THE STRENGTHENING MECHANISM OF SHORT GLASS FIBER REINFORCED PLASTIC FOAM

By

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THE STRENGTHENING MECHANISM OF SHORT GLASS

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PREFACE

This study deals with new ideas in composite material technology. Specifically it is a representation of work done to improve the physical strength and stiffness properties of a cellular plastic by reinforcing it with short chopped glass fibers. Previous work has been examined to discover what has been accomplished in the area of fracture mechanics and the reasons for improved properties of the fiber filled material over the unfilled matrix. Several ideas are presented which suggest a different or modified fracture mechanism over what was gleaned out of the literature. Tests were performed to check their validity.

The author wishes to express his personal gratitude to his major adviser, Dr. Richard L. Lowery, for his patience and encouragement in the exploration of new fields of technology. Thanks also goes to Dr. C. E. Price and Dr. J. Murali for their listening ear and valued response in discussion. Thanks also goes to Charlene Fries for preparation of the final copy on such short notice.

Many a humble thanks is given to a patient family and those few steadfast friends whose encouragement and positive attitudes made these years some of the most rewarding, educational, and productive yet.

Gratitude is shown to those persons in the library who, through their expertise in Library Science, pursued many avenues in locating the scattered, related literature and securing copies at my request.

My humblest thanks goes to God, who through Jesus Christ, has taught me the discipline and given me the ability necessary to achieve.

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INTRODUCTION

The use of cellular plastics has grown at an ever increasing rate since they first became feasible and commercially available. Two basic reasons for this growth are the savings in material, and thus money, and their unique physical and mechanical properties. Cellular plastics are unique because of their low density which gives them a wide range of uses as safety flotation in boats and related equipment. Also, rigid foams have begun to move into new markets where wood was formerly used. These include: the furniture industry where chairs, tables, and television cabinets are reaction injection moulded to give rigid, one-piece structures in one step, saving both time and money; the automotive industry that employs fibrous reinforcement in urethane foam for external body pieces, bumpers, and interior functions; the boat building, aircraft, and architectural industries that use foamed plastics as insulation and as core material in structural sandwich panels.

Rigid plastic foams have unique characteristics because of their low weight which gives the material a very high specific strength and stiffness. Their use as core material in sandwich panels is common because of the demands of the structure for stiffness, insulation, and reliability. The core must space the facing pieces of the panel so that bending moments taken by the structure are absorbed as tension and compression in the faces. The core must then absorb the shearing forces while supporting

the faces to keep them from buckling or wrinkling under very high stresses (1). An optimum level of stiffness and strength can be calculated where the buckling loads may be very nearly the same as the fracture loads for the faces. Thus, the efficiency of the structure depends on how highly stressed the skins are. A more rigid core will allow the skins to be made thinner and therefore lighter and less costly, since thick skins are often used to meet buckling requirements.

Rigid foams with improved properties are useful as structural materials by themselves or with other materials. Better strength would lend itself well to opening new markets and initiating new products. Since the use of a material depends in part on its ability to do the job, then tailoring a material to a specific application would seem ideal. This is the concept behind using composite materials. Rigid foams can be altered through their chemical formulation to give a wide variety of physical and mechanical properties. Urethane is a very versatile material that can have a wide variety of properties from rubbery to rigid by changing the primary constituents (2). Another common practice is to add a filler or other material to change its mechanical properties (3).

Urethane plastics are produced by the reaction of a polyol and an isocyanate. The physical properties of the finished product, whether flexible or rigid, are controlled by the molecular weight of the polyol and may be modified by the use of catalysts and surface active agents. The density of the foam is altered by the use of different types and quantities of blowing agents (4). Two basic types of blowing agents are used: a nonreacting type such as a flourocarbon which depends on the heat of reaction to expand the liquid to a gas, and a reacting type such as water which produces carbon dioxide. The morphology of the foam can

be altered by the use of catalysts, surface active agents, and blowing agents (5).

Foam Morphology

In trying to alter the properties of any material, a knowledge of what the material is and how it is made is essential. A foamed plastic is simple a plastic in a liquid or semiliquid form into which is mixed another liquid, gas, or solid which releases a gas by thermal or chemical means to form bubbles in the liquid. The bubbles may bump into each other causing strong interaction between cells if there is enough gas in the foam. If there is more than 76 percent by volume of gas in the foam, then the morphology tends toward a structure that looks roughly like a pentagonal dodecahedra (6) (Figure 1).

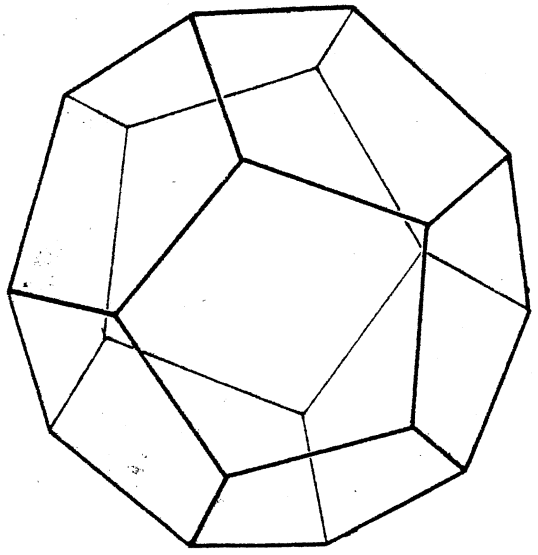

Figure 1. Pentagonal Dodecahedra

As the foam expands the material between the cells is stretched thin causing membrane thin walls or windows. While still in the liquid form, the foam is thermodynamically unstable and therefore tends to try and reduce its surface energy. It does this by redistributing the bubble sizes and by draining the film between the cells. The bubble sizes are changed by pressure differentials between individual cells. The gas in the smaller, higher pressure cells tends to transfer to the larger, lower pressure cells by diffusion. Large individual cells may form in the matrix, since large bubbles have a lower surface area and thus a lower energy per unit volume. Film draining reduces energy by making the surface tension forces smaller in a single cell (7).

The geometry of the individual cells depends on the influence of its siamesed neighbors and must fill two criteria: it must fill the volume and it must have a minimum surface energy for that volume. The basic structure of cells consists of cell struts which are triangular in shape due to three cell walls meeting at each strut and joints where four struts come together (Figure 2). The average angle between each pair of struts is then $\cos^{-1}(1/3)$ which equals 109.5. In modeling the structure the geometric and volume compatibility are closely matched by those of a pentagonal dodecahedra which has angles of 108 and a quite small volume mismatch. The cell will assume this shape if the volumes are equal. However, the volumes are very rarely equal. Therefore, distorted polyhedra result which have four, five, and six-sided faces in their structure (7). Since the cells are not uniform, this will result in the distribution of stress among cells to be nonuniform.

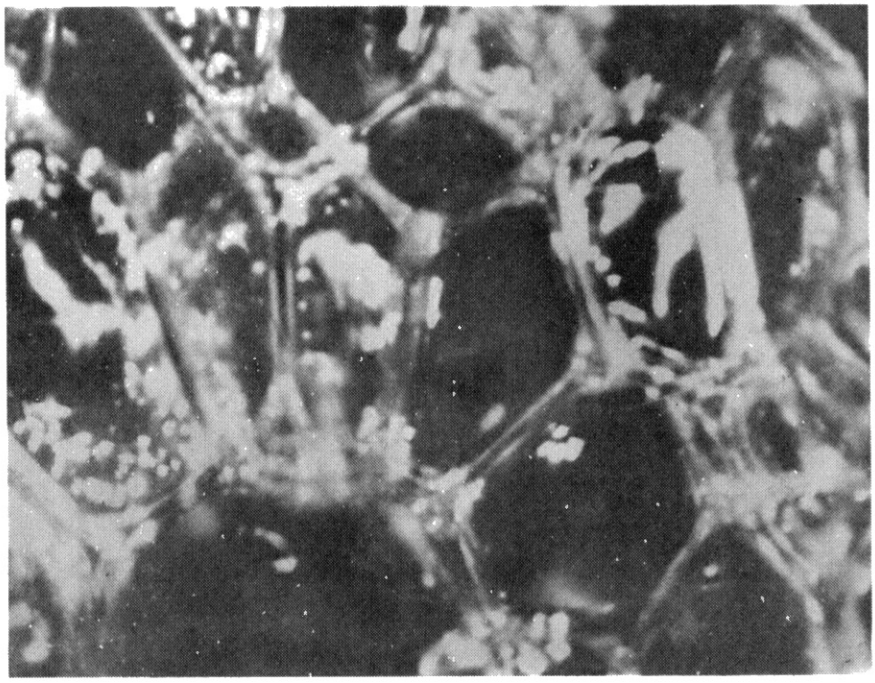

Figure 2. Basic Cell Structure

Fracture Mechanisms

A number of works have been done to suggest how the matrix in a plastic foam fractures under stress. A study was done to examine the role of the cell window in the fracture process (6). It was performed by studying the mechanical properties of the foam before and after the cell walls were chemically removed. The morphology changed in one basic manner in that there were no longer any cell walls. It was found that the strength of the material along with the flexibility were doubled in the specimen with no cell windows. The reason for this was found to be a result of the windows themselves. Only about ten percent of the material was removed in the process of leaching the windows from the matrix, but the windows were found to act as triangular stiffeners in the matrix. When the cell is elongated, the window flexes and then splits on an axis that is perpendicular to the stress axis. This causes severe stress concentrations in the adjoining struts. Another result discovered was that the tensile strength of the material increases with decreasing cell size.

