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DETERMINING AND ANALYZING THE STRENGTH AND IMPACT RESISTANCE OF HIGH MODULUS GLASS

by

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United Aircraft Research Laboratories

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Determining and Analyzing the Strength and Impact of High-Modulus Glass

SUMMARY

A second experimental glass, UARL 417, has been prepared in large quantity as a monofilament and used to form a number of glass fiber-epoxy resin test specimens. The only prior UARL experimental glass studied as a composite component, UARL 344, had a fiber density of 3.29 gms/cm^3 in contrast to the fiber density of 3.09 gms/cm^3 for UARL 417, a fiber with a Young's modulus of 17.5 x 10^6 psi. The composite samples made contained 65% glass fiber and were used to measure flexural strength, flexural modulus, bending stress-strain curve, short beam shear strength, tensile strength, tensile modulus, and tensile stress/strain curve. For several of these properties the UARL 417 glass fiber-epoxy resin composites gave results as high or higher than the DuPont experimental fiber PRD-49-I incorporated in a similar resin. UARL 344 glass fiber-epoxy resin composites also gave superior results for several properties.

A sizing applicator was developed during this period and used to coat UARL 344 fiber as this fiber was pulled at high rates of speed.

Several new glass compositions were prepared and the Young's modulus of these glasses was determined on bulk samples. Several of the new compositions were also fiberized and the Young's modulus of the fiber determined.

Research has been started on the question of why a given glass should have an impact strength superior to other similar glasses. Unfortunately, the full-size notched Charpy impact specimens used in this study fail to give a clear-cut grouping of glasses by impact strength presumably because the preparation of the notch in these samples damages such brittle materials. Other tests will be used in subsequent work on this subject.

INTRODUCTION

The present report is the first quarterly report for the new UARL-NASA Headquarters Contract NASW-2209, Determining and Analyzing the Strength and Impact of High-Modulus Glass. This contract follows the earlier UARL-NASA contracts NASW-2013, Investigation of the Kinetics of Crystallization of Several

High Temperature Glass Systems and NASW-1301, Investigation of the Kinetics of Crystallization of Molten Binary and Ternary Oxide Systems. The time period covered by the present report is February 1, 1971 through April 30, 1971.

The earlier UARL-NASA contracts were primarily concerned with the consideration of new and unusual molten oxide systems that could be made by control of their kinetics of crystallization into high-modulus, high-strength glass fibers and preliminary studies of the variables of importance in the manufacture of several selected high modulus fibers. This contract does not exclude the continuation of these types of research but will emphasize two additional fields of glass research. UARL will attempt to find out why a given glass is superior to other glasses in impact resistance and the directions in which to move for the development of glasses with still greater impact strength. UARL will also try to find out why some glass compositions have greater tensile strength than others and what can be done to develop still higher strength glasses.

The latter two research investigations may, in a small part, fulfill the need for more information about glass in massive form that the National Materials Advisory Board of the National Research Council has indicated (Refs. 1,2) to be a prerequisite for the successful use of glass as an engineering material.

NEW GLASS COMPOSITIONS

The new glass compositions melted in this quarter are shown in Table I. It will be noted that all of the glasses recently prepared are without beryllia and that glasses 460 through 472 are additional extensions of the UARL invert analogue series of glass compositions. Glasses 473, 474 and 475 are base glasses from which glass-ceramics of high modulus were prepared by McMillan (Ref. 3). We have melted these to see if the action of pulling fibers will furnish a sufficient heat treatment to develop crystals in phosphate catalyzed glass-ceramics and to ascertain for ourselves the contribution made by the crystals to the resultant modulus and strength of the glass fibers.

RECENT DETERMINATIONS OF YOUNG'S MODULUS OF BULK GLASS SAMPLES

Those values for Young's modulus recently measured on aspirated circular rod bulk glass samples are shown in Table II. None of our newer glasses have values as high as many of the earlier UARL glasses which showed Young's moduli of 20 million psi or higher. Glass UARL 425B is the old National Bureau of Standards glass #389 (Ref. 4) prepared primarily to study the problems encountered in fabricating very high temperature calcium aluminate glasses. Our Super-kanthal

Table I

New Glass Compositions Expressed in Mol %

Actual Ingredient	460	461	462	463	464	465
SiO_2	25	25	25	25	25	25
MgO	13	13	12	12	15	14
Li_2O	13	13	12	13	15	14
CaO	13	13	13	13	15	14
ZnO	13	13	12	13	10	8
B_2O_3	13	13	12	12	15	15
Y_2O_3	10	--	10	10	5	10
TiO_2	--	--	4	2	--	--
ZrO_2	--	10	--	--	--	--

