High cycle tensile fatigue of unidirectional fiberglass composite tested at high frequency
by Richard Francis Creed, Jr

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Chemical Engineering
Montana State University

Abstract:
This thesis is part of a more general study of high cycle fatigue resistance of composite materials for use in wind turbine blades. Wind turbine blades experience roughly 10^8 to 10^9 significant loading-unloading fatigue cycles in their 20 to 30 year lifetime. This number of fatigue cycles would require 100 to 1000 days for a single fatigue test using a typical test frequency of 10 Hz. (cycles per second). Frequency limitations with conventional composite fatigue tests derive from hysteretie heating and poor thermal conductivity. The objectives of this research were to develop a test method for unidirectional fiberglass composites which would allow testing at a frequency of up to 100 Hz, and to obtain tensile fatigue (R=0.1) data beyond 10^8 cycles.

Attempts were made to develop a very small specimen while maintaining the fundamental material properties in order to improve the heat transfer. By modelling the heat transfer in a finite element analysis, it was shown that the thin specimens used in this study should not generate significant heating. This was confirmed by surface temperature measurements. Stress distributions in the specimen tab area were also analyzed by finite element analysis.

Fatigue tests were run over a range of stresses and lifetimes out to 1.8 x 10^8 cycles at frequencies ranging from 30 to 100 Hz. The S/N data trend was consistent with standard coupon data tested at low frequency in the low to moderate cycle range. Direct comparisons of 75 and 10 Hz tests show a slightly longer average lifetime at 10 Hz. The high cycle data indicate a less-steep S/N trend at higher cycles than is commonly observed in low to moderate cycle data sets for fiberglass materials.

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APPROVAL

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Richard Francis Creed, Jr.

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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Date March 29, 1993

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ABSTRACT

This thesis is part of a more general study of high cycle fatigue resistance of composite materials for use in wind turbine blades. Wind turbine blades experience roughly 10^8 to 10^9 significant loading-unloading fatigue cycles in their 20 to 30 year lifetime. This number of fatigue cycles would require 100 to 1000 days for a single fatigue test using a typical test frequency of 10 Hz (cycles per second). Frequency limitations with conventional composite fatigue tests derive from hysteretic heating and poor thermal conductivity. The objectives of this research were to develop a test method for unidirectional fiberglass composites which would allow testing at a frequency of up to 100 Hz, and to obtain tensile fatigue (R=0.1) data beyond 10^8 cycles.

Attempts were made to develop a very small specimen while maintaining the fundamental material properties in order to improve the heat transfer. By modelling the heat transfer in a finite element analysis, it was shown that the thin specimens used in this study should not generate significant heating. This was confirmed by surface temperature measurements. Stress distributions in the specimen tab area were also analyzed by finite element analysis.

Fatigue tests were run over a range of stresses and lifetimes out to 1.8 x 10^8 cycles at frequencies ranging from 30 to 100 Hz. The S/N data trend was consistent with standard coupon data tested at low frequency in the low to moderate cycle range. Direct comparisons of 75 and 10 Hz tests show a slightly longer average lifetime at 10 Hz. The high cycle data indicate a less-steep S/N trend at higher cycles than is commonly observed in low to moderate cycle data sets for fiberglass materials.

CHAPTER ONE

INTRODUCTION

Fatigue in windmill blade materials is an important design consideration which has been based on an inadequate data base to date. The primary reason fatigue is so important with windmill materials is that each time a blade passes the tower, there is a lull in the wind and the blade flexes. Since a windmill usually operates at between one and three revolutions per second, the materials in the blade may see thirty million significant fatigue cycles each year, and in the twenty to thirty year lifetime they may see between one hundred and nine hundred million cycles. Catastrophic service failures early in the expected lifetime were not uncommon with many earlier blade designs [1].

Much of the previous research done in the area of glass reinforced polymers (GRP) under fatigue loading was only carried out to moderate numbers of cycles. There is a clear need for fatigue data in the 10^8 to 10^9 cycle range experienced by blades over their 20 to 30 year lifetime. Existing fatigue test methods for fiberglass have been limited to the 10 to 20 Hz range because of hysteretic heating and poor thermal conductivity, which overheat the material [2]. At 10 Hz, 10^8 cycles in a single test would take about 100 days, and is , therefore, impractical. The objectives of this study were to develop a test method for tensile fatigue of unidirectional fiberglass which would allow testing in the range of 100 Hz, and to obtain data beyond 10^8 cycles. The approach was to use a small enough volume of material so that heat could be rapidly dissipated, while still maintaining the behavior of larger volumes.

CHAPTER TWO

BACKGROUND

Review of General Composite Fatigue Testing

The basic principle behind any cycle dependent behavior is that nonconservative changes occur in internal nature or geometry due to the loading history. In general, this implies that some of the energy introduced into a system is not stored as strain energy, but dissipated as any number of possible events, such as crack formation, heat loss, stress-corrosion, etc. [3].

Many early investigators of the fatigue of composite materials experimented with polyester reinforced with chopped strand E-glass mat. Owen and Dukes [4] performed many cyclic tests on this material, and proposed several mechanisms for failure. The first damage mechanism was debonding, initially of the fibers lying normal to the tensile stress. The next mechanism was the initiation of cracking in resin rich areas. The third and final mechanism was fiber failure, and separation into two pieces. Each of these mechanisms occurred upon higher stress or increased cycles.

Many of the investigations into unidirectional fiberglass fatigue ended without testing beyond one million cycles. Dharan [5] performed an investigation of unidirectional fiberglass and described the failure mechanisms in three regions. The first region was dominated by fiber catastrophic failure, and usually occurred up to two hundred cycles with a corresponding high stress. Region II was once again dominated by fiber failure, but the broken fibers were far enough apart that failure was not immediate. These breaks were initiated by cracks in the matrix emanating from the surface. At later stages of Region II, the crack was said to follow the along the interface between fiber and matrix. The third region, which was beyond one million cycles, had no fiber failures. Dharan concluded that the stress level was below that which would be required to propagate a crack since the glass fiber stress corrosion mechanism requires a minimum stress, below which the crack tip radius in glass increases. This increase in crack tip radius results in little further crack growth [6]. Dharan discontinued testing at two million cycles because of this hypothesis.

Defining failure in a fatigue test is somewhat ambiguous. Many researchers consider that the specimen has failed when there are two pieces; others define failure as when there has been a degradation of modulus, or stiffness, to a percentage of the original value [7,8,9]. In windmill applications, a loss of modulus above a particular value will allow the blade to have a much greater flex than originally expected and may allow the blade to hit the tower.

Fundamental testing of fatigue in GRP has been concentrated on laminates made from different fabrics and matrices. Fabrics can be made from chopped strands with random orientation or axial fibers stitched together with organic thread. Different matrices would include primarily epoxies, vinylesters, and polyesters for windmill applications. With a majority of laminates there are fibers in multidirectional arrays, a large portion of which are in the primary loading direction. Fibers in the other directions are for loads in other directions, but are responsible for damage initiation with loading along the primary axis. Fibers in the transverse direction act as stress concentrations in the very brittle matrix material. This causes the matrix in these layers to crack, and eventually cause damage in the axial layers which, in turn, will fail at some point. With the failure criterion of loss of stiffness, however, the material may be considered failed when the transverse layers fail [6].

Owen and Dukes performed many tests on chopped strand mat impregnated with polyester resin. Upon static and fatigue testing, damage was apparent at only thirty per cent of the ultimate strength of the material. This damage was associated with fibers perpendicular to the loading direction, and was initiated at many points on the strands.

At a load of twenty percent of the ultimate strength, damage was found along the interface between fibers and matrix at only one thousand cycles. The laminate could be expected to survive at least one million cycles before breaking into two pieces even though damage had begun two orders of magnitude of cycles earlier [4].

The effect of matrix on the fatigue strength of a composite has been described by Broutman and Sahu [10]. They concluded that epoxies had the best properties for high cycle low stress fatigue, and phenolics had the best properties for short term high stress tests. Polyester matrix materials started out with properties between phenolic and epoxy, but dropped off rapidly. For long life tests, polyester had slightly lower properties than phenolics, but much lower than epoxide materials [10].

Determinations of residual (remaining) strength at different stages of fatigue lifetime were performed by Broutman and Sahu [10]. The strength of a GRP decreases with increasing cycles, although there is much associated scatter. The methodology for determining the decrease in residual strength was to initially determine the stress versus number of cycles (S/N) curve for crossplied prepreg laminate. Based on expected lifetimes, for particular load levels, specimens were fatigued to percentages of that lifetime and then broken. Plots of number of cycles versus residual strength for different fatigue load levels were reported. At higher load levels the ultimate strength tends to drop off rapidly, but at low load levels the strength tends to remain almost constant. Unfortunately, the report does not show the strength of the low stress specimens at high cycles [10]. Similar work was done by Rotem [11] who developed a mathematical model for predicting residual strength from cumulative fatigue theory. Resulting calculations show that the degradation of residual strength only occurs near the end of the fatigue life. Experimental results from Rotem [11] and Broutman and Sahu [10] show that the model closely predicts actual behavior.