According to another author, the use of milled glass fibers was used to strengthen the matrix and short glass fibers were combined into the matrix (3). His study examined the process by which the fibers acted in the matrix and how the interface bond altered the overall properties of the material. He found that the fracture path of the foam was lengthened because the crack was diverted around the fiber.

The Challenge

The project currently underway is set to examine the possibilities of altering the fracture path by incorporating the fibers into the matrix in a different manner. By using filaments of length about the same size

as the cells in the matrix, it is considered that the crack will be reduced by some fraction in importance by several different methods of action of the fiber in the matrix.

As the number of reinforcing elements increases, the viscosity of the resin with fibers increases. Large bundles have a lower surface area to volume ratio than do individual filaments. Thus as the fibers become more dispersed, not as high a weight percentage of fiber can be mixed into the resin of a pour foam. Many more reinforcing elements are available causing more fiber to fiber interaction both before pouring and after the matrix has set. Thus the more fibers the more improvement in mechanical properties. The effect of stress concentrations in the struts caused by the windows splitting may be reduced by stopping the crack or slowing it down. If this takes effect, then the stress will be transferred to other struts and the nearby joints, allowing more material to act in strengthening the matrix (Figure 3).

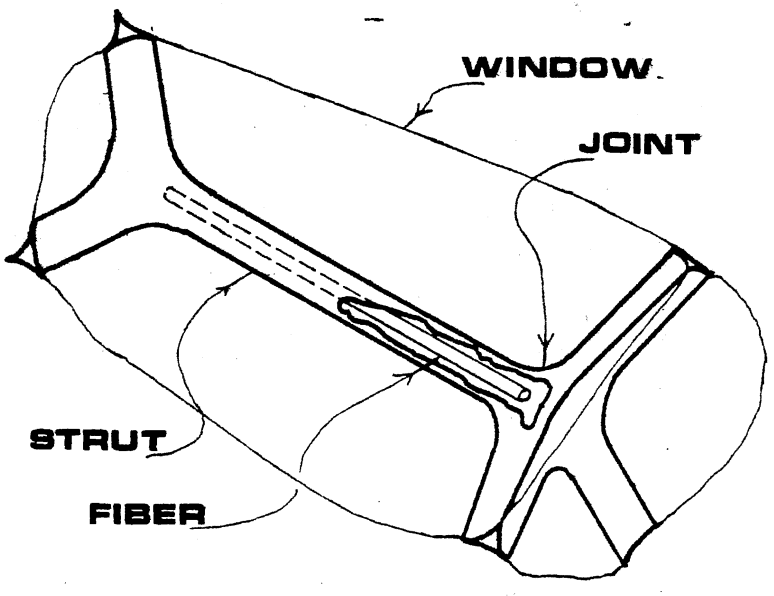

Figure 3. Short Fiber in Strut

CHAPTER II

REVIEW OF LITERATURE

Time spent in the library revealed a scarcity of pertinent literature on the specific topic of fiber reinforced foams. A literature search was performed which produced several related articles. Only one good source was located that was studying the fracture mechanism that is involved in fiber reinforced foam which produced several good interrelated articles (3). Several were found that discussed fracture in a plain foam (6, 9). This suggests an opening for further investigation into the field.

One source produced the material about foam formation in Chapter I and several other ideas (7). According to this author, the strength is a direct function of the foam density and is dependent on the amount of material resisting deformation. Upon application of a load to the foam individual cells resist buckling of their struts by the cell walls. The walls then are the first part of the structure to fail in that they split in a direction perpendicular to the axis of load. The struts are then without their support along their length and can buckle. Struts aligned with the load will take stress in tension while those perpendicular to the load direction will be in compression due to bending moments induced by the rigid joints and the geometry. The broken windows can cause severe stress concentrations in the struts leading to premature fracture.

Polyurethanes are very notch sensitive, having a notched strength about half of the unnotched strength (6).

An empirical analysis revealed a basic dependence of the structural strength and elastic modulus on the foam density (7). This is simply due to more material resisting deformation. This is true of all foamed plastics and is estimated by an equation of the form

$$\text{Strength or Stiffness} = f(\rho)\alpha\ A(\rho)^{B}$$

where B is between the values 1.1 and 1.8 for a polyurethane foam. For an anisotropic foam, which is normally the case as the cells elongate in the rise direction, an equation of the form

$$\frac{P_\theta}{P_o} = \cos^2\theta + \sin^2 \frac{\theta}{r^2}$$

where P represents load, θ is the angle between the load and rise direction, and r is the ratio of radii of the major and minor axes of the ellipsoid after which the elongated cell is modeled.

Since the structure is nonuniform due to geometrically incompatible structure, the cells tend to load some struts at different stress levels than others. Thus, as the number of load carrying members increases, the properties of the material improve. From this it is surmised that a foam with a finer cell density will have better properties than a foam with bigger cells (7).

Another author studied the effects of cell density and the cell windows (6). An empirical formulation defines the strand length for all the cells combined to be

$$L = 6.45\ P^2/\text{in.}^2$$

where P is the number of pores or cells per linear inch. It was determined

than an increase in strength of the finer celled foam was related to the ratio of strut length to its thickness. Shorter struts have a higher thickness ratio and so have a higher buckling load for their size. The author reiterated previously noted work in showing the cause of lower strength values to be the result of notches in the struts due to the windows splitting under stress. He predicted the strength according to the strength of individual strands and discovered an error of 250 percent. This was due to geometric incompatibilities.

At the University of Liverpool in Liverpool, England, work was conducted to discover the action of the reinforcing elements in a plastic foam matrix (3). Specifically the relationship between the structure of the reinforced foam and the mechanical properties was studied along with the role of the interface in altering the fracture process.

Observations of the morphology of the foam used in this study revealed several important concepts of the fracture behavior. The fibers were included in the foam only in quantities of about 5 percent or less due to a dramatic increase in the viscosity of the base material. No gross distortion of the matrix was noted due to fibers in the foam. Large bundles of fiber contained inner fibers that remained unaffected by the resin. The outside of the large fiber bundles was coated while the inside remained dry. Very small bubbles formed on the fiber and this was attributed to the cool surface temperature which did not allow gas generation. Very small fiber bundles encased fibers of normal size while single filaments formed a core along which the bubbles formed in a radial manner down its length.

In examining the fracture behavior, observations were made to determine how the fibers improved the strength. As the crack approaches the

fiber in its resin sheath, the struts break along the fiber to the end and the crack will then continue to grow. This results in the observed "pull out fragments." The crack does not reach the fiber/resin interface and no debonding occurs (Figure 4).

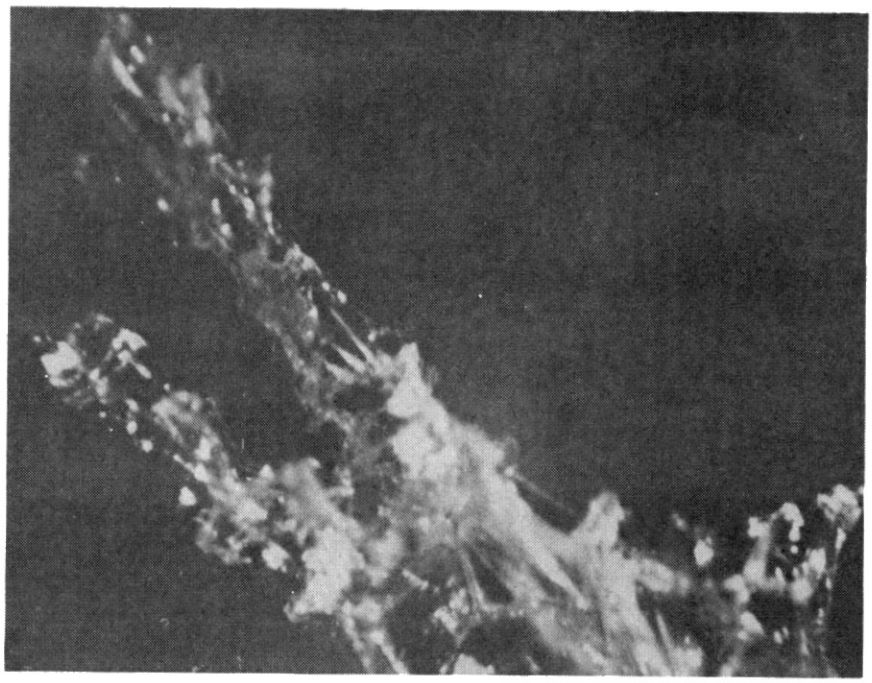

Figure 4. Pull Out Fragments

Different fibers affect the matrix in different ways. Larger bundles with a higher concentration of "size" or binding agent arrested the crack but generated a secondary crack at the fiber tip. This revealed a high stress concentration in this area. Long single filaments fractured in the plane of the matrix without any debonding or fiber pull out from its sheath.