	466	467	468	469	470	471
SiO_2	25	25	25	25	25	40.5
Al_2O_3	--	8	8	8	8	14.5
MgO	15	15	15	15	15	29.0
Li_2O	15	10	7	5	15	8.0
CaO	15	15	15	15	10	--
ZnO	15	15	15	15	15	--
B_2O_3	12.5	5	8	10	5	--
Y_2O_3	2.5	7	7	7	7	8.0

	472	473	474	475
SiO_2	40.5	78.78	78.0	70.1
Al_2O_3	6.5	--	3.9	--
MgO	29.0	--	--	--
Li_2O	8.0	12.0	12.1	10
CaO	8.0	--	--	--
ZnO	--	7.5	--	20
Y_2O_3	8.0	--	--	--
P_2O_5	--	1.00	3.00	--
K_2O	--	0.72	3.00	--

Table II

Recently Measured Values for Young's Modulus
(Circular Rod Bulk Samples)

Glass No.	Density gms/cm^3	Density lbs/in^3	Young's Modulus millions psi	Specific Modulus 10^7 inches
134	3.0983	0.1116	15.61	14.0
152	4.3834	0.1580	15.27	9.63
160	3.2452	0.1170	15.95	13.65
345B	3.3594	0.1216	19.82	16.32
*425B	2.7561	0.0995	18.19	18.24
467	3.4302	0.1238	15.63	12.65
468	3.4426	0.1242	15.48	12.45
469	3.3773	0.1219	15.25	12.54
470	3.3020	0.1193	16.02	13.43
471	3.1743	0.1145	16.98	14.82
472	3.2183	0.1162	16.93	14.55

*UARL 425 is National Bureau of Standards Glass #389 (Ref. 4) hairpin platform furnace which reaches temperatures greater than 1700°C was not adequate for the fabrication of this N.B.S. glass. Incidentally, the value reported by N.B.S. for the Young's modulus of their number 389 is 19.2×10^6 psi in contrast to the value of 18.19×10^6 psi obtained in this laboratory and 19.51×10^6 psi obtained for the first UARL melt of this glass, UARL 425.

COMPARATIVE IMPACT RESISTANCE OF SEVERAL GLASSES IN BULK FORM

As indicated in the introduction to this report, one of the more important objectives of this contract is to attempt to discover why a given glass has a superior impact resistance compared to some other glass. Eleven high modulus glasses were selected for the initial study and the results obtained when full-size notched Charpy specimens prepared by cutting the test samples from fully annealed glass discs are shown in Table III together with a similar result from the common commercial fiber-glass base, "E" glass. For "E" glass and UARL glasses 237, 304, 350, 383, 419, 425, and 447, four specimens were tested and for UARL glasses 323, 336, 344 and 454A, two specimens were tested to obtain the average values shown in Table III.

It will be immediately noticed that the notched full-size Charpy impact specimen does not give a clean-cut separation of these glasses on the basis of their impact strengths. One can say that UARL 323 glass has the lowest impact strength, next "E" glass, UARL glasses 350 and 425 (N.B.S. 389), then at slightly higher level UARL glasses 237, 304, 344, 383, 419, 447, and 455A, and finally UARL 336 has the highest impact strength. The separation on the basis of their impact strength is much less than found in preliminary experiments in which an unnotched Izod specimen was used (Ref. 5). It would seem, therefore, that the formation of the notch in the specimen damages it and that we are not measuring quantities directly dependent on the impact strength of the material because of the notch sensitivity of the material. When testing is resumed, unnotched Izod and Charpy specimens will be tried.

The appearance of a typical full-size Charpy impact specimen after failure is shown in Fig. 1 as observed by scanning electron microscopy. The propagation of the Charpy impact across the specimen can be clearly seen.

RECENT EXPERIMENTAL GLASS FIBERS

Results for those glass fibers produced recently by mechanical drawing from UARL experimental glasses are shown in Table IV. The values for Young's modulus tabulated here are measured using thin-line ultrasonic equipment. Most of the fibers are beryllia-containing glasses with densities greater than 3.23 gms/cm^3 and, therefore, have specific moduli too low to be of interest. The single exception is UARL 464, a non-beryllia containing glass of lower density, but which also has a lower value for Young's modulus.