Reifsnider *et al* [3] reported extensive research with unidirectional carbon fiber/epoxy laminates with 0, 90, and ± 45 degree plies. By utilizing light microscopy and edge replications, characterization of damage processes within laminates has been possible. Initially, cracks occur in the matrix of the off-axis plies either in the matrix material, or more commonly, in the interface between fiber and matrix. This is commonly called interfacial debonding. These initial cracks form and meet axial plies and eventually begin to cause damage in these main load bearing plies. This damage comes in the form of broken fibers and delamination. At some point, the amount of damage in the laminate tends to level off for a period of time. This area is called the Characteristic Damage State (CDS). Up to this point, the amount of stress necessary to cause localized cracking has been enough to cause cracks spaced far apart in a ply. At a transverse crack surface the stress in the axial (0°) direction is zero, building up to the overall applied stress some distance from the crack face. Eventually, the stress or cycles will increase to a level high enough to cause another crack in the off axis ply. At some point, there will be a saturation level of cracks because the stress level between cracks will not be able to reach a high enough value to cause further cracking. This state is the Characteristic Damage State as described above. Further cycling beyond this point will cause delamination and fiber failure in the axial plies, eventually generating total separation [3].

One interesting characteristic of composite materials is the ability to withstand a large amount of damage without a significant loss of strength. In some cases where the specimen has a flaw such as a hole in the center or a notch in the edge, the strength of the composite actually goes up after some cycles have been put on the specimen. Such an example was reported by Stinchcomb and Bakis [12]. In the case where a static test is performed on a composite specimen with a round hole machined through the center, failure occurs on a line across the center of the hole. The hole generates a stress concentration and damage begins at its edges. When a fatigue test is run on a similar specimen, cracks and delaminations occur in the region around the hole. This damage allows the stress to be redistributed around the hole, and consequently the specimen will have a higher static strength than one with no cycling. Although the static strength of the composite is improved with some damage from cyclic loading, the alteration of the stress field around the hole will eventually cause wear out of the specimen upon further cycling [12].

Much of the research covered thus far has considered matrix cracking as a primary concern in the fatigue of composite materials. Work by Mandell *et al* [13] has shown that the matrix has little effect on the fatigue sensitivity of fiber dominated GRP. When comparisons are made between the slope of maximum stress versus number of cycles (S/N) curves and corresponding single cycle strengths for different strength materials, fiber orientations, distribution of fibers, fiber length, and fiber content, the fatigue resistance seems to be insensitive to the listed factors. Typically, all types of glass fiber dominated composites, with the exception of woven fabric composites, tend to lose about ten percent of their initial strength per decade of cycles. This corresponds to a slope of negative one tenth on a normalized S/N curve for most E-glass reinforced composites [13].

Single strand tests were performed by Mandell *et al* both with and without matrix material, and the S/N curves for both were similar. This led to the conclusion that the fatigue behavior derives primarily from the reinforcement [13]. This conclusion derives from a comparison of the ratio of ultimate strength of many composite materials to the slope of their S/N curves. The slope of an S/N curve usually fits a linearized semi-logarithmic curve of the form [14]:

$$\frac{S}{S_0}=1-b\cdot(\log N) \qquad (1)$$

Where S is the maximum stress on each cycle and S_0 is the one-cycle (static) strength. This comparison was made for many different matrices and volume percent fibers, as well as for fibers alone, and always came out to be about b=0.1 [14].

Although the fibers provide the dominant factor in material properties as well as fatigue performance, other factors may play significant roles in the breakdown of the composite in fatigue. Several sources note a sudden drop in modulus with different fibers and matrices, mostly attributable to debonding of the fiber matrix interface and matrix cracking. A study of the flexural fatigue of unidirectional fiberglass by Shih and Ebert, run in stroke control, showed significant fiber/matrix cracking corresponding to a loss in stiffness. Since the tests were run in stroke control, any loss in stiffness results in a lower load on the specimen [15].

Review of Windmill Composite Material Fatigue

A great deal of research has been completed specifically for wind turbine applications of composites. The major concern, as has been stated previously, is the reduction in properties with continued cycling which has been the emphasis of a majority of the work.

One of the most complete studies was done by Bach [8]. Several types of tests were run including tension-tension (R = 0.1, where R = minimum stress/maximum stress), reverse loading (R = -1.0), and variable amplitude (WISPER, wind energy-specific load spectra) tests. Test specimens for the R = 0.1 tests were standard coupon sized specimens run at frequencies between 1 and 20 Hz and stresses between 35 and 65 percent of the ultimate strength of the unidirectional glass reinforced polyester. Conclusions from the tests were that a fatigue limit would only be reached in the range of fifteen percent of the ultimate strength and greater than one billion cycles. Another significant conclusion was that the data tended to follow a negative ten percent slope similar to that reported in other studies.

Appel and Olthoff [from Ref. 8] utilized this data to statistically arrive at a prediction for lifetime of composites. This prediction is a modification of that made by Mandell and includes the possibility of a fatigue limit (equation 2 [8]).

$$S_n=S_0(1-(0.15(1-\frac{signS_{\min}*|S_{\min}|}{signS_{\max}*|S_{\max}|})+0.08)\log N) \qquad (2)$$

Tabs on the specimens used by Bach were 50 mm by 25 mm by 1.5 mm and had an angle tapered toward the gauge section for the last 5 mm. The author noted that almost all the specimens began delamination at the point of contact with the tab which spread as failure was imminent [8].

Much of the work done on windmill materials has either been done with reverse loading of full blades or coupon sized specimens. Conclusions by Kensche and Kalkuhl [16] show that even in the reverse loading regime there appears to be no fatigue limit before 100 million cycles for either coupon tests or full scale tests. WISPER loading on spar beams indicated that local instabilities, such as buckling, are the cause of most failures. When these instabilities are constrained, a spar can withstand more than five hundred WISPER cycles equivalent to eighty years of service. This conclusion was based on maximum strain levels of 0.6 percent on the spar. These results imply that higher design limits are possible on large diameter blades, greater than 25 meters, and therefore lighter more economic blades can be utilized [17].

The European design criterion for blade certification has a limit of 0.3 percent strain in the tension zone and 0.2 percent strain in the compression zone. Much of the work done shows that these values are quite conservative and blades could be made much lighter and have adequate lifetimes to those made presently. Design criteria are often developed from laboratory scale testing which shows a large decrease in stiffness shortly before failure. Fatigue failure of larger components may not have this noticeable stiffness decrease, and therefore, failure prediction requires some method of inspection [18].

Recent studies reported by Mandell *et al* [19] on high cycle fatigue of windmill blade materials have led to several conclusions. Uniaxially reinforced materials were found to have an S/N data trend falling below the 10 percent loss of static strength per decade of cycles at high stresses expected from previous studies. The trend followed by the data is a power law with exponent of about m = 13.5.

$$\frac{S}{S_0} = N^{-(\frac{1}{m})} \tag{3}$$

Effects of specimen width were studied by a comparison of data for 1 and 2 in. wide specimens. The study reported similar lifetimes at similar stress levels for the different width coupons. Specimens used in testing usually are machined and, therefore, have free (cut) edges. To study the effects of free edges, standard size specimens machined from sheets of material were tested and compared to specimens molded 2 in. wide, with reinforcement wrapped around at the edges. The resulting S/N data trend showed little or no effect of the free edges. Comparisons of specimens with similar reinforcement but different matrix materials (polyester or vinylester) revealed that the matrix has little effect in overall composite lifetime. However, vinylester composites tend to have slightly higher static strength [19].

Effects of Frequency on Fatigue

Effects of testing frequency on fatigue have been studied for many types of chopped strand fiber composites with the following areas of concern: hysteretic heating, rate of damage generation, and strain rate effects on the residual strength on the last cycle [20].

Hysteretic heating is the greatest problem with obtaining high cycle fatigue data for fiber reinforced plastics. The heat transfer within the plastic is very poor and even small amounts of strain energy absorbed in cycling can build up and cause the plastic to fail. To determine the amount of hysteresis for a particular stress level, one method is to find the loss factor (η), sometimes referred to as the tangent decrement. The loss factor can be arrived at experimentally with the use of a torsion pendulum and equation 4 [21]:

$$\eta = \frac{\ln \frac{A_n}{A_{n+1}}}{\pi} \tag{4}$$

where A_n and A_{n+1} are amplitudes of successive cycles [21].

Relating the loss factor to the amount of energy dissipated in one cycle is done with equation 5 [22]:

$$D_s = 2\pi Q\,\eta \qquad (5)$$

where D_s is the strain energy at the maximum displacement and Q is the heat generation. Gibson [22] has shown that PPG SMC-65 has a constant loss factor over the frequency range from 10 to 1000 hertz and typically falls around 0.01.

Although frequency does not play a role in the loss factor, the amplitude of the input wave does. Kensche [17] has shown that η decreases nonlinearly with decreasing amplitude. The results show a drop of about a factor of two in the loss factor with a drop in amplitude of about twenty to thirty percent for many specimens.

Frequency effects other than from hysteretic heating are small. Glass fibers and polymeric matrices can show significant effects of constant load (static) fatigue, and it has been shown that time at maximum load causes much higher damage than the strain rate used in reaching that load [20,23]. However, fatigue behavior tends to be most influenced by the number of cycles not the frequency of cycling, particularly at high cycles [20,21].

CHAPTER THREE

EQUIPMENT AND MATERIALS

Test Facility

The procedure used for fatigue testing of E-glass unidirectionally reinforced polyester is similar to that of testing larger coupons, but on a smaller scale. Fatigue testing was done on a servohydrolic Instron Model 8511 with a load capacity of 2248 pounds force. The machine is controlled by an Instron Model 8500 controller and computer software. This low force machine is designed for high frequency testing, with low friction bearings, a hydraulic supply of 20 gallons per minute, a ten gallon per minute servovalve, and a system pressure of 3000 psi. Figure 1 is a photograph of the Instron 8511.

