOR 10-HOUR B-STAGED LAY-UP

Source of Variation	Sum of Squares	Degrees Freedom	Mean Square	Variance Ratio
Temp. - Main Effect	0.30	2	0.15	-
Press. - Main Effect	387.74	2	193.87	68.75*
Post-Cure - Main Effect	5.22	2	2.61	-
Temp. x Press. Interaction	173.86	4	43.49	15.42*
Temp. x Post-Cure Interaction	10.22	4	2.55	-
Error	33.80	12	2.82	
Total	611.14			

*Significant at the 99% level.

10. Laminate tension modulus, 10-hour B-staged lay-up used.

a. Experimental data in the analysis: average values from Table 17.

b. 10-psi pressure level not included in this analysis.

c. Pressure post-cure interaction included in estimate of experimental error.

d. Value for 70 psi, 160°F, and 1-hour post-cure estimated to be 2.52.

TABLE 39
LAMINATE TENSION MODULUS,
ANALYSIS OF VARIANCE SUMMARY FOR 10-HOUR B-STAGED LAY-UP

Source of Variation	Sum of Squares	Degrees Freedom	Mean Square	Variance Ratio
Temp. - Main Effect	8,959	3	2,986	31.10*
Press. - Main Effect	204	1	204	2.13
Post-Cure - Main Effect	241	2	121	1.26
Temp. x Press. Interaction	3,907	3	1,302	13.56*
Temp. x Post-Cure Interaction	889	6	148	1.54
Error	770	8	96	
Total	14,970			

*Significant at the 99% level.

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U. S. Army Transportation Center and Fort Eustis	1
U. S. Army Tank-Automotive Center	1
U. S. Army Aviation Maintenance Center	1
U. S. Army Armor Board	1
Air Force Systems Command, Wright-Patterson AFB	4
Air Proving Ground Center, Eglin AFB	1
Air University Library, Maxwell AFB	1
Chief of Naval Operations	1
Bureau of Ships	1
Bureau of Naval Weapons	8
U. S. Naval Postgraduate School	1
Naval Air Test Center	1
U. S. Naval Ordnance Test Station	1
David Taylor Model Basin	1
Ames Research Center, NASA	1
NASA-LRC, Langley Station	1
Lewis Research Center, NASA	1
Manned Spacecraft Center, NASA	1
NASA Representative, Scientific and Technical Information Facility	2

Research Analysis Corporation	1
National Aviation Facilities Experimental Center	1
Canadian Liaison Officer, U. S. Army Transportation School	1
British Army Staff, British Embassy	1
Defense Documentation Center	10
U. S. Patent Office	1
U. S. Government Printing Office	1