Table III

Impact Resistance of Bulk Glass As Determined By
Full-Size Notched Charpy Test Samples

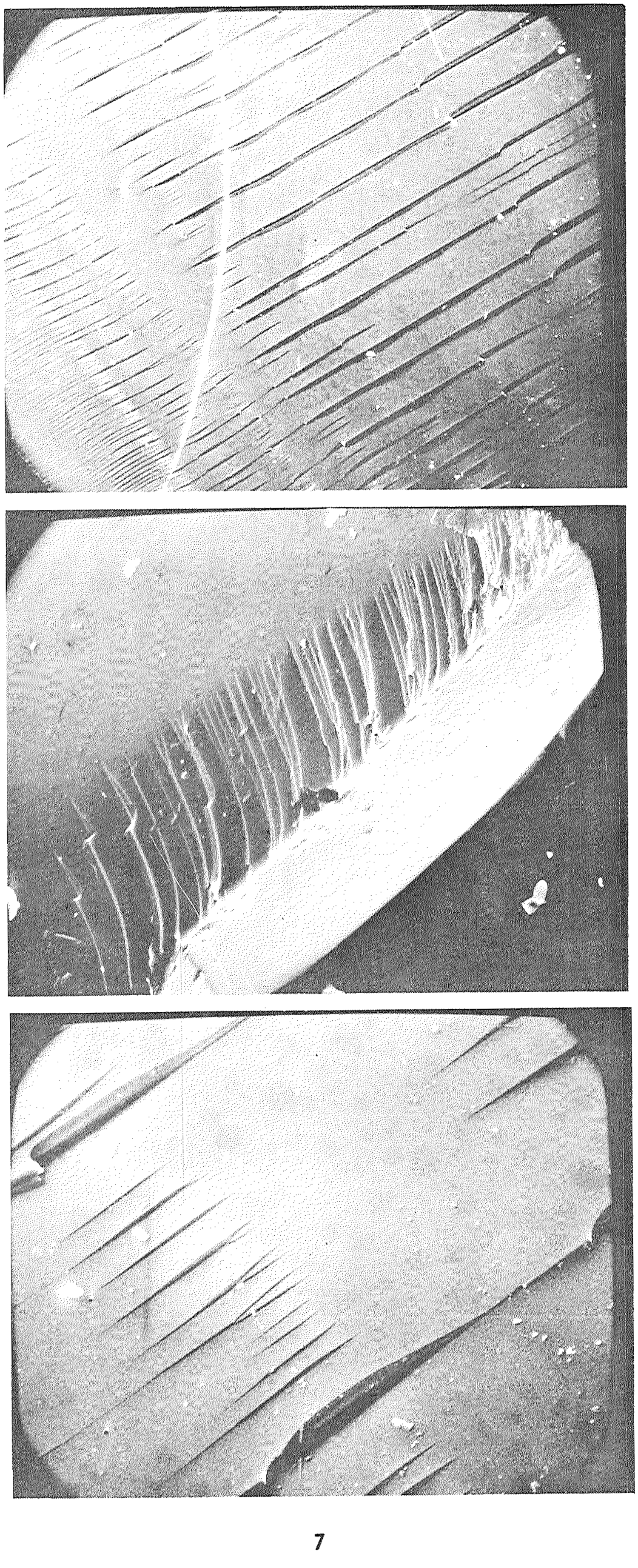
Glass No.	Result, ft-lbs
E	0.0626
237	0.0752
304	0.0740
323	0.0586
336	0.0844
344	0.0730
350	0.0643
383	0.0757
419	0.0754
425	0.0655
447	0.0727
454A	0.0750

Table IV

New Values for the Young's Modulus of Mechanically Drawn
Fibers of UARL Experimental Glasses (Sonic Results)

Glass No.	Young's Modulus 10^6 psi
433	17.39
434	16.83
438	16.48
448	15.88
449	15.82
464	14.83

TYPICAL NOTCHED FULL-SIZE CHARPY TEST SPECIMEN AFTER FAILURE



SELECTED GLASS FIBERS PREPARED IN LARGE QUANTITY AS MONOFILAMENTS

As shown in our final report on the earlier NASA contracts (Ref. 6) one of the more outstanding compositions, UARL 344, was selected for intensive investigation of the problems arising when large quantities of glass fiber are to be produced. Over a hundred million feet of monofilament were prepared from this composition over a variety of winding speeds, orifice temperatures, heads of molten glass in the bushing, etc. This fiber in general had an average strength of 772,000 psi, a Young's modulus of 18.6×10^6 psi, and a specific modulus of 157 million inches. The monofilaments produced were made into epoxy resin-glass fiber composites and fully evaluated. The results of these composite test samples are given in detail in the final report (Ref. 6) and shown in abbreviated form in the next section of this report. In addition, a satisfactory surface finish and size were developed for this composition as described in Ref. 6.