The specimens were clamped into the load train by grips developed in this study (see Figure 22 in Appendix C). Gripping force is provided by four screws tightened to 10 in.-lbf. torque. Force and displacement were measured by a load cell, -5000 to 5000 pounds force capacity, and an LVDT (linear variable displacement transducer) respectively. An oscilloscope was used to define waveform quality at different frequencies. Specimen surface temperature was measured with Omega Templaq liquid crystal paints.

All tests were run in load control with a constant sine

Figure 1. Photograph of Instron 8511.

wave input. The loading rate (maximum load/time to maximum load) was generally held constant between load levels by varying test frequency. Loading rate was varied somewhat because some testing frequencies gave poor waveforms and either speeding up or slowing down gave much better waveforms. Typical loading rates were between 8000 and 15000 pounds per second. The value chosen for single cycle tests was 4000 pounds per second, which was between one half and one third of the cyclic loading rate, in order to take many data points on a stress-strain curve. With higher loading rates, the stress-strain curve would be based on only a few points. This difference in loading rate should not significantly affect results [21].

All tests were conducted in ambient laboratory air. These ambient conditions are generally low humidity with temperatures between 65° and 80° F.

Materials

Raw materials were supplied by Phoenix Industries, and consisted of Manville Star Rove 502 EA glass fiber roving, one-quarter in. wide, and slow set orthopthalic polyester. Properties supplied by the manufacturer of the polyester are as follows: 0.68 msi modulus, 8.5 ksi ultimate tensile strength, and 1.10 g/cm^3. Figure 2 is a photograph of the glass roving showing the inherent fiber misalignment. The specimens were made in the laboratory by applying enough

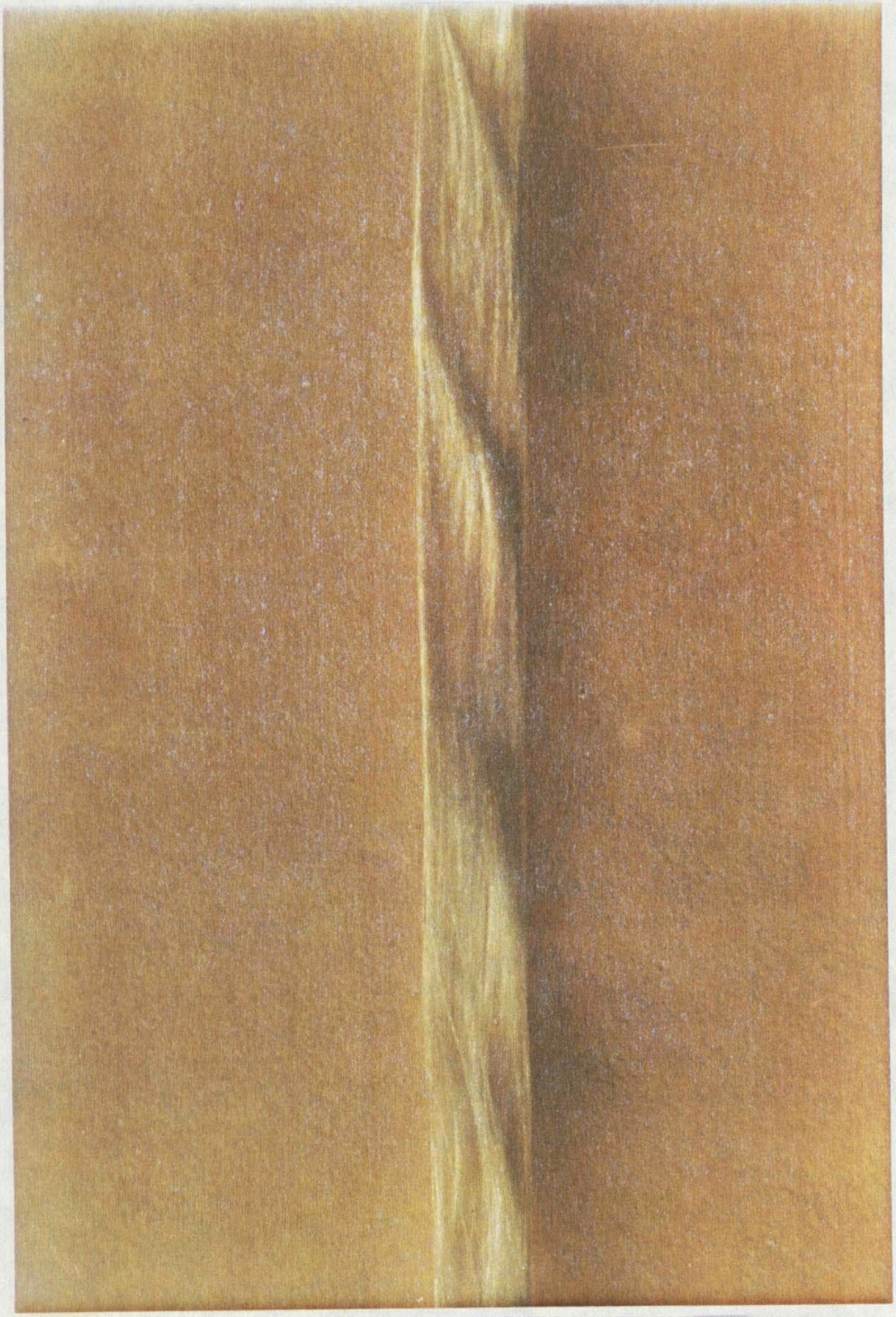

Figure 2. Photograph of Manville Star Rov 502 EA unidirectional E-glass roving.

tension to the glass fibers that they remain tight and impregnating them with the catalyzed polyester. Then, when the fiber/matrix combination became tacky, the composite was pressed between rubber sheets and cured for 24 hr. at 140° F. This gave a flat sample with parallel faces in the width direction. These samples, approximately 0.25 in. by 0.017 in. by 12 in., were then cut into 2.5 in. lengths. The fiber content of the specimens was between 45 % and 52 % by volume calculated from weight percent values and densities. The strength of the specimens was experimentally determined at 94,200 ± 4100 psi with a Young's modulus of 5 msi.

To prepare the test specimen tabs (Figure 3 shows an exaggerated cross section of tab area and dimensions of specimen), a single layer of 3M SP-250E unidirectional E-glass prepreg was cured into a flat sheet and cut into pieces 0.25 in. by 0.75 in. by 0.02 in., with the fibers in the long direction. These were used as the first layer of the tab. Each specimen had four of these prepreg pieces, one on both sides of both ends, bonded on with Hysol 9309.2 NA high toughness epoxy. The method of keeping the prepreg fibers aligned with the specimen fibers was to put the specimens between rubber sheets and apply roughly 0.5 psi over the entire surface. The prepreg pieces tend to slip out of alignment with other assembly methods. The last part of the tabbing procedure was to again use Hysol 9309.2 NA to bond on a relatively thick piece of 0/90 glass reinforced