The coating on the fiber alters the performance by changing the length of fiber for pull out. This allows a material to be tailored to meet specific performance levels. In the reinforced foam the mechanical properties improved with the low fiber binder concentrations than with higher concentrations. The surface treatment has no direct observed effect on the fracture process but does alter the dispersion of the fibers. It was discovered that elimination of all chemical bonding was insufficient to allow fiber debonding on tensile fracture. This was due to a squeeze put on the fiber by the sheath due to thermal contraction after the polymer had set.

From these observations several conclusions were set forth (3). The foam with fibers is considerably tougher than unfilled material which leads to the conclusion that energy is absorbed in a longer crack path which causes more struts to be stressed and broken. Only low concentrations of fiber were used so that each fiber acts independently of the others. This led to the derivation of a critical fiber length where a shorter fiber is not stressing as many cells as it could and a longer one will fracture in the plane of the crack.

Additional observations include notes about the fracture in areas where more than one fiber interact and the relative sizes of the cell struts (3). As the cell size decreases the relative strut thickness will increase, resulting in a greater shear strength along the fiber. Thus the critical fiber length will decrease with finer cell structure. Large fiber bundles cause stress concentrations and will not increase the foam properties as much as smaller bundles of fibers. Also, the greater the number of fibers, the greater the number of fiber interactions and the higher the modulus. Fibers that crossed locally anchored each other and

so resisted fracture. The joint of the struts was never observed to fracture.

Hypothesis

Fibers are desirable reinforcement because they perform the following functions: the crack path is made longer causing more struts to be broken during the fracture, thus increasing the toughness; stresses are distributed among the cells more evenly, not allowing single struts to be stressed as highly and so absorbing more energy; the fracture path is diverted, prolonging catastrophic failure. These conclusions along with the previous observations made concerning the strengthening due to fibers, the chemical bond at the resin/fiber interface, the interaction among fibers (3), and the foam cell morphology (6) suggest another set of conclusions involving a change in the fracture mechanism.

The finest cell structure available is desired because more struts will accept a greater fraction of the load in the material. Also, as the cell size decreases the thickness ratio of the struts increases, which means a higher shear strength. Shorter struts are also stiffer struts which means a higher load before fracture initiated by window splitting. This project seeks to obtain a uniform cell structure among all the samples so that these effects are not noticed in studying the strengthening due to the fibers.

If the fracture of the matrix is through the struts, then reinforcing the struts would seem to help. In fiber reinforced foams crack propagation may take place through the sheath and to the fiber so that strengthening may be limited in individual struts to a level below that which would occur with no crack transfer across the fiber/resin interface.

A low bond strength will allow the crack to be stopped and redirected at the fiber/resin interface. A high bond strength will tend to cause the fiber to fracture in the plane of the crack (8). The bond strength between most thermoset plastics and glass fibers can be attributed to a chemical bond and a mechanical bond due to the matrix shrinking around the fiber. According to Reference (3), complete elimination of the chemical bond is insufficient to give low bond strengths. Thus, it is anticipated that a satisfactory minimum fiber length cannot be reached. However, even if there is a chemical bond on the fiber as well as a mechanical bond, there is still some point where the shear strength between fiber and matrix is equal to the fracture strength of the fiber.

If interactions occur at the unions of the fibers, then some way can be found to increase the number of interactions so that better reinforcement occurs. The method of inclusion of the fibers in the matrix is important because of fiber interactions. A small number of fibers will act as though they are the only fibers in the matrix which they are in their near vicinity (3). More fibers will increase the elastic modulus and also the tensile strength. The more fibers that can be caused to efficiently interact the more they will strengthen the matrix.

Some practical difficulties arise in combining fibers in a foam matrix. The foam rises from a high density to a low density material so that it is difficult to mix a significant volume percentage of the fibers into the finished product without increasing the viscosity of the liquid to an unmanageable level. The viscosity increases due to the fibers interacting while in the liquid and the liquid being taken up to wet the fiber surface. Bundles of fibers have a lower surface area for the volume displaced than do individual filaments for the same weight of

material. Thus, it is anticipated that more weight percentage of fiber bundles can be mixed into the resin than can individual filaments of the same length. Very short filaments interact with fewer numbers of each other than longer filaments do. Thus, more shorter filaments should be able to mix easily in the resin than the longer filaments which will provide many more reinforcing elements for the matrix. A slightly lower weight percentage is expected since there is a slight increase in the total surface area of the fiber for a given weight.

The project at hand deals with including glass fibers into the matrix so that the struts are more highly stressed without fracture and the stiffness is increased so that window split does not occur until higher loads are reached. This is to be done by putting short glass filaments into the foam such that the length of the fibers is about the same as the struts in the individual cells.

A method to achieve this has been developed to calculate the approximate filament length and fiber loadings to put about one fiber in each strut in the structure. A check can be run by using the formulation by Cotgreave and Shortall for the maximum critical fiber length for reinforcement of a plastic foam (3).

$$L_{cm} = \frac{2\sigma_f r_f^2}{t_m d}$$

Here L_{cm} is maximum fiber length for reinforcing the foam for a system that is matrix limited in failure where the fracture is remote from the fiber/matrix interface. Comparison of fiber lengths is made using this value and a value for the minimum filament length where the system will make the transition to a fiber limited system due to the decrease in total shear load on the fiber.

To calculate the minimum filament length, assume for now that the load applied is in the axial direction on the strut (Figure 5). At some length the shear forces will balance the applied load the fiber would prefer to pull out of the matrix rather than break. The total shear stress is found by multiplying the shear strength of the material by the affected area. This is assuming that the fiber length is sufficiently long to neglect end effects.

$$V = t_m \cdot A$$

where V is the total shear load, t_m is the maximum shear strength, and A is the total shear area. This must equal the fracture stress of the fiber which is

$$P_f = \sigma_f \cdot A_c$$

where P_f is the fracture load, σ_f is the fracture stress, and A_c is the cross sectional area of the fiber. Equating these two:

$$t_m \cdot \pi D\ L = \sigma_f \cdot \frac{\pi D^2}{4} .$$

Solving for the length for pull out and multiplying by 2 to give the total filament length yields

$$L_{\text{pull out}} = \frac{\sigma_f}{t_m} \frac{D}{2} .$$

This might be used to optimize properties of a short fiber reinforced foam in conjunction with an estimate of the fiber loading provided the bond strength of the two materials is known or can be estimated.

To get an estimate of the quantity of fiber needed to put one fiber in every strut, the following technique should be used. Estimate the cell diameter from the foam geometry and find the factor P, or pores per

inch, by inversion of the cell diameter. Calculate the total strand length by

$$L = 6.45\ P^2.$$

Estimate the weight of glass needed by

$$Wt = L \cdot A_c \cdot \rho.$$

Calculate the individual strand length by dividing the total strand length by the total number of strands which is found by (6)

$$\text{Total number of strands} = 10 \cdot P^3.$$

Divide this length by the filament diameter to find out if it will even strengthen the matrix. As a general rule the ratio must exceed 10 in order to provide adequate strengthening.