The next step in learning to manufacture UARL 344 glass fiber was clearly to learn to apply the surface finish and size as the fiber is pulled. After several false starts the sizing applicator shown in Fig. 2 was developed. It worked very well but the sizing solvent proved to have too low a flash point and the initial startup of the glass fiber inevitably caused a flash fire. However, about three million feet of UARL 344 glass fiber was successfully coated after the fire was extinguished. To improve the flash point of size-solvent solution, higher molecular weight solvents were tried but using the method of mixing we had at that time, these solvents caused precipitation of the size. Since then this problem has been solved but no additional UARL 344 fiber has as yet been sized as drawn.

Recently, a second UARL experimental glass composition, UARL 417, has been selected for intensive investigation of the process of making large quantities of glass fiber suitable for the preparation of epoxy resin-glass fiber test samples. To date, approximately three million feet of monofilament have been prepared from this glass composition and used to form composites. Although the monofilaments from UARL 417 have been obtained under a variety of processing conditions, no problems were encountered in its preparation. The fiber has a modulus of 17.5×10^6 psi, a density of 3.09 gms/cm^3, and again a specific modulus of 157 million inches. Its strength as a virgin fiber has not yet been determined. Its properties when incorporated in an epoxy-resin matrix are shown in the next section.

PROPERTIES OF GLASS FIBER-EPOXY RESIN COMPOSITES MADE WITH UARL GLASS FIBERS

Table V compares the properties of four epoxy resin-fiber composites. The S glass, UARL 344, and UARL 417 glass fiber-epoxy resin composites were all made in this laboratory by identical methods but the data for the DuPont PRD-49-I fiber composite are taken from DuPont brochures. The experimental evidence