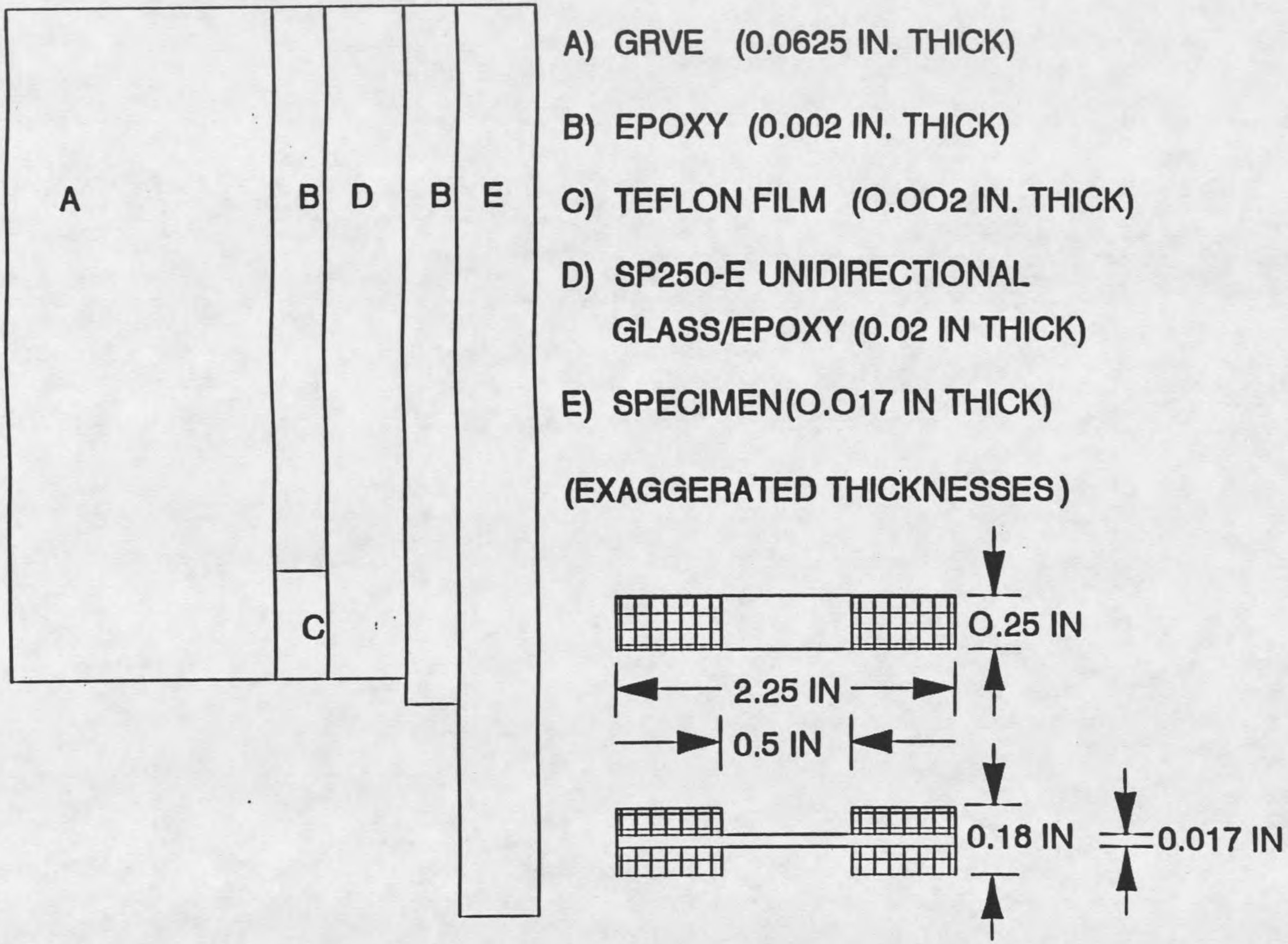

Figure 3. Schematic of tabbing for test specimen.

vinyl ester (GRVE) 0.0625 in. by 0.25 in. by 0.75 in. on both sides of each end (this is unpunched electrical vectorboard obtained from Plastifab inc.). Between the SP250-E and the GRVE, a 0.125 in. wide layer of teflon film was added on the gauge end of the tab (Figure 3). After each layer was added, a curing period of 24 hr. at 140° F. was necessary to cure the adhesive.

The specimen was then placed in the grips so that the top of each tab was flush with the grip. Alignment was achieved by marking the center of the specimen and lining this up with the vertical center lines on the grips. Some fiber misalignment is inherent in the material, causing waviness to the specimen, but care was taken to reduce misalignment to a minimum.

Several other tabbing arrangements were attempted, with generally poor results. These are discussed in Appendix A.

CHAPTER FOUR

RESULTS AND DISCUSSION

Finite Element Analysis

Modelling of the specimen for stress analysis and heat transfer was done with a commercial software package, COSMOS/M version 1.65. The elements used in both cases were plane two dimensional (plane2d) elements. These are four node, two dimensional linear displacement elements. The following material properties were used:

Table 1. Summary of Material Properties.

MATERIAL	E_L 10^6 psi	E_T 10^6psi	ν_{LT}	G_{LT} 10^5	K_{ALL} $\frac{10^{-6} BTU}{in^2 * \sec * ^\circ F}$
Specimen [24,*]	5.0	1.3	0.25	7.0	2.4 [25]
SP250E [26]	6.0	1.5	0.25	8.5	1.5 [25]
0/90 Vinyl Ester [24]	1.5	1.5	0.3	6.0	1.5 [25]
Epoxy [27]	0.35	3.5	0.35	1.0	N/A
Teflon [27]	0.08	0.08	0.35	0.25	N/A

* Experimental results, E_L: Longitudinal Elastic Modulus; E_T: Transverse Elastic Modulus; ν_{LT}: Poison's Ratio; G_{LT}: Dynamic Modulus; K_{All}: Thermal Conductivity

Two types of analysis were necessary to qualify the specimen geometry. First, the specimen had to be analyzed for stress concentration near the tab. There is likely to be some stress concentration in the axial direction where the tab meets the specimen, and finite element analysis can show the approximate size and shape of the affected area. One quarter of the specimen was modelled utilizing symmetry boundary conditions on the specimen mid-length and mid-thickness. Other boundary conditions used in the model were translation in the Y-direction on the tab edge, a pressure of 50 psi on the tab, and a pressure of 10000 psi in the X-direction on the end of the specimen. Figure 4 shows the boundary conditions and the specimen geometry. The epoxy layer thickness was obtained from approximating the thinnest film between an average specimen and its tab, as can be seen in Figure 5.

The results from the analysis show a maximum stress about 0.001 in. (two fiber diameters) in from the edge at the point of contact with the tab material. Figure 6 is the output from Cosmos/m zoomed in on the point of interest, also showing the element mesh. The stress at this point is calculated at about 18 percent higher than the axial stress. However, this may be higher than the actual stress in the material because the specimen has discrete fiber and matrix regions which will tend to spread out the stress transfer. Discrete fibers and matrix could not reasonably be modelled

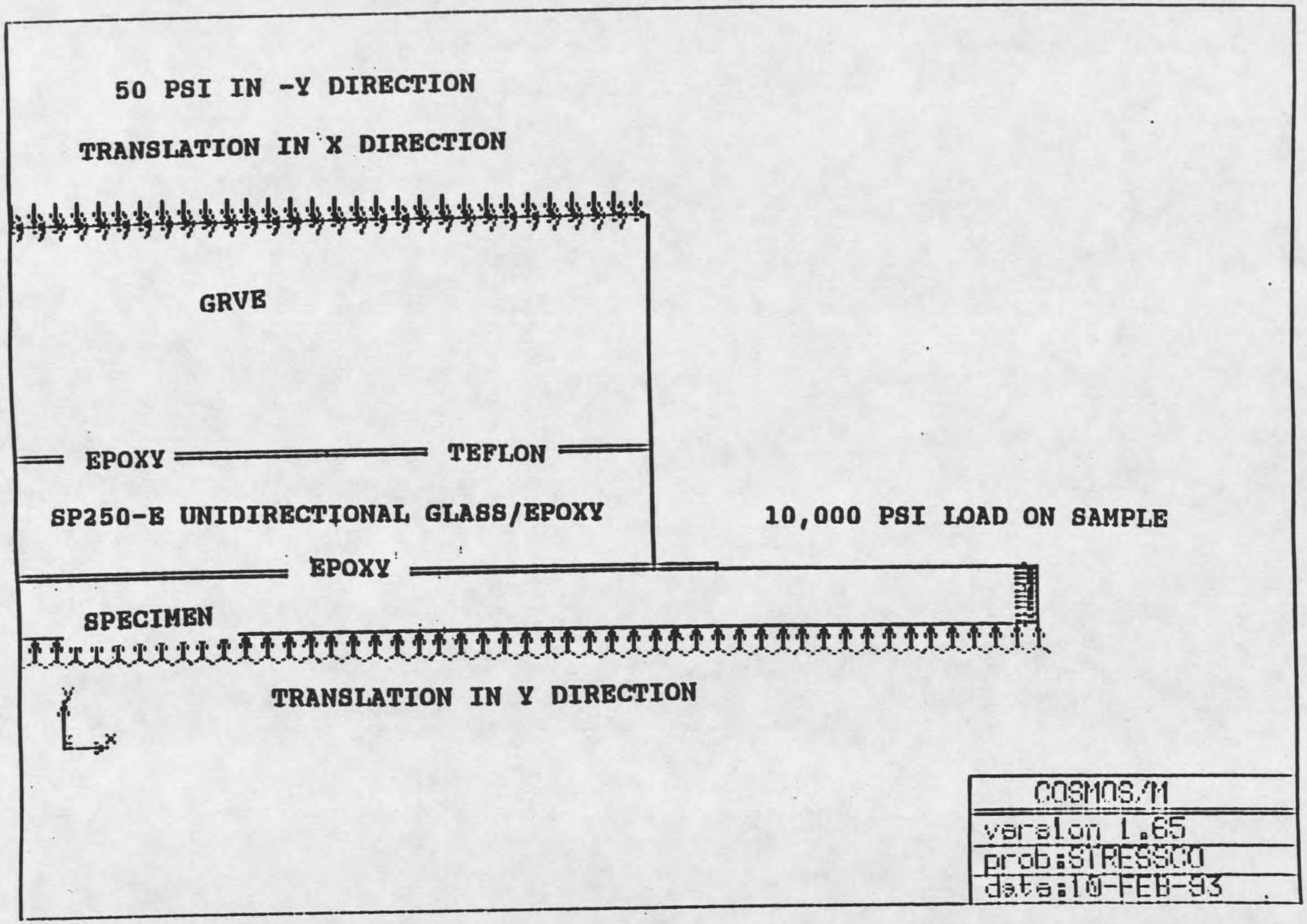

Figure 4. Boundary conditions for FEA of stress concentration.