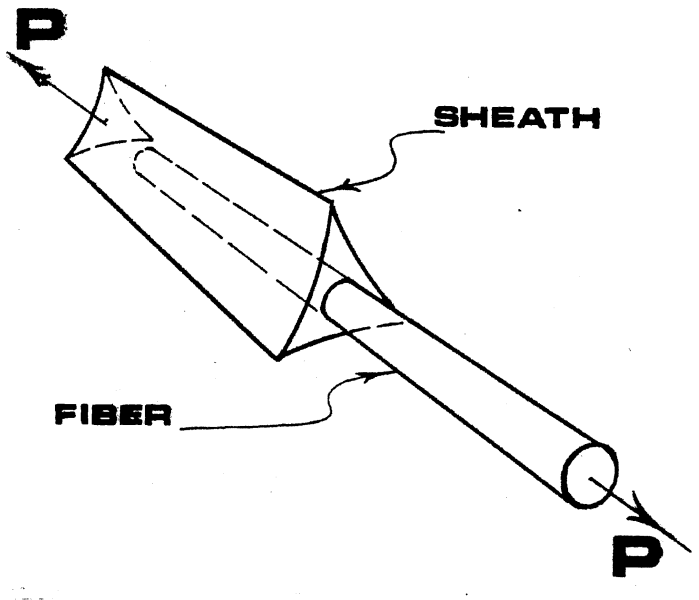

Figure 5. Composite Strut Under Load

Since the addition of fibers increases the liquid viscosity of the resin, it limits the weight of fibers that can be included in the matrix. It is important then that all the fibers contribute as much as possible to the strengthening of the matrix. For this reason milled fiber is unsuitable because of the large quantity of nonuseful dust and fiber fragments. Longer fibers provide some reordering of the matrix and cause more cell struts to be affected during loading but still do not attempt to divert the fracture from the matrix or address the basic fracture initiating mechanism of stress concentrations due to split cell windows.

The equations suggested here to support the concept of a fiber in the individual struts to divert the crack and stiffen the junctions to prolong window failure should provide at least a starting point for investigating changes in the fracture mechanism. In order to better understand these ideas, experimental analysis is necessary.

CHAPTER III

EXPERIMENTAL TECHNIQUE

In order to discover if there has been any change in mechanical properties, some tests need to be performed. If there is a significant change in the properties, then some explanation of why there was change should be provided. Tensile tests were conducted to show that glass fibers do affect the foam matrix and a study on the foam morphology was used to demonstrate why.

Sample Preparation

Urethane pour foam was used as the matrix into which glass fibers were placed. Urethane was chosen because of its simplicity, availability, and because it was employed in other studies. Glass fibers of three different types were used (Figure 6). Fiber bundles of up to 170 individual filaments bound together about 0.19 in. long were commercially available. Individual filaments about 0.19 in. long were prepared by heating the bundles to 500°C in order to remove the binder. Very short individual filaments were produced by hand chopping the long fibers under a zoom microscope to lengths of between 0.01 in. and 0.03 in. The lengths were determined to be shorter than the maximum critical fiber length by Cotgreaves' equation. Lengths were found using the technique in Chapter II and knowing the filament diameter is 0.0004 in. and the shear strength to be about 3500 $lb_f/in.^2$ between the fiber and matrix.

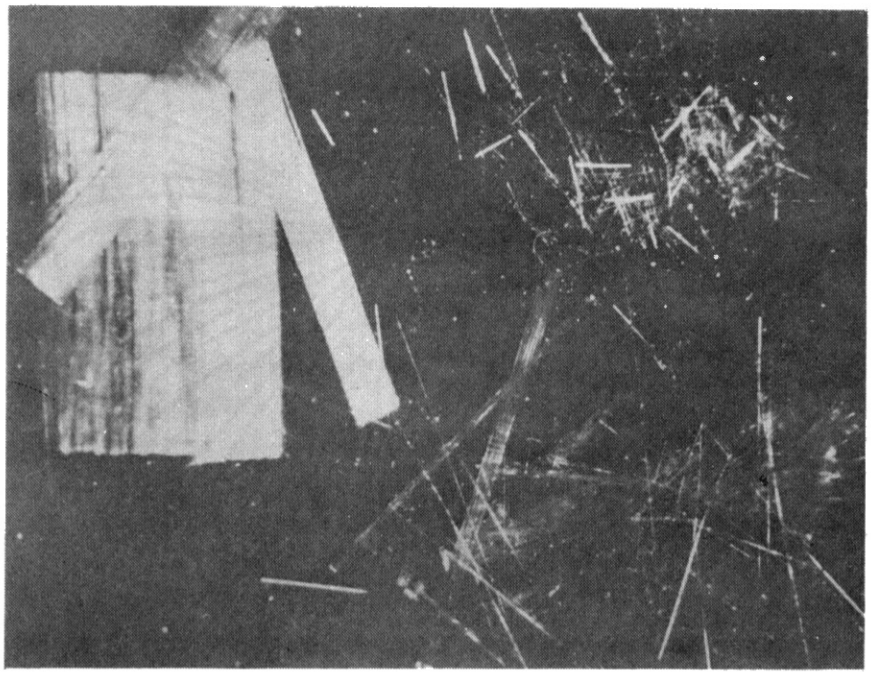

Figure 6. Glass Fibers

Some preliminary "muffins" were produced in paper cups to test the mixability of the samples, how much glass could be forced into the matrix and the general effects of the glass on rise, and final morphology. Generally less than 35 wt% of the bundles can be mixed in while only about 20 wt% of the long filaments can be successfully introduced.

Urethane "loaves" were produced by weighing part B, estimating the quantity of glass desired, mixing the glass into Part B to disperse the fibers evenly, weighing part A to give equal parts of A and B, stirring the components together using an electric drill with a paint stirrer until cream time began (about 25 sec) and pouring into an aluminum box that was 6½ in. x 8½ in. x 12 in. tall. After rising, the foam was let stand for 36 hours at room temperature before proceeding. The "loaves"

were then cut into blocks 2 in. x 2 in. x 6 in., placed in a lathe and cut into tensile specimens according to ASTM standard D-1623-78 for rigid cellular plastics (9).

A second type of specimen was used because of the difficulty in obtaining a sufficient quantity of very short fibers. The specimens have a square cross sectional area of 0.25 $in.^2$ instead of 1 $in.^2$ for the ASTM specimens. Samples of the control material, the strongest reinforced material, and the very short fiber (VSF) reinforced material were cut into "I" sections with a gage length of 0.5 in.

Tensile Tests

The specimens were broken on a Materials Testing System Series 312 load frame with a servo-controlled hydraulic actuator (Figure 7). The servo was managed by a feedback loop utilizing either a load or displacement transducer to control the loading function. For these tests the displacement transducer was used to give a constant strain rate in the material. Some experience showed that an actuator speed of about 0.10 in./min was sufficiently slow to give consistent results without straining the material too rapidly. A 500 lb load cell was used giving a resolution of ±0.1 lb. A 10,000 lb load cell was later used giving a best resolution of ±1.0 lb.

Two sets of grips were used to test both types of samples. One set was built according to ASTM D-1623-78 while the other was designed for the small samples to reduce deflection by constraining elongation more closely to the gage section.

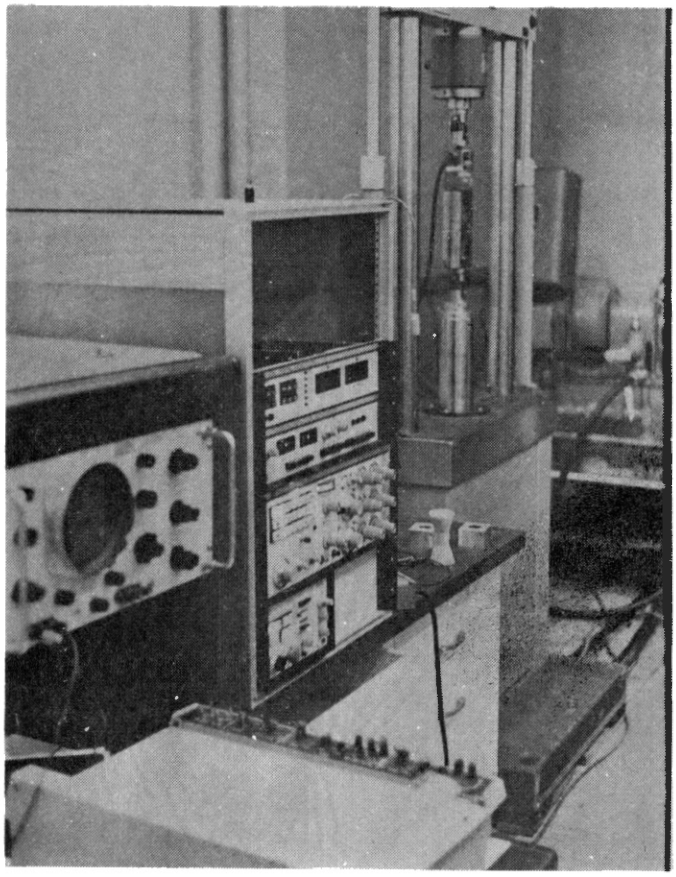

Figure 7. Materials Testing System

Morphology

After fracture the broken specimens were examined on a large scale for general observation and then under closer scrutiny by using a Bausch and Lomb 10x to 70x zoom microscope with an attachment for a camera. The camera used was a Miranda Sensorex II 35mm single lens reflex type. Photographs of the cell structure were taken between 1/8 sec and 1/2 sec exposure times.