FIG. 2

FIRST EXPERIMENTAL SIZING APPLICATOR

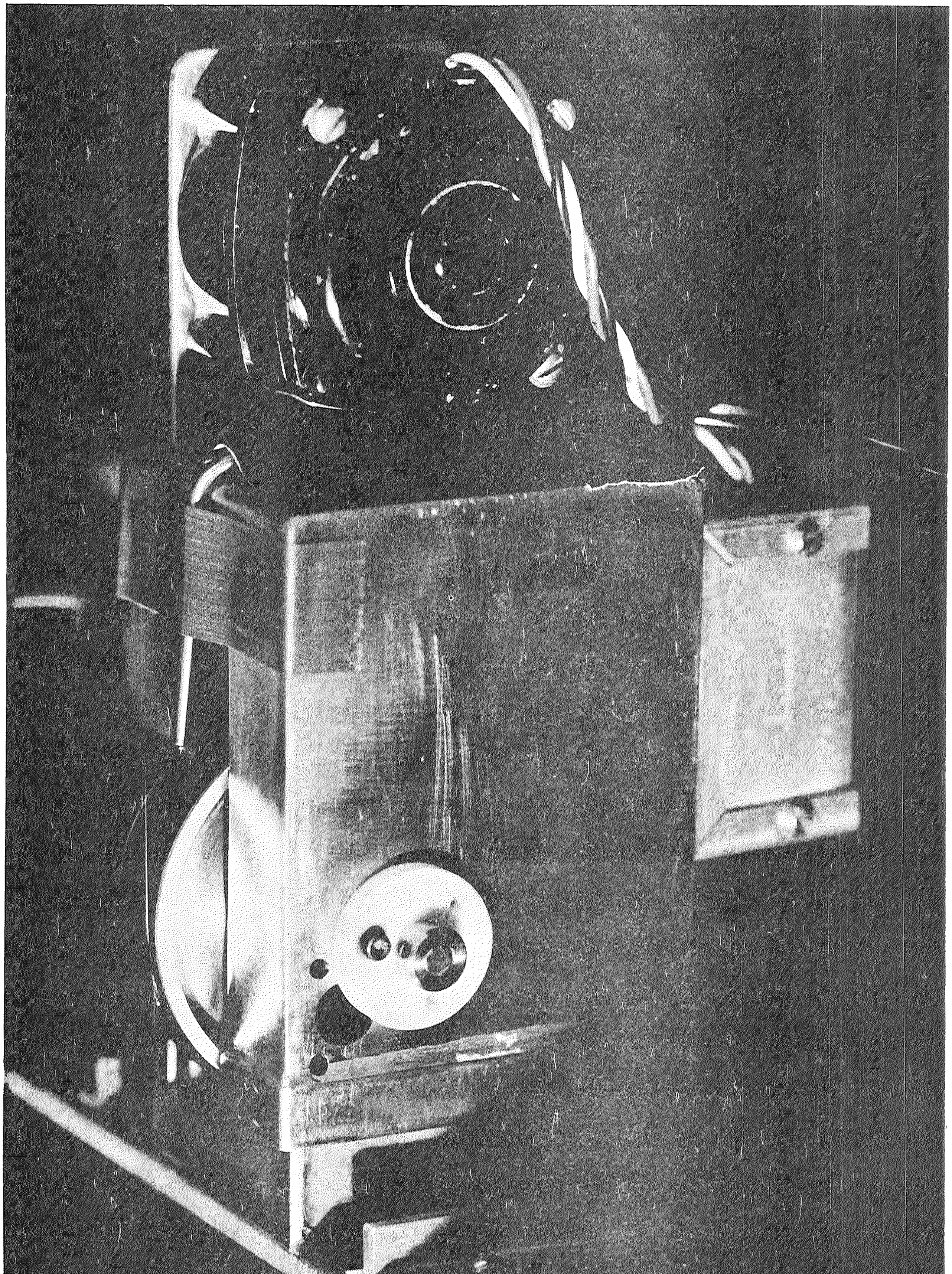


Table V

Properties of Several Glass Fiber-Epoxy Resin Composites Compared

Composite Number and Glass Identity	Fiber Finish	% Voids	% Fiber	Density Composite gms/cm^3	Flexural Strength 10^3 psi	Flexural Modulus 10^6 psi	Short Beam Shear Strength 10^3 psi	Tensile Strength 10^3 psi	Tensile Modulus 10^6 psi
634 (S glass)	Commercial	0.6	67	2.07	215	---	13.9	266	8.27*
Average of 7 composites UARL 344	Proprietary	3.1	62	2.47	254	11.3	14.4	250	10.9
695 (UARL 344)**	Proprietary	2.5	60	2.49	290	11.2	16.7	250	10.9
UARL 417	Proprietary	1.0	71.5	2.55	228	12.07	15.5	298	11.9
DuPont PRD-49-I	None	---	65	1.38	95	17	7.5	200	14.0

S glass fiber has a density of 2.49 gms/cm^3 and a Young's modulus of 12.4 x 10^6 psi
UARL 344 glass fiber has a density of 3.29 gms/cm^3 and a Young's modulus of 18.6 x 10^6 psi
UARL 417 glass fiber has a density of 3.09 gms/cm^3 and a Young's modulus of 17.5 x 10^6 psi
DuPont PRD-49-I organic fiber has a density of 1.38 gms/cm^3 and a Young's modulus of 20 x 10^6 psi

*Estimate based on fiber % and known modulus of S glass
**Results obtained after an initial series of learning experiments had been carried out in making and testing UARL 344 glass fiber-epoxy resin composites

indicates that the glass fiber-epoxy resin composites are superior in flexural strength (both absolute and specific), short-beam shear strength (both absolute and specific) and in absolute tensile strength in comparison to the DuPont PRD-49-I epoxy resin composite. Further, the UARL 417 epoxy resin composite has a specific tensile strength 80% that of the DuPont PRD-49-I epoxy resin composition. This absolute strength of the UARL fiber-epoxy resin composite indicates a very high strength retention for UARL 417 without sizing and after the considerable amount of handling necessary to form a glass fiber-epoxy resin matrix.

The composite tensile stress-strain curves for UARL 417 epoxy resin composite and DuPont PRD-49-I are shown in Fig. 3 and similar composite bending stress-strain curves for these materials are shown in Fig. 4. In both cases the comparison favors the UARL 417 glass fiber.