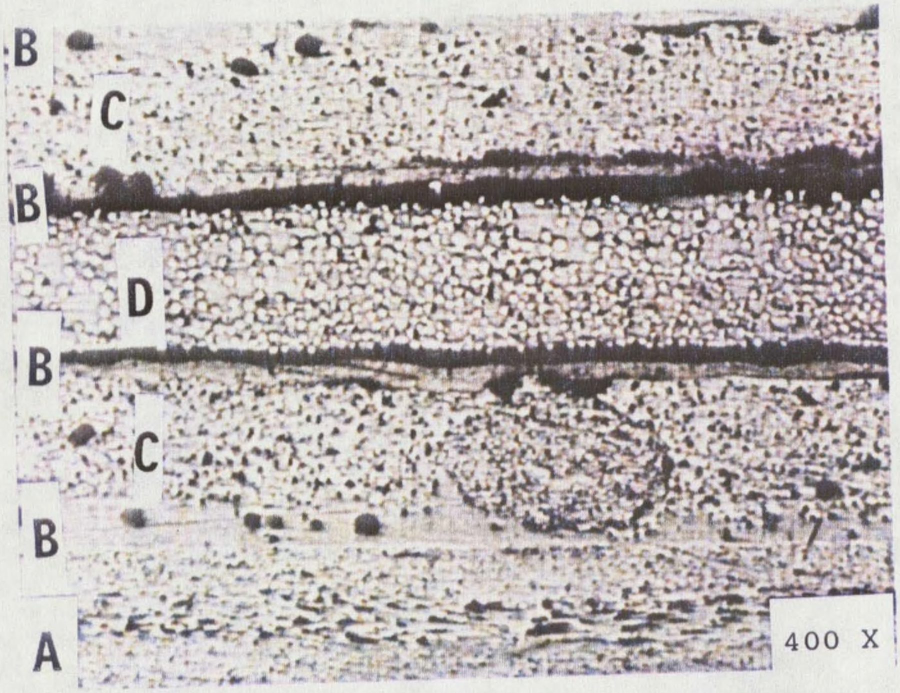

Figure 5. Micrograph of specimen and tabbing, end view, A is GRVE, B is epoxy, C is SP250E, and D is the specimen.

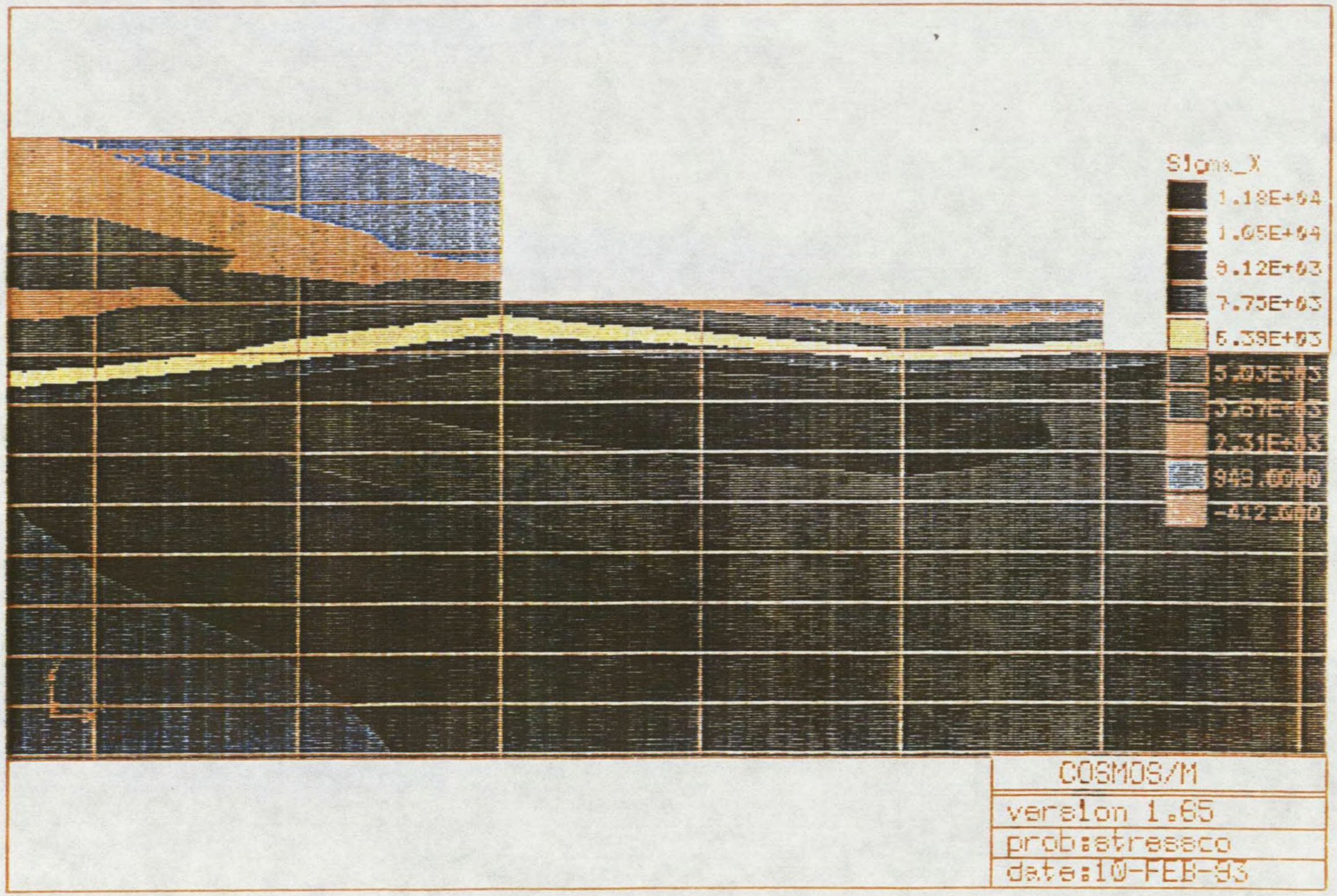

Figure 6. FEA results showing mesh and stress concentration near the tab (close up).

within the scope of this study. Figure 7 is of a larger portion of the specimen (with mesh), showing the stress dropping off inside the tab region. Some concentration of stress at the intersection of two materials is almost unavoidable. However, combined with the observation that specimens appear not to break in the tab region on every test (discussed later), the low level of stress concentration is considered to be acceptable.

One question about the validity of the FEA solution was whether the Teflon should be "bonded" to the surfaces around it. In order to determine if this had an impact, the same model was run with very low properties (10 percent of the original values) for the Teflon. This would closely simulate a free surface without problems of materials overlapping in the results. The stress concentration at the tab/specimen intersection came out to be exactly the same as the above model. Thus, the Teflon may not be essential to the tab arrangement.

For comparison, a model of the same tab arrangement was performed with the same boundary conditions, but with no filet layer of epoxy at the surface of the specimen. The stress concentration is much higher in this case, sixty four percent higher than the applied stress as opposed to eighteen percent. Figure 8 shows the model geometry and the boundary conditions, and Figure 9 shows the stress concentration in the area of concern. This comparison shows

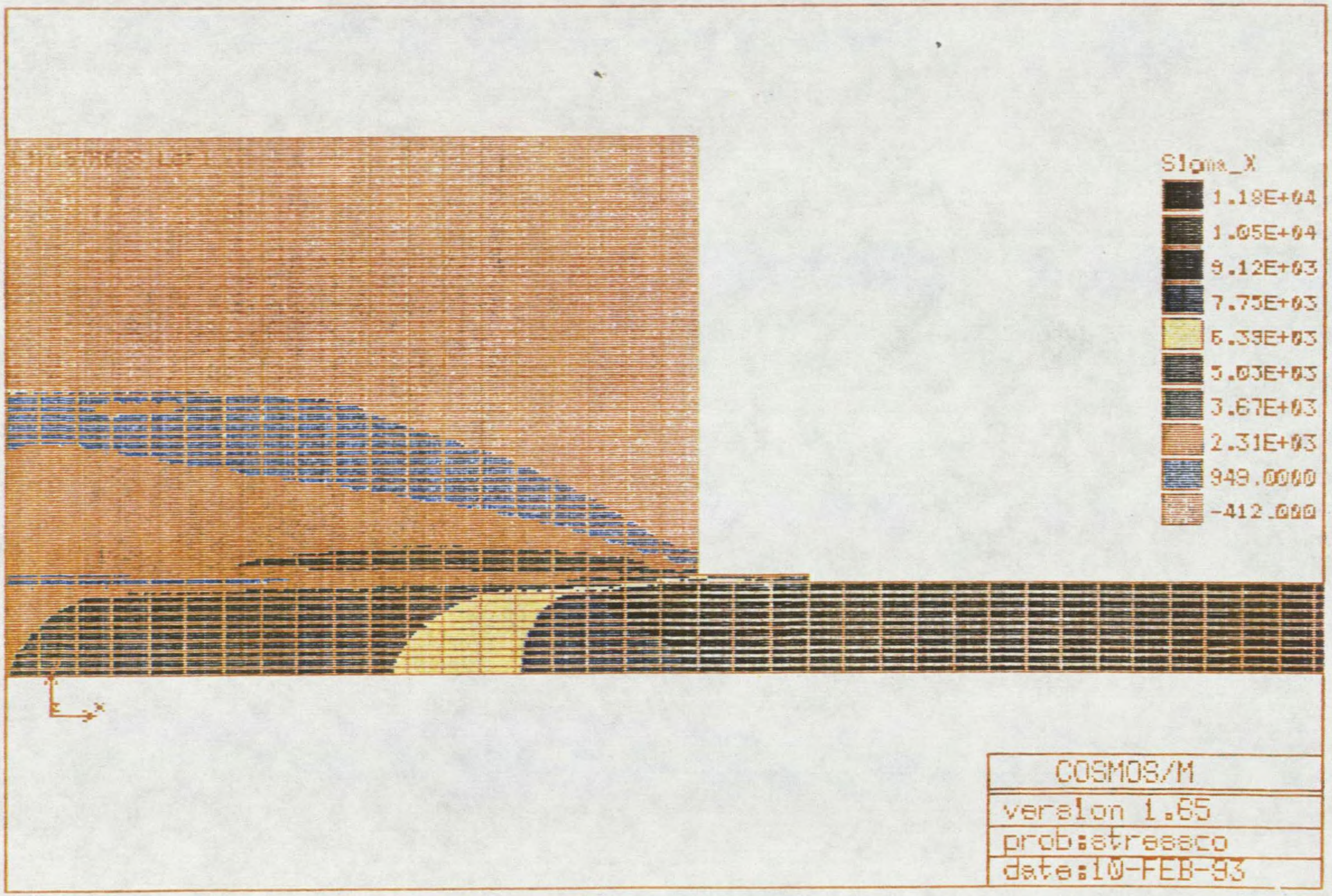

Figure 7. FEA results showing stress redistribution into the tab region.