The salient features of the structure were examined, then correlated with previous observations of strength and modulus. The features examined

include cell elongation and orientation, fiber orientation, bubble size and uniformity, and areas of possible stress concentration. Matrix damage was evaluated by looking for window damage and fracture, strut breakage and pull out fragments.

CHAPTER IV

RESULTS AND DISCUSSION

Experiments and observations were made either to support the conclusions drawn from the literature or to show that they are incorrect. Tensile tests were run to observe the effects of glass fibers on the mechanical properties of ultimate strength and elastic modulus. The basic morphology of the material was carefully examined to provide an explanation of why the mechanical properties were altered.

Tensile Properties

A general trend observed here is an increase in tensile strength with any addition of fiber. Fiber bundles gave the least strengthening with long filaments next and very short filaments the highest. The modulus increased similarly. The foams tend to become less directional as the fibers become more finely dispersed and with shorter lengths. The curves show local maximum and minimum values at higher strengths under slow strain rates which correspond to popping noises from the samples. This relates to local fracture in the matrix as extension increases.

Both the strength and modulus of fiber bundle reinforced foam increases with increasing weight percent of glass all the way up to the limit of putting the fibers successfully into the matrix at about 20 percent. The best strength was between 60 psi and 70 psi for 20 wt% glass with about 45 percent elongation. This compares to 35 psi to 45 psi and 55 percent elongation for the control specimens. This is an increase of

about 60 percent in strength. The elongation dropped some but two reinforced specimens out of six exceeded 70 percent elongation. The total energy absorbed increased 50 percent over the control. The average modulus rose from 90 psi to 170 psi, an increase of 85 percent. The strength and modulus both increase more in the rise direction than in the perpendicular or cross direction. This is explained from an examination of the morphology which reveals a high degree of bundle orientation in the rise direction.

Filaments were dispersed into a second sample and again both the strength and modulus rose. In these specimens the strength reached a peak at about 4 wt% glass fibers and then dropped off dramatically with higher concentrations. Maximum strengths were observed with 4.2 wt% glass at between 70 psi and 85 psi. The modulus rose from 90 psi to 250 psi or an increase of 180 percent. Total energy absorbed remained about the same as the control sample due to greatly reduced elongation. Local peaks in the curve were not as severe or as frequent as either the bundles or samples with more filaments. This suggests that not as many major load holding members fractured during the test. This makes sense because there are fewer reinforcing elements to break.

The very short fiber reinforced foams yielded the highest relative strength and stiffness. The ultimate strength was about 61 psi as compared to 55 psi for the long filament samples. Lower values here can be attributed to the smaller samples which caused both a higher apparent strain due to better constraint of the specimen and lower fracture stress due to sharp corner stress concentrations. The modulus is about 360 psi or four times the control modulus. This is an average value for samples giving between 320 psi and 400 psi for a modulus. The elongation has

been corrected to give comparative values. The elongation has dropped from about 50 percent to about 30 percent by putting less than 5 wt% of very short fibers in the matrix.

The general trends then can be seen in viewing the data all in one place (Figures 8 and 9). Table I gives a listing of data averaged from between three and six data points. The trend in strength shows a maximum ultimate strength at about one-half to one-third of the predicted optimum glass loading which was about 13 wt% for filaments and very short fibers. The modulus appears to increase as the number of reinforcing elements becomes higher. This fails to show in the very short filament foam but follows well for both long filaments and bundles. The elongation drops as the number of reinforcing elements increase for all the samples tested. The foams become less directional as the number of reinforcing elements increase and as the fibers become shorter, which may be one and the same effect since shorter fibers mean more fibers for the same weight.

Morphology

Having successfully increased strength and stiffness leads to the questions of how did the fibers act to bring about change. By observing how the foam is structured with relation to the fibers, data from stress/strain tests and the morphology after fracture, the mechanism of how this occurs may be identified.

Fibers are placed into the matrix by the forces acting on them during rise. Fiber bundles have a large surface area and are pushed into alignment with the rise due to the viscosity of the rising foam (Figure 10). This may account for the slightly higher directionality than the control sample. Some added strength comes in the cross direction from