We had anticipated that this report would also include a comparison of the compressive strengths of UARL 417 glass fiber-epoxy resin composites with that of DuPont PRD-49-I fiber-epoxy resin composites but our test fixtures caused mushrooming of the UARL 417 glass fiber-epoxy resin samples as shown in Fig. 5 and the test therefore gave much too low a value for UARL composite. Even these low values, however, for the UARL 417 glass fiber-epoxy resin samples ranging from 117,200 to 122,000 psi indicate that true test data will show the UARL composite containing UARL 417 glass fiber to have a compression strength two to three times that of the DuPont fiber composite. These tests will be repeated when new special design test fixtures become available.

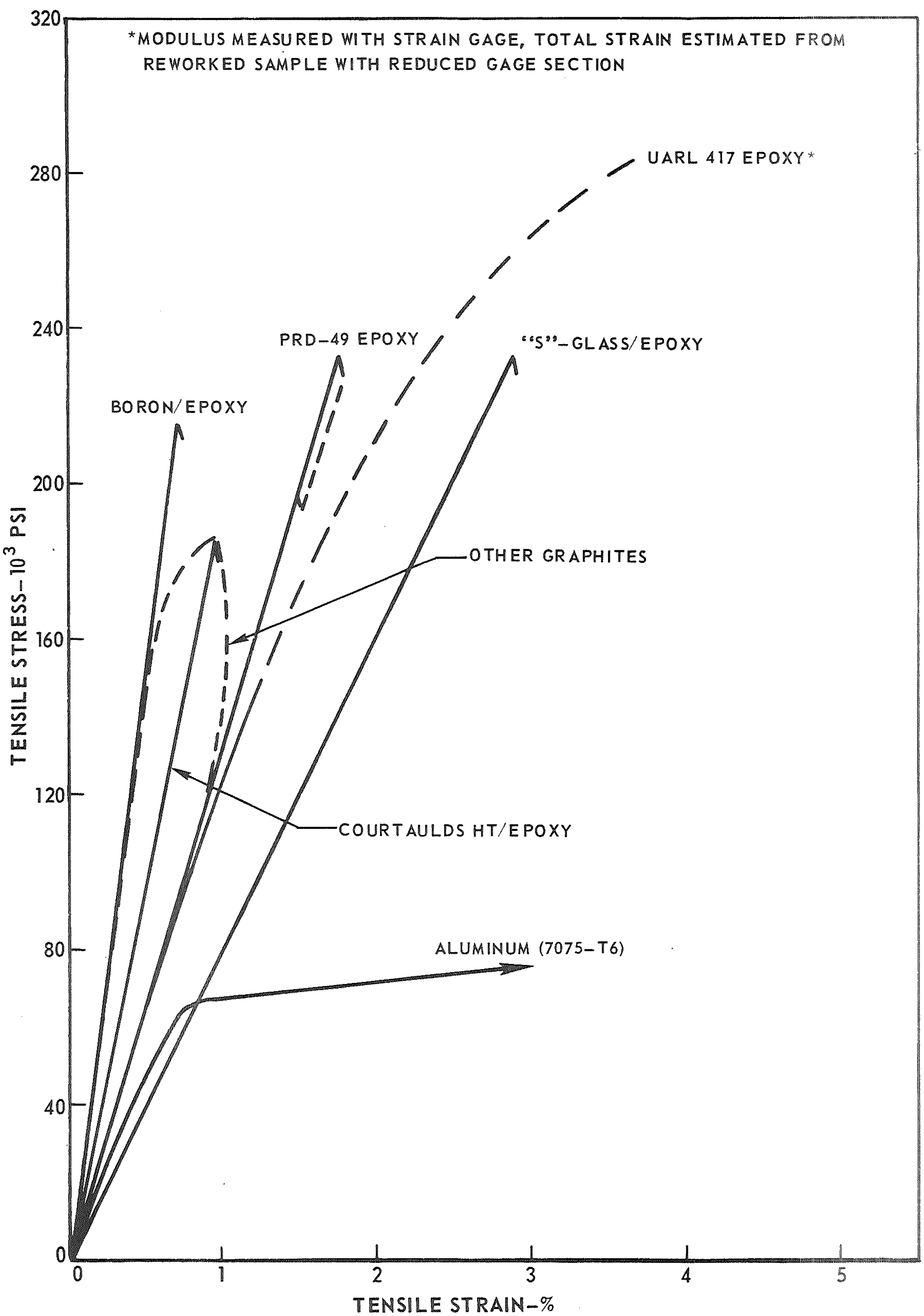
It should also be mentioned that the fractures obtained with all of the glass-fiber epoxy resin composites were generally not in tension, and accordingly, the tensile moduli thus obtained are too low.