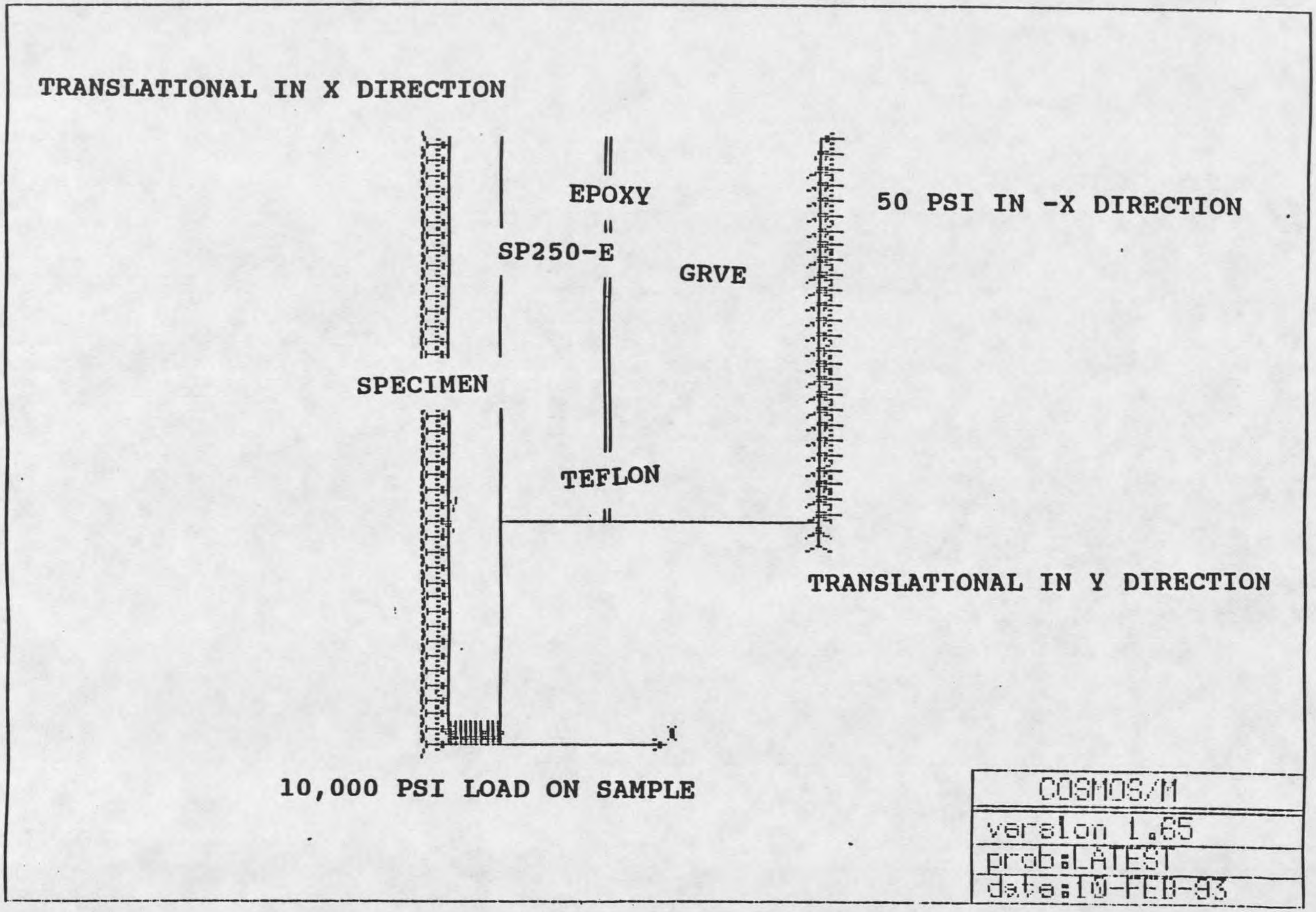

Figure 8. Boundary conditions for FEA of stress concentration with no epoxy layer next to the specimen.

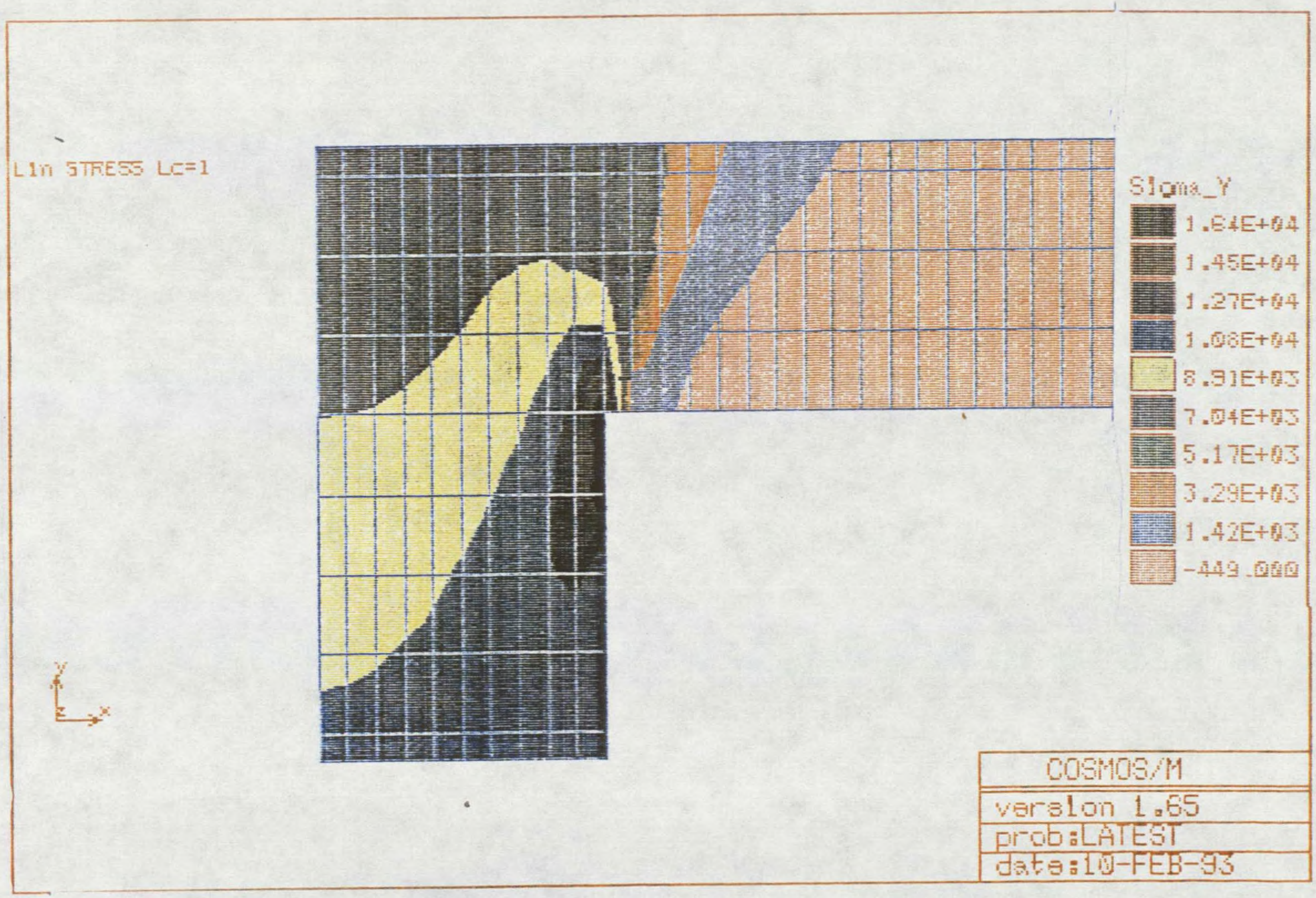

Figure 9. FEA results showing higher stress concentration with no epoxy layer next to the specimen.

that the thin layer of soft material makes a significant difference in the stress concentration. This would also probably be true if discrete fibers and matrix were modelled in the specimen.

The other finite element model was of the heat transfer in the specimen. The model is of a cross section in two dimensions, run for several thicknesses. Input variables were obtained as follows: the convection coefficient of air on the surface was obtained from Geankopolis [28], the heat transfer coefficient for polyester and vinylester matrix/ fiberglass was obtained from Reference [24], and the heat generation term is an order of magnitude approximation from a damping test and a computer program hysteresis analysis (see Appendix B for these tests).