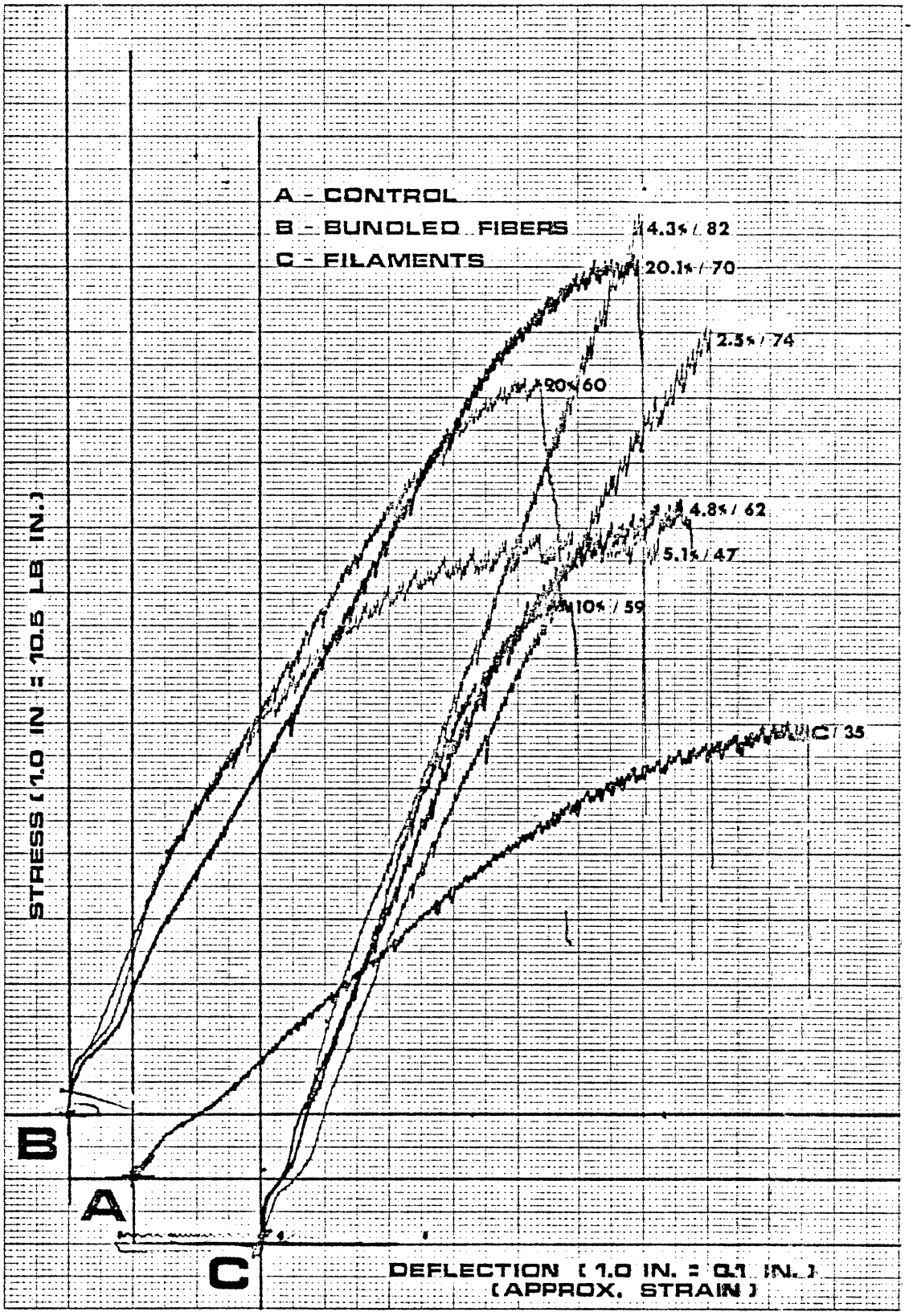

Figure 8. Stress/Strain Curves--ASTM Specimens

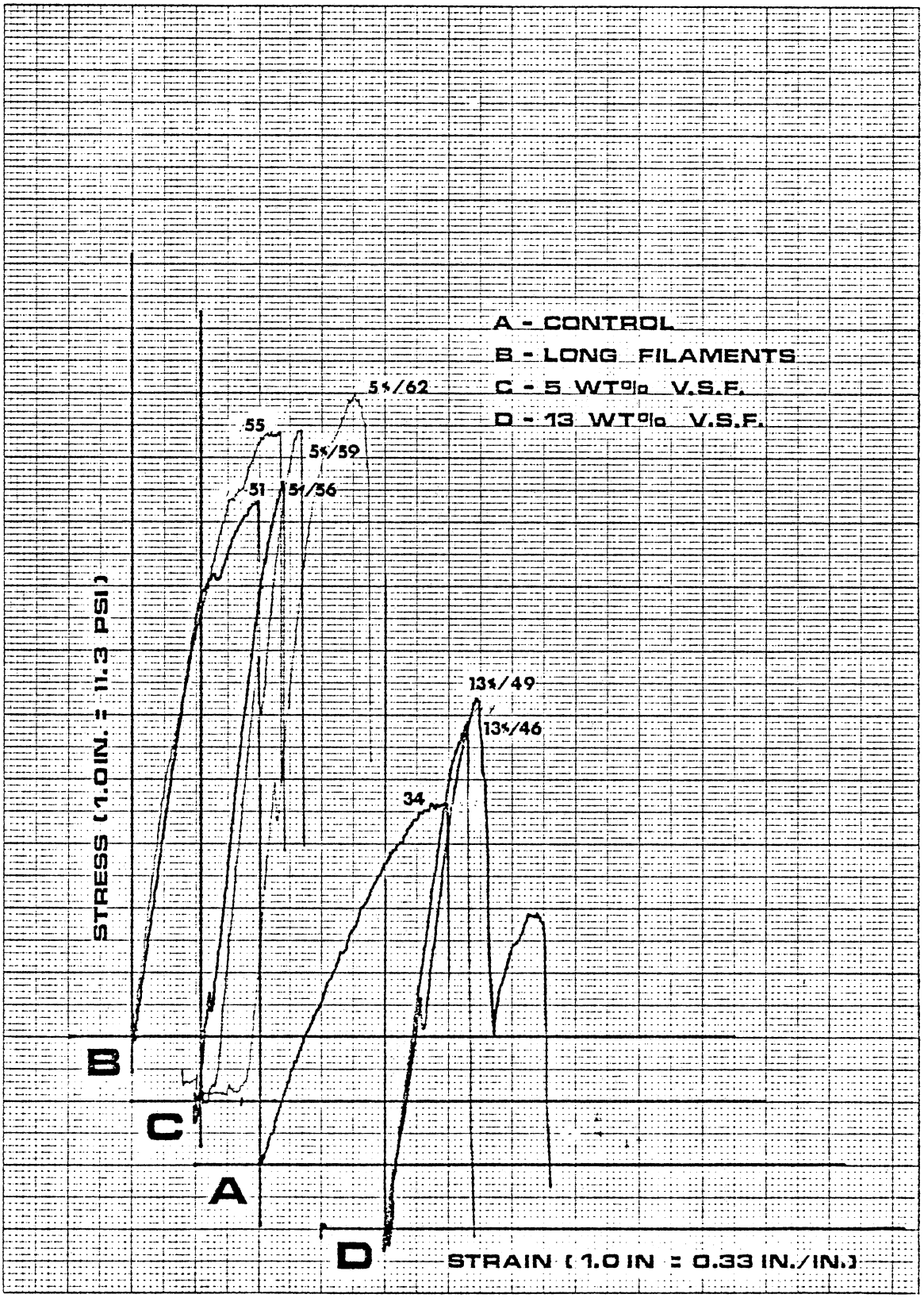

Figure 9. Stress/Strain Curves--"I" Specimens

TABLE I

SUMMARY OF DATA

Type of Reinforcing	Wt% Glass	Ultimate Strength*	Percent Increase in Strength	Modulus (psiP	Percent Increase in Modulus	Percent Elongation
None (Control)	---	40/35+	---	90/90+	---	53/50+
Fiber Bundles	4.6	50	25	130	45	46
	9.0	60	50	150	67	40
	20.1	65	60	170	90	40
Long Filaments	2.6	75	90	240	170	35
	4.2	80/55+	100/60+	250/240+	180/170+	30/35+
	5	65	65	250	180	34
	13	60	50	270	200	25
Very Short Filaments	5	61+	75+	360+	300+	30+
	13	55+	60+	250+	180+	25+

*Strength in rise direction in psi.

+Samples using "I" configuration; all others ASTM specifications.

angled fibers in the matrix and from a Poisson effect due to strain. This will cause some stiffening since the majority of the fibers are now in compression.

Filaments are placed due to viscosity as well. Filaments form ordered "composite struts" where cells build uniformly around a filament encased in a resin sheath (Figure 11). This increase in order in the matrix may cause some strengthening in itself.

Very short fibers are also influenced by viscous effects during rise but are short enough to be locally affected by bubble growth and reordering as well. This would account for very little directionality in the properties. The fibers may in turn affect the bubble orientation by placing constraints on the forces that alter cell shapes. Some evidence appeared that supported this. Cells in the rise direction became uniform in size and structure in small patches of the foam. These did not show up frequently in the control samples. With better structural order there are fewer geometric incompatibilities which would lend itself to better strength. Because the reinforcing elements are smaller, there are more reinforcing elements for the same weight as compared to longer fibers. This too could cause better strength and almost certainly a higher modulus.

The quantity of fibers may cause both the strength and modulus to increase up to the viscous limit of mixing, but because of other effects does not act efficiently in the matrix. Evidence suggesting poor dispersion of fibers correlates with a slackening of the mechanical properties. The fibers may cling in one area, locally changing the structure and stiffness. Also, sufficient quantities of fibers may have a negative effect on foam formation and matrix polymerization (3).