CONCLUSIONS

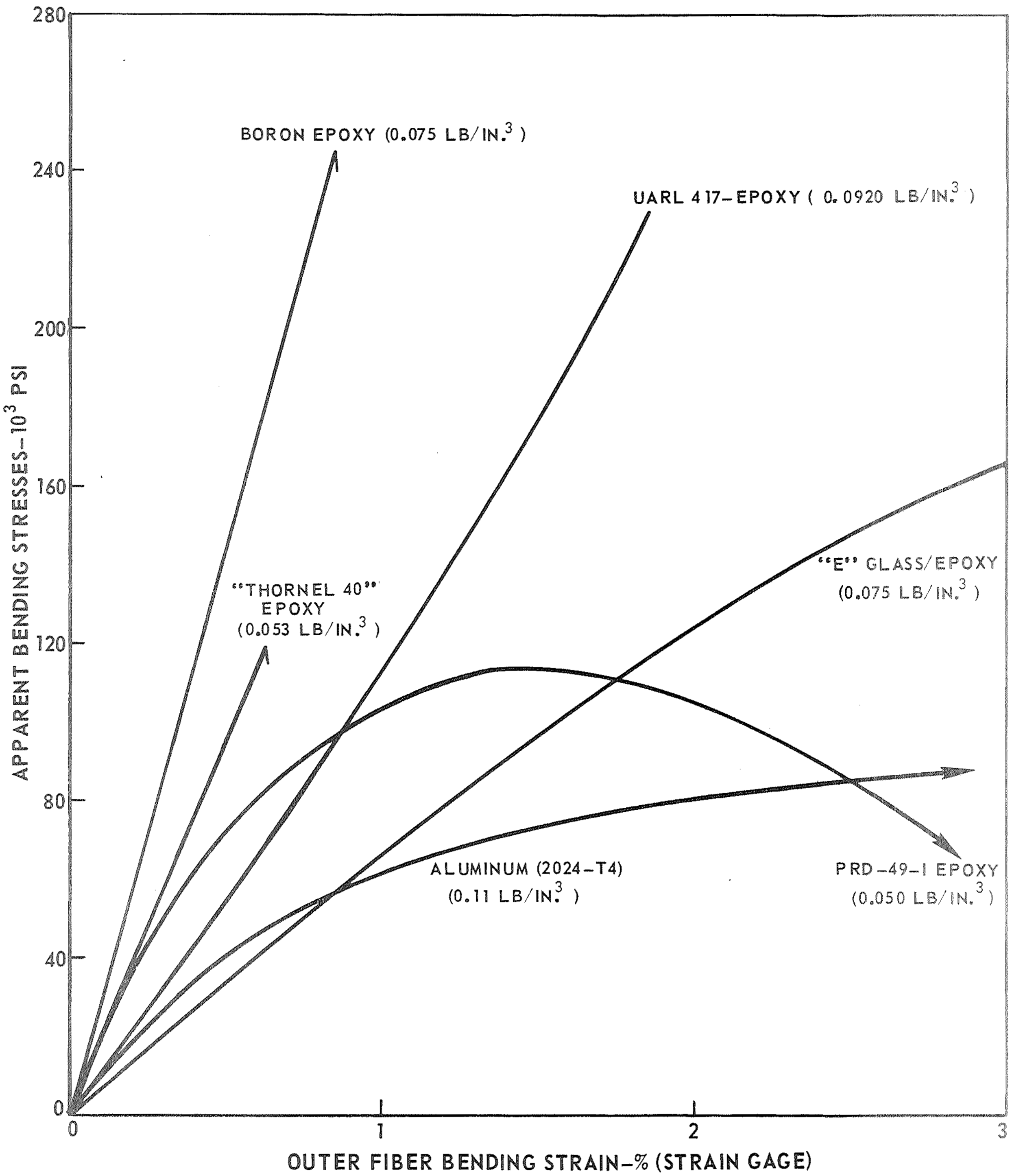
1. UARL experimental glass fibers added to epoxy resin form composites superior in flexural strength, short-beam shear strength, compressive strength, and absolute tensile strength compared to the new DuPont experimental fiber PRD-49-I epoxy resin composites. These glass fibers should prove useful in aerospace and naval structural applications.