The model of the actual specimen at 100 Hz with the best approximations of the constants gave a temperature plot that was between the limits of 71.0° F in the center (mid-thickness), and 70.8° on the surface. On the progressively thicker specimens, the temperature at the center increases, which is observed experimentally [2]. Figure 10 shows the results for the three different trials with the depth into each specimen normalized by its thickness. For a specimen that is 16 times as thick as the test specimen, under the same conditions, the center of the specimen is over 225° F. The temperature where polyester begins to yellow is near 175° F (experimentally determined), which is an indication

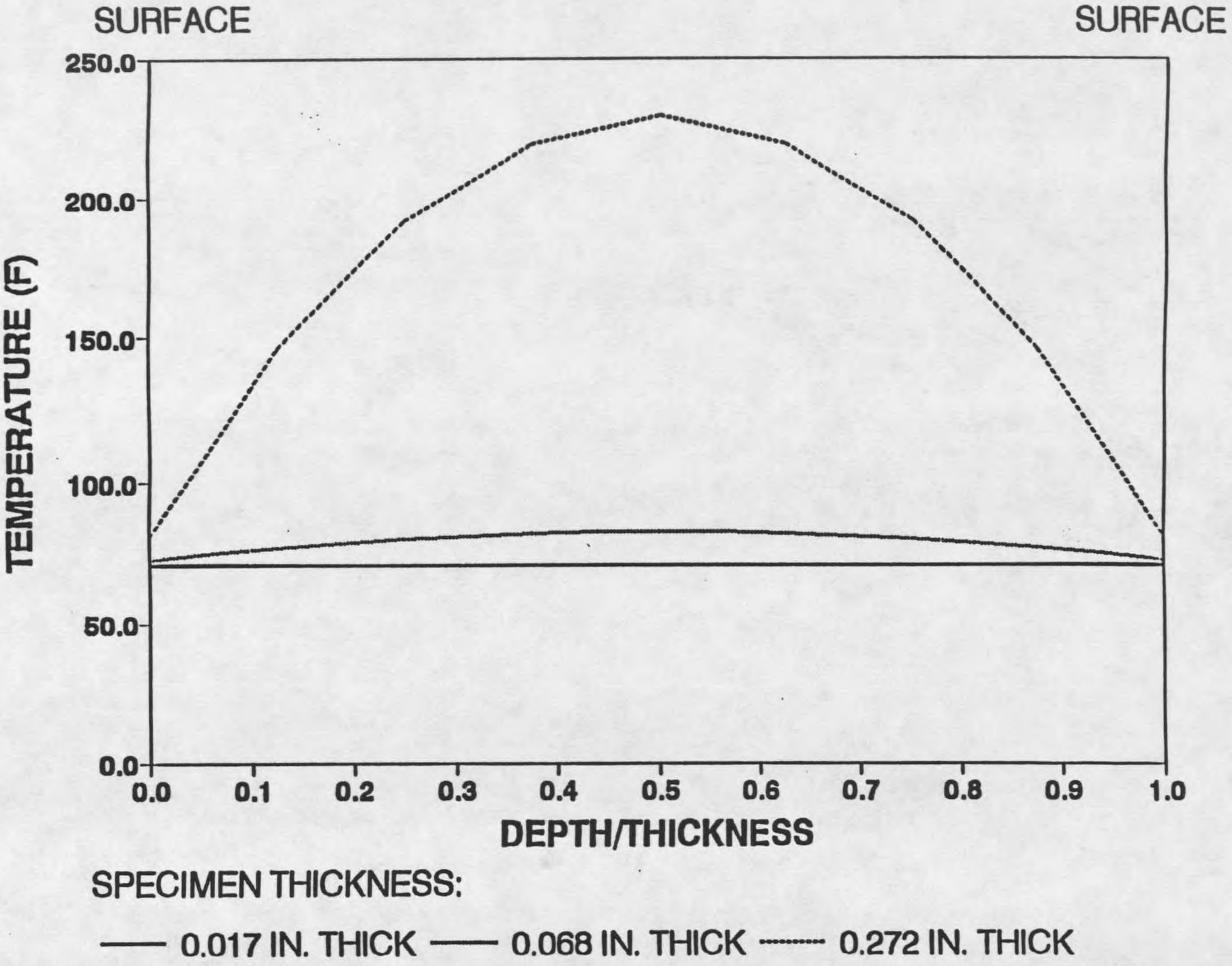

Figure 10. FEA heat transfer results of temperature versus normalized distance for progressively thicker specimens.

of damage. The following table shows the results of the finite element models:

Table 2. Summary of Finite Element Analysis of Heat Transfer, 100 Hz.

Model Name	Heat1	Heat2	Heat3
Thickness	0.0017 in.	0.068 in.	0.272 in.
Center Temp.	71.0° F	83.0° F	229° F
Surface Temp.	70.8° F	73.3° F	84.5° F

In order to model the worst case scenario, the model was expanded to involve the tab region and the change in heat generation with differing stresses. Hysteresis based heat generation is assumed to vary with the square of the stress level for most materials, so the stress at different points could be related to the amount of heat generation at a particular point. The regions of stress (from the stress analysis) were then scaled for the amount of heat generation and the analysis was run (Figure 11). The essential finding is that even though the amount of stress in the tab region goes up slightly and the effective thickness goes up significantly, there appears to be little added heating of the specimen.

Experimentally, the surface temperature was monitored during testing at up to 100 Hz by using Omega Templaq. The lowest temperature paint melts at 125° F, and was not observed melting on any specimen. This supports the results of the finite element analysis, and establishes the

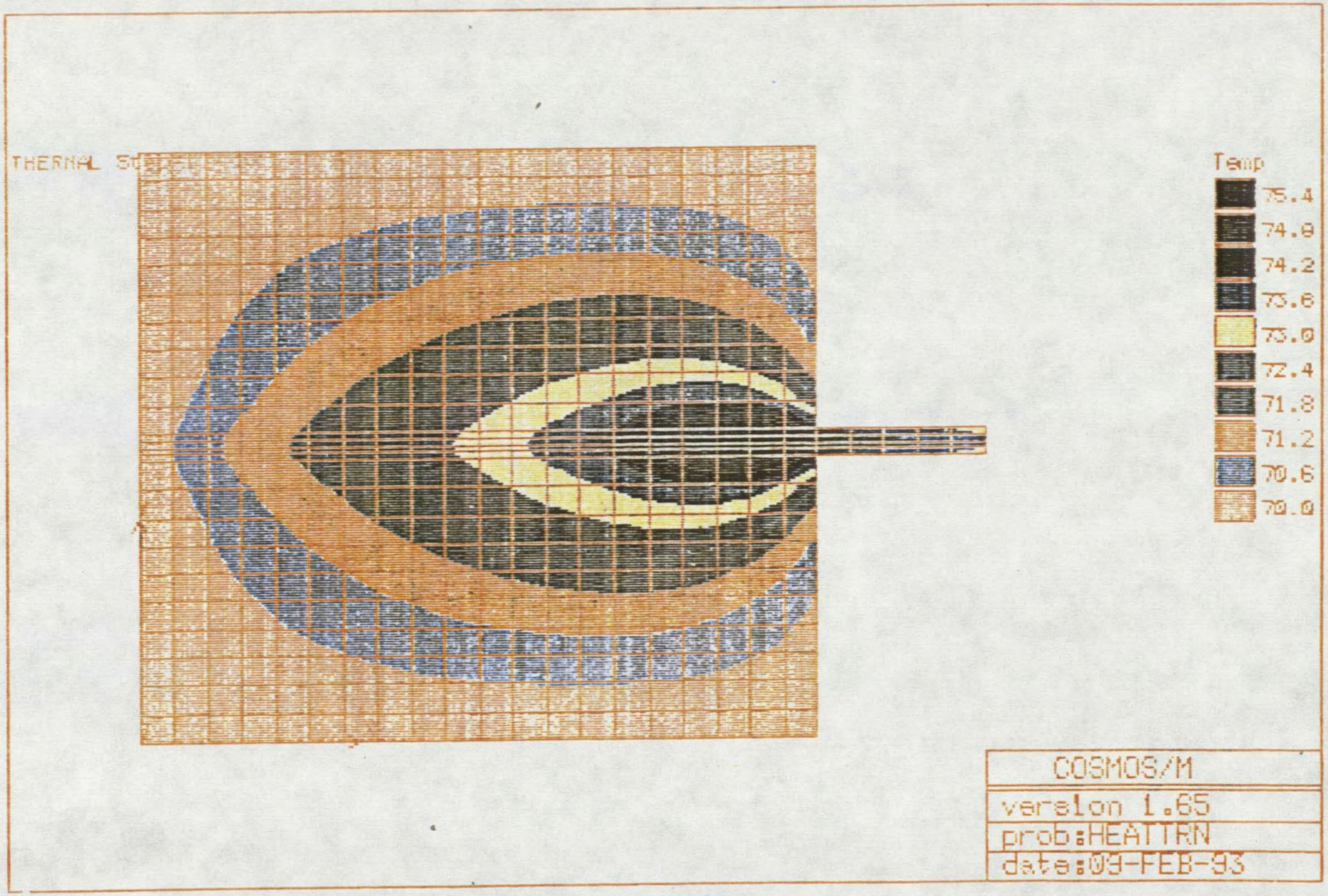

Figure 11. FEA heat transfer results showing heat dissipation into the tab region.

viability of the test method for high frequencies.

Stress Versus Number of Cycles Results

The maximum stress versus number of cycles to failure (S/N) data for the unidirectional E-glass/polyester composite are given in Figure 12. There are two trend lines for comparison. The linear equation, with a slope of ten percent of the one cycle strength per decade of cycles, has been shown to fit a variety of E-glass composites with well aligned fibers, as discussed above. The power law trend is a least squares fit to the data, forced through 1.0 at one cycle.