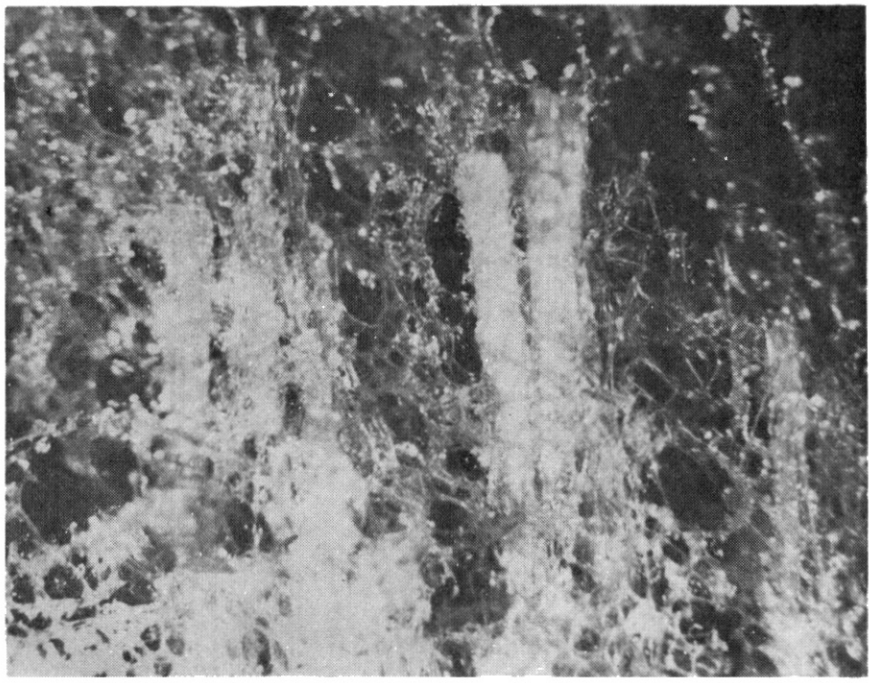

Figure 10. Fiber Bundles in Matrix

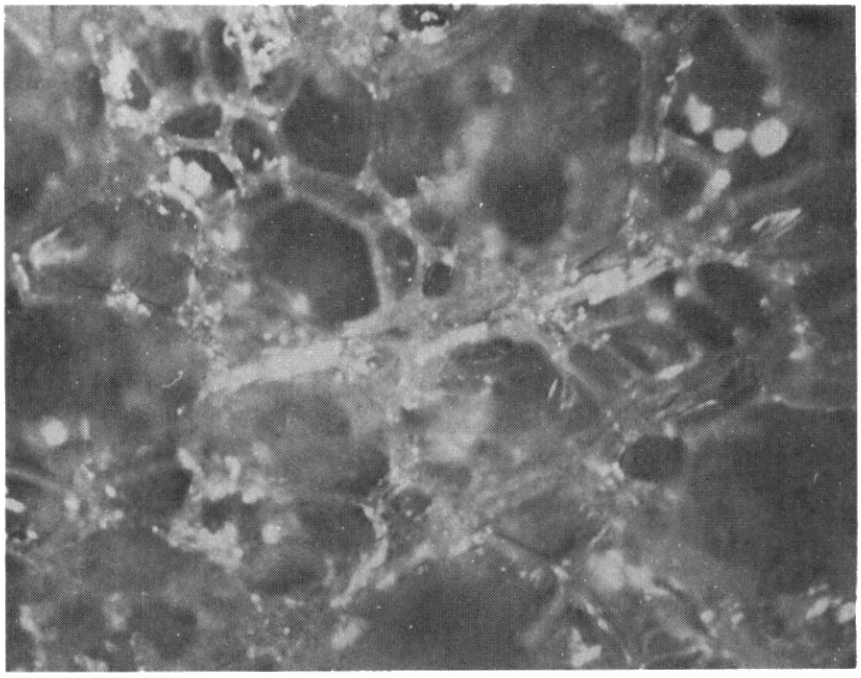

Figure 11. Composite Struts

Many fibers interact in the liquid causing the viscosity to rise. Perhaps this increase in viscosity, electrostatic effects, or some binding agent still on the fibers causes fibers to mat together in small regions (Figure 12). This is especially true with higher glass loadings because of the many more fibers. This was noticed mainly in the long filament reinforced material but occurred with the very short filaments as well. The fibers disturb the normal cell formation and orientation during rise. With more fibers there is greater disruption in the process. If the rise of the foam cannot separate the individual fibers, then they will remain disordered when the matrix sets. This causes a local change in the morphology and may be highly disordered. This, along with a local increase in stiffness, leads to a stress concentration which inhibits the overall strength. Evidence that supports this is the stiffness increasing with fiber loading but not the strength in the long filament reinforced foam.

Large quantities of fibers may affect the rise qualities and the final morphology as well. Since heat generated by the reaction of the two components causes the material to rise, then high quantities of fiber may extend the rise time by absorbing heat. They may also provide additional surface area for bubble formation, although this is considered to be a minor addition since the components are well mixed. By absorbing heat they provide the foam more time to rise and set. More importantly, additional time is given for bubble growth and reordering by gas diffusion. This leads to large bubbles in the matrix which are again local stress concentrations. Large, long bubbles do form in the rise direction. This is predominant in the high wt% glass foams and may account for a higher degree of directional properties in these foams. A possible

remedy would be to catalyze these foams faster or preheat the fibers or the entire mixture before rise.

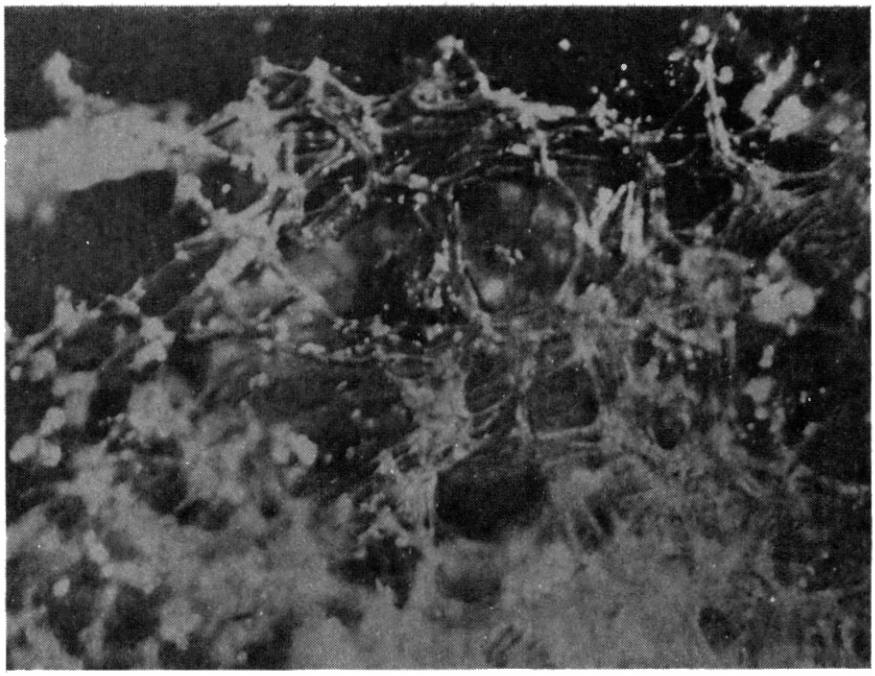

Figure 12. Filament Matting

The fracture of the foams may be followed by examining the local geometry and surfaces around a cell or several cells. Fiber orientation, zones of strut failure, and the relation between cell window rupture and strut failure will provide information as to how the fibers alter the matrix fracture. Since the system is limited by the matrix, fracture will always occur and propagate through the matrix.

Bundle reinforced foam absorbed the most energy. The fracture surface was the most jagged and corresponds well to increased toughness.

Loading causes failure by starting with a local stress concentration which is probably due to rupture of a cell window. That ruptured window will notch two adjacent struts which, unless constrained, will break. This causes four more windows to rupture and four more struts to notch. This continues until the crack locally runs up to a fiber. The fiber then accepts the load and stresses every cell along its length. More load will cause these cells to rupture in shear and so pull the fiber from the matrix. This forms so-called "pull out fragments." When one fiber relieves its load, then at least one more should pick up that load or the crack will continue to grow. When enough fibers in one area cease to support a load, then fracture will occur catastrophically since the stress is much higher than the brittle matrix alone can stand. The broken surface reveals that windows rupture perpendicular to the load direction and break straight across to the struts on either side (Figure 13). This is the same fracture initiating mechanism that occurs in the unreinforced samples. The bundles then do not alter the fracture process but divert the crack and cause more cells to be loaded without failure, causing both strength and stiffness to increase.

Filaments act similarly to the bundles because of their length, but may break if the crack reaches the fiber/resin interface. Fracture occurs in the same manner and again the cells break due to stress concentrations caused by window rupture (Figure 14). Windows in the filament reinforced foam as in the fiber bundle reinforced material and the control remain largely unaffected by the stress in a position remote from the fracture. Again the filaments divert the crack and promote strength by loading more cells.

Very short fibers appear to act differently in the matrix during

Figure 13. Fracture of Cell Windows (Control)

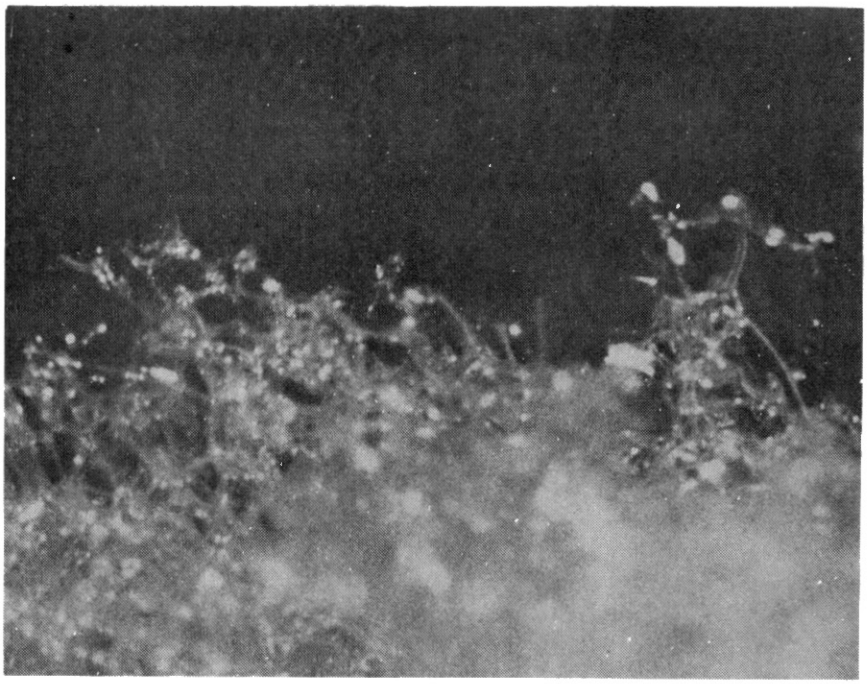

Figure 14. Fracture of Cell Windows (Filaments)

fracture than do either bundles or long filaments. The morphology of the short fiber foam is not drastically different from the control samples. The filaments cannot be detected under the zoom microscope except for isolated instances. The fracture surface is fairly flat as with the control, but a closer look reveals some basic differences. The windows on the fracture surface are no longer broken off straight from strut to strut. In some instances the window is pulled from the struts without fracturing the struts or is entirely gone (Figure 15). The windows in a position remote from the interface show some damage due to wrinkling which comes from shear on the cells (Figure 16). The crack proceeds into the cell by breaking a strut notched by a previous crack and splitting the window in several directions (Figure 17). This diverts the crack by forcing the most highly stressed point in the cell to rupture. The fibers then are constraining window deflection and thus rupture. More load is absorbed due to more cells under stress simultaneously. More cells are stressed due to stiffened struts by short fibers and a more ordered cell geometry. This prolongs window fracture by depending more on bending and axial stiffness in the struts to lessen the material deflection. Less deflection means lower window stresses and higher loads. Final fracture would occur when a local member broke, leading to a local stress concentration and sudden fracture.