2. The investigation of impact in bulk glass samples should be carried out with unnotched specimens since notching the specimens causes premature failure and gives results too closely grouped to be helpful in understanding this property.

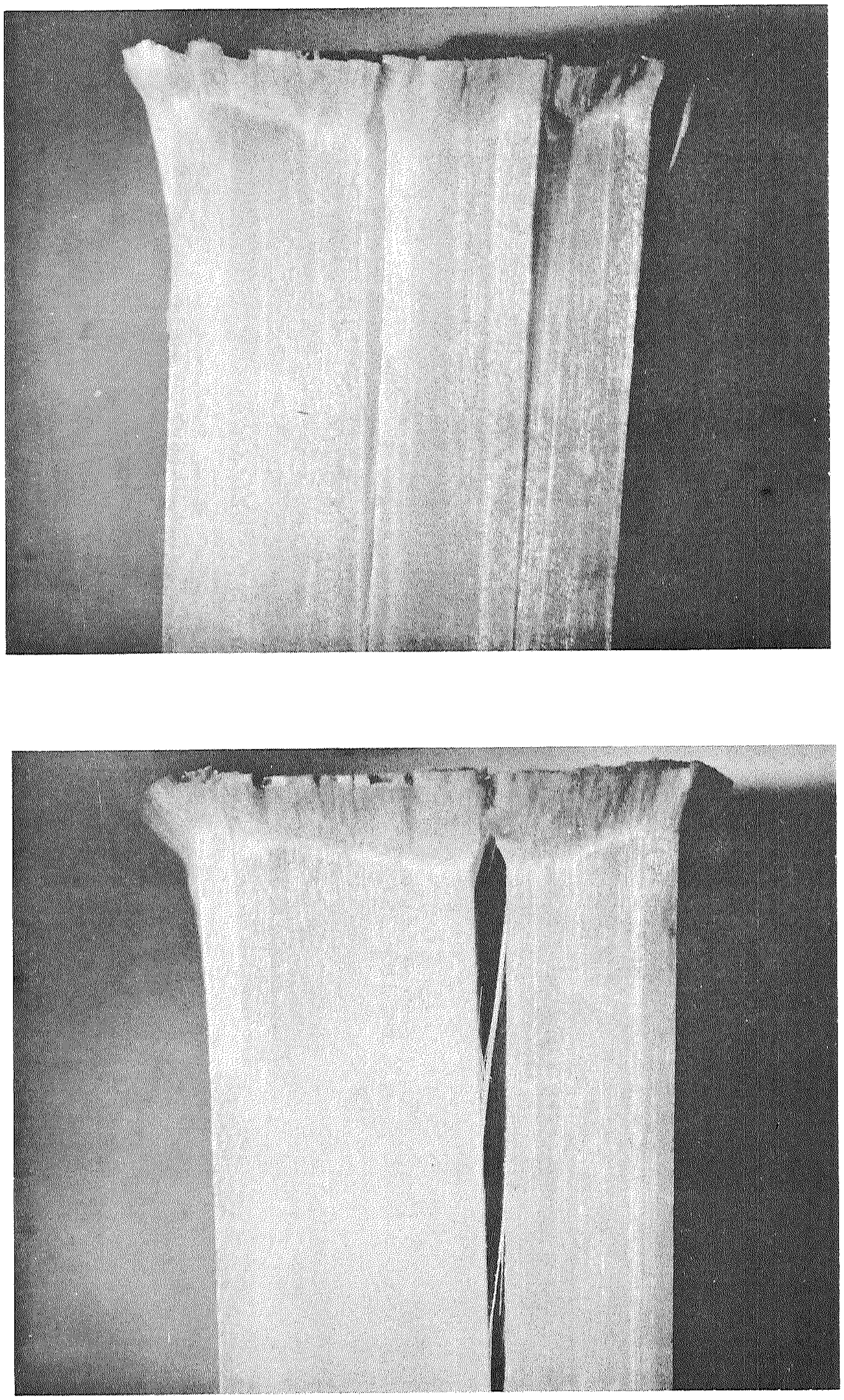
COMPOSITE TENSILE STRESS/STRAIN CURVES



COMPOSITE BENDING STRESS/STRAIN CURVES IN DIRECTION OF FIBER ALIGNMENT



MUSHROOMING OF FIBER GLASS-EPOXY COMPOSITE IN NORMAL UARL COMPRESSION TESTING



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