Representative specimens broken at different stress levels and frequencies can be seen in Figure 13. One characteristic of all failures was the development of axial splits in the specimens at different times depending on the load level. The high load level test specimens developed axial cracking on the first cycle, but the high cycle tests only showed these cracks after some period of cycling. For example, the first test run at the 20.5 percent load level did not have any axial cracking until over half the total number of cycles had been run. This damage began at a wave in the material (Figure 2), where most of this type of damage originates. Little other damage was evident prior to total failure, similar to observations with larger unidirectional coupons [2].

For comparison with literature S/N data, Figure 14 has

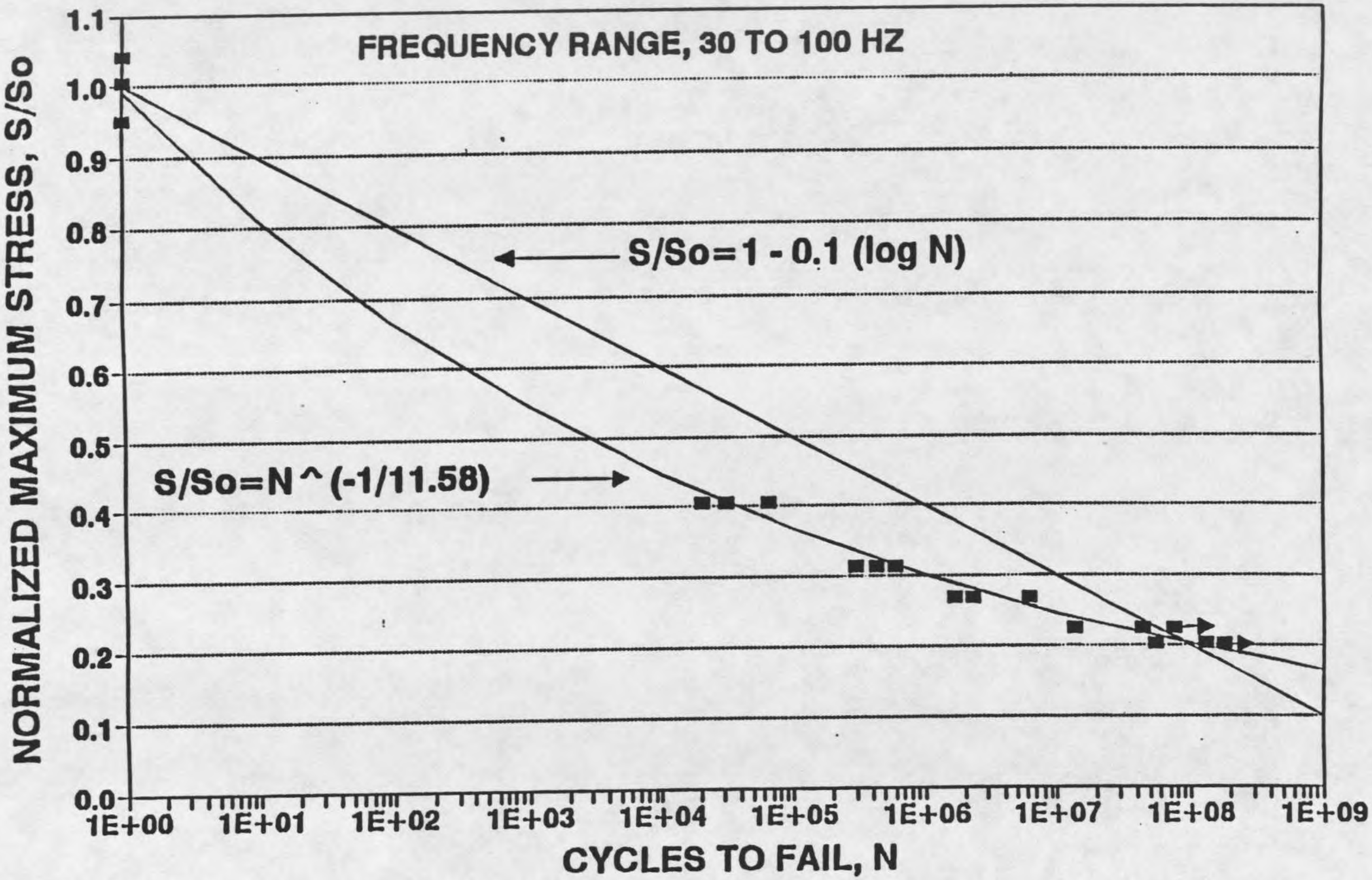

Figure 12. Normalized S/N curve of high frequency fatigue tests.

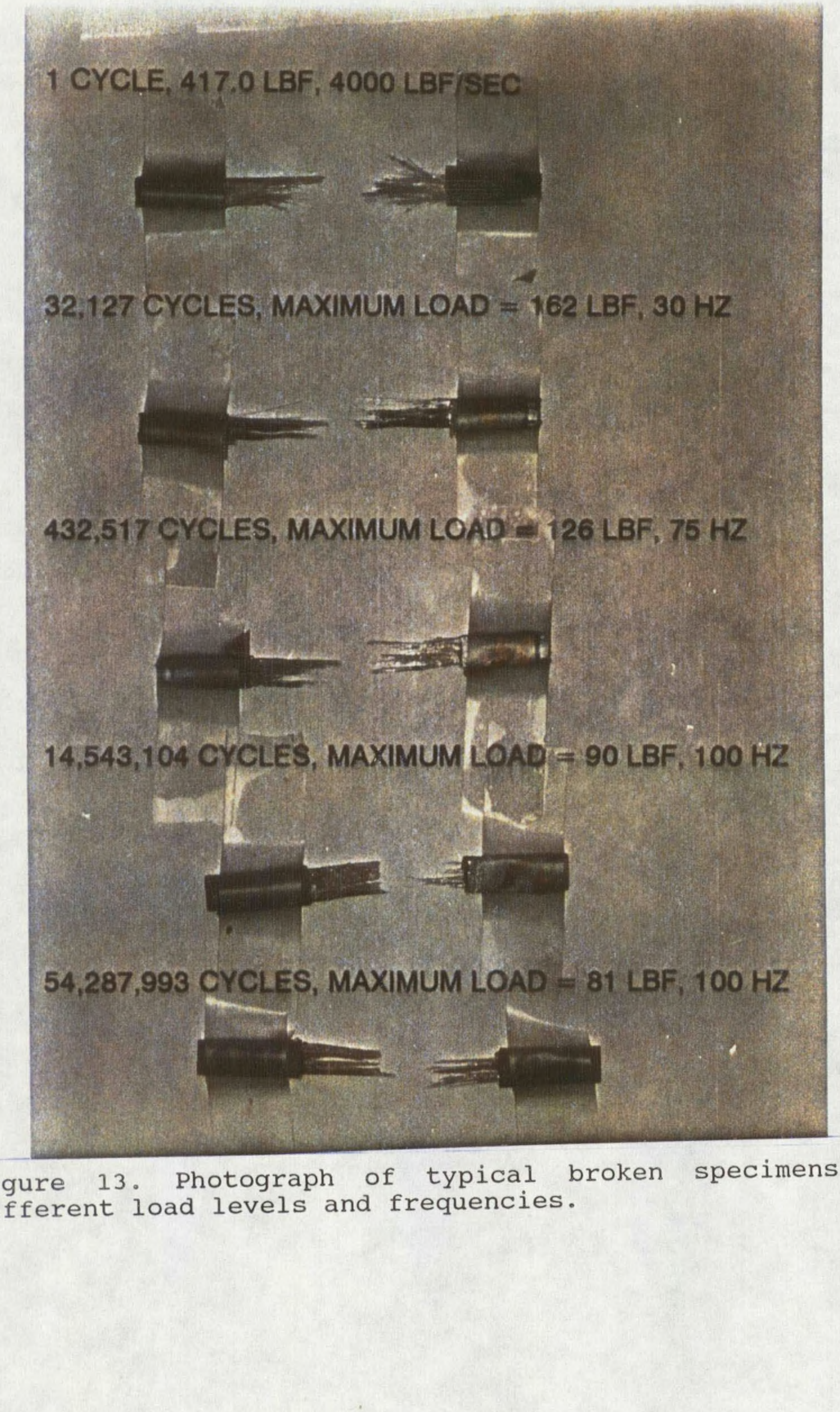

Figure 13. Photograph of typical broken specimens from different load levels and frequencies.

standard coupon data from a thesis by Reed [2] on the same plot as the data from this study. Both materials were unidirectional E-glass reinforced polyester, a standard coupon being in the form of 2 in. wide by 0.125 in. thick by 4 in. gauge section length tested at up to 10 Hz. Our tests were conducted at from 30 to 100 Hz. As can be seen, the data for both cases fall close to the same trend line, when both are normalized against their respective ultimate strengths. The ultimate strength for material A was 80,000 psi [2], while the ultimate strength for our case was 94,200 psi. This demonstrates that the specimen in question gives results in fatigue which agree with literature data in the moderate cycle range.

Also for comparison, Figure 15 shows an S/N curve with both our data and published data from Bach [8]. Specimen geometry used by Bach was unidirectional reinforced glass fiber/polyester plate (0.2 in. thick) machined into specimens with dimensions of 6.7 in. by 0.98 in. with a gauge section length of 3.1 in. The discrepancy between the two data sets may be attributable to the quality of the materials tested: typical windmill materials have a large amount of fiber misalignment which may be responsible for lower failure lifetimes, while prepreg or nonwoven specimens tend to have better alignment. Better alignment may result in less matrix splitting damage from stress concentrations caused by fibers even slightly off axis [19].