All of the data acquired are used to show an increase in mechanical properties. The results are affected by the quality of the apparatus. The grips contributed to some disorienting answers. The ASTM grips had two drawbacks: first, the edge on the small hole should be blunted or pounded so as not to cause a local stress concentration; second, the beveled grips allowed an elongation along more than the gage length which

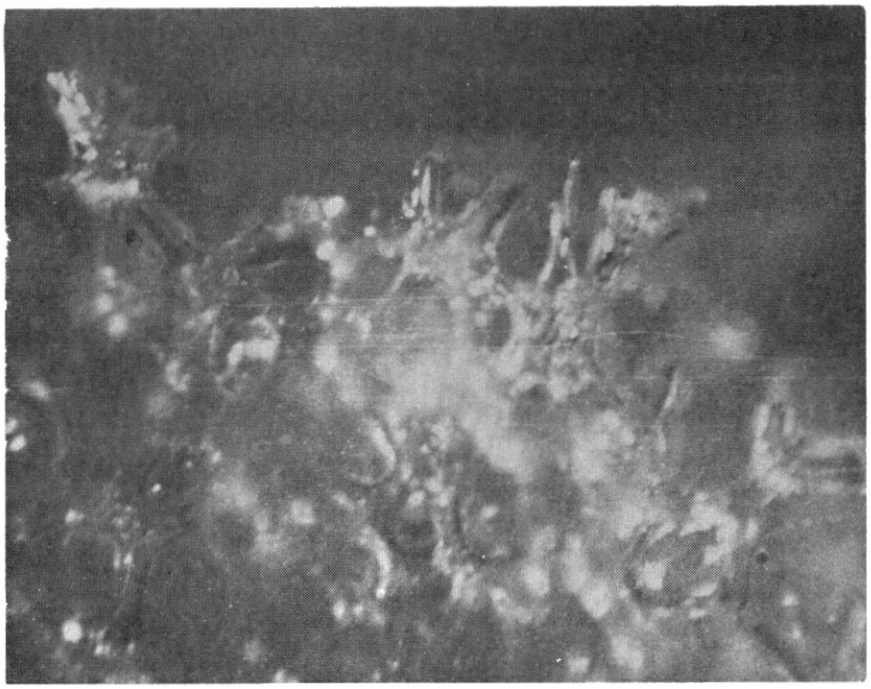

Figure 15. Very Short Fiber--No Windows

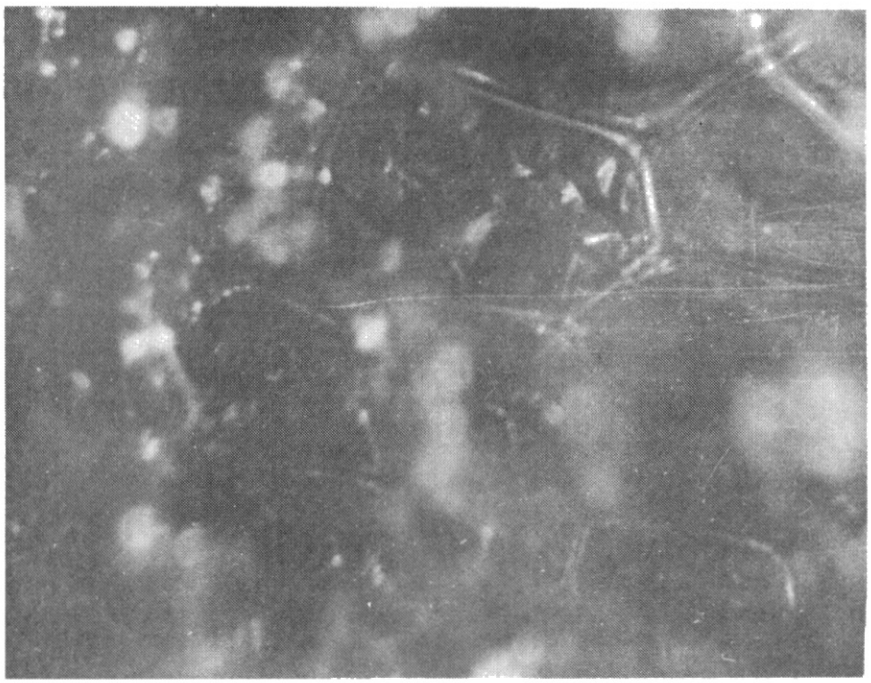

Figure 16. Very Short Fiber--Warped Windows

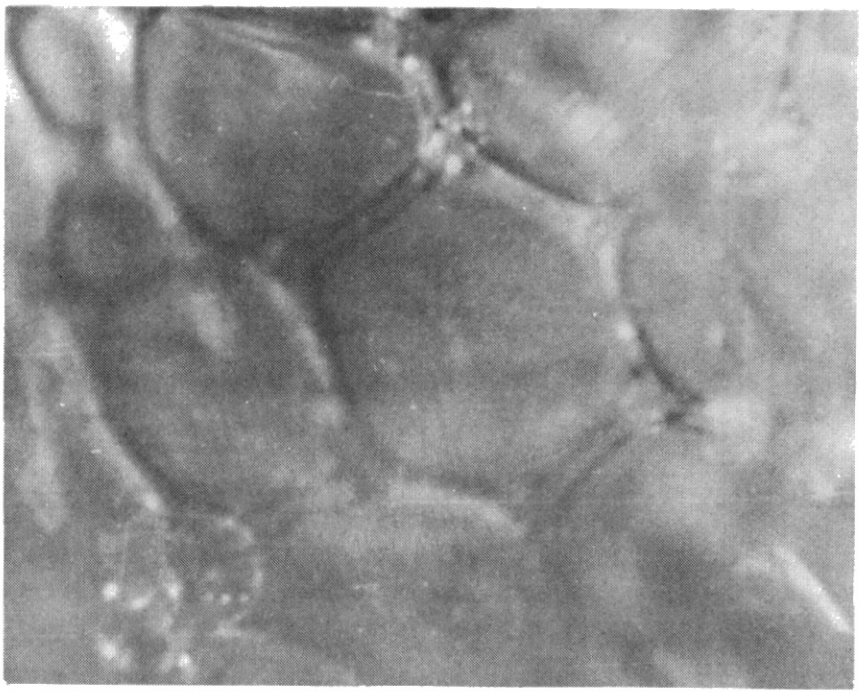

Figure 17. Very Short Fiber--Crack in Window

may have given misleading answers. The "I" specimen grips gave better constraint for stiffness calculations but square corners on the samples again caused local stress concentrations. The MTS gave outstanding linearity in loading but lacked sufficient resolution and stability due to electronic "noise" at high load cell bridge amplifications. Overall the results are believed to be adequate at least for comparison.

CHAPTER V

SUMMARY AND CONCLUSIONS

A material was produced from a theory concerning the reinforcement of a cellular plastic matrix by use of short chopped glass fibers. The theory was proposed after examining the literature to discern the action of glass fibers in a plastic foam. Theory supposed that by including filaments into a cellular plastic matrix such that each strut in the finished product was reinforced by a fiber, that the mechanical properties would improve due to alteration of the basic fracture mechanism. A second mechanism expected was the diversion of the crack due to split windows to other stress areas instead of fracture through the strut at the notch. Samples were prepared and tests performed to determine the changes in mechanical properties. Morphology was studied to determine the alteration of the fracture characteristics of the material.

The weight percentage of fiber loading is limited by efficient dispersion into the matrix. Matting results from fiber interaction in the liquid resin and continues during foam rise and matrix polymerization. Morphology shows the results and tensile tests demonstrate its effect.

The method of inclusion of the fibers into the matrix affects the morphology by reorganizing cells during rise and absorbing heat during set. The fibers constrain cell reordering by inhibiting bubble movement and by absorbing heat, possibly allowing additional time for gas diffusion and bubble growth.

Fibers affect the ultimate strength and stiffness by causing cell reordering during formation and by causing more cells to be stressed during loading. Long filaments form composite struts and load the cells along its length. Very short fibers increase bending and axial stiffness.

Long fibers modify the fracture mechanism by diverting the crack around the element. Very short fibers change the fracture process by prolonging window splitting due to an increase in local stiffness and apparently diverting the crack to the weakest point in the cell.

For any future study into this area it is suggested that efforts be concentrated on two basic areas to start with. First, the mechanism of fiber dispersion into the matrix should be investigated to bring about more uniform properties. Second, the effects of fiber length on the orientation and morphology of the foam should be studied.

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