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# Non-Metallic Antenna-Support Materials

First Annual Interim Report

Donald E. Marlowe, Nixon Halsey, Richard A. Mitchell, and Leonard Mordfin

Engineering Mechanics Section
Mechanics Division
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National Bureau of Standards
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Interim Report for Period October 16, 1971 – October 15, 1972

Prepared for
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NATIONAL BUREAU OF STANDARDS, Richard W. Roberts, Director

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ABSTRACT

A program was initiated to develop a non-conductive, fiber-reinforced-plastic rod material for use as guy lines and catenaries in large antenna systems. It is intended that the long-term mechanical properties of the new material, under adverse weathering conditions, be superior to those exhibited by the glass-reinforced-polyester rod and rope materials which are available at the present time. The program centers around three principal phases: development of an improved manufacturing process, selection of a superior non-metallic fiber-reinforcement material, and selection of a superior polymeric matrix material.

During the first year of activity on this program, two new end fittings for fiber-reinforced-plastic rod were developed which out-perform commercially available fittings and which are generally capable of achieving the full tensile strengths of available glass-reinforced-polyester rod materials. These two fittings, which were developed to enable the tensile strengths of the rod materials to be accurately determined, include a shear-type fitting (Mod 4) and a compression-type fitting (H3M).

Deficiencies in the physical characteristics of existing glass-reinforced-polyester rod materials were identified, and modifications to the manufacturing processes were proposed to overcome these deficiencies. A subcontract was let for the manufacture of experimental glass-reinforced-polyester rods using the modified processes.

A bank of six 30000-lbf-capacity creep testing machines was designed and is being assembled. These machines, which will accommodate 9-ft specimens, are equipped with environmental chambers for stress-rupture tests up to 200°F under saturated humidity conditions.

Key Words: Composite materials; end fittings for FRP rod; environmental resistance of FRP rod; fiber-reinforced-plastic rod; glass-reinforced-polyester rod; guys, antenna; mechanical properties of FRP rod; pultrusion; reinforced plastic rod; stress rupture of FRP rod.

## 1. INTRODUCTION

Glass-reinforced-polyester rod and rope materials constitute one of the more interesting and valuable -- although lesser known -- products of composite materials technology. These products are generally fabricated from unidirectional glass fiber roving and a thermosetting plastic matrix by a process called pultrusion. They are strong, lightweight, nonconducting, corrosion resisting and comparatively inexpensive. This combination of properties has led to the use of these products in a variety of applications where steel wire rope had previously been employed almost exclusively. In terms of total volume, the largest application has been in communications towers and arrays, wherein the use of non-metallic rod and rope as guys and catenaries has permitted the elimination of the large, expensive, ceramic insulators which are required when steel wire rope is used.

As frequently happens when promising new products are developed, the rod and rope were introduced into service before they were adequately characterized and without the benefit of carefully compiled design data. The result has been the occurrence of failures in several field installations. Fortunately, however, most applications have performed satisfactorily.

Some of the reported failures of non-metallic guys and catenaries involve tracking and flashover damage, and burning, in intense electromagnetic fields. Most of the other reported failures are apparently mechanical, although environmental effects are probably involved. Rope-type guys and catenaries fail, at locations apart from their fittings, by a progressive strand-by-strand breakage. The cause of these failures is unknown but opinions that have been advanced include undetected damage incurred during installation, wind-induced rubbing of adjacent strands, and strength degradation due to ultraviolet exposure. In the case of rod materials, failures usually entail splitting or delamination that progresses along the rod at a slight inclination to the longitudinal axis. These splits often appear to start in or adjacent to an end fitting but in many instances they evidently initiate at a transverse crack. Some of these transverse cracks are particularly interesting because, prior to splitting, they appear only as hairlines on the surface of the rod; the surfaces of the crack itself are very smooth. The cause of the transverse cracks is unknown but most opinions attribute them to some kind of dynamic loading mechanism.

Although the causes of mechanical failure in these materials are apparently many and varied, at least one generalization can be made. Most mechanical failures of non-metallic antenna support materials have occurred after a period of service, ranging from months to years, during which the materials have been under tension in a moist environment. With this as a point of departure, the National Bureau of Standards embarked upon a three-year program to develop a new non-metallic fiber-reinforced-plastic (FRP) rod or rope material which would exhibit superior mechanical properties and greater resistance to moisture in the form of a hot, humid environment. This program, which was initiated October 16, 1971, is being carried out in the Engineering Mechanics Section of NBS under the sponsorship and with the financial assistance of the Air Force Materials Laboratory. This interim report covers progress during the first year of activity.

The U.S.A. is a signatory to the General Conference of Weights and Measures which gave official status to the metric SI system of units in 1960. However, for simplicity, only U.S. customary units have been used in this report. Conversion factors for these units are given in the Appendix.

## 2. SCOPE

The development of a superior rod or rope product centers about three principal phases of activity.

In Phase I the physical characteristics of existing FRP rod and rope materials are examined in order to identify deficiencies, if any, which can be traced to improper or inadequate manufacturing practices. The intent, then, is to have these manufacturing practices corrected or improved, and to test samples of the improved material in order to assess the significance of the improvements. The principal result of the activity under Phase I is, thus, the development of an improved manufacturing process for FRP rod or rope.

Using the improved manufacturing process, Phase II calls for the fabrication of FRP rod or rope using reinforcements other than E-glass, which has been used most commonly. The reinforcing materials are to be continuous, non-metallic fibers. The properties of the resulting products are to be evaluated and compared with the corresponding E-glass product.

The improved manufacturing process is again used in Phase III to fabricate FRP rod or rope with other, potentially better, resin matrix materials. The resulting products are to be evaluated in comparison with FRP products fabricated with conventional resin systems.

The evaluations of the experimental materials which are fabricated in this program are based primarily upon two types of mechanical tests: tensile tests at normal and high rates of loading, and stress-rupture tests at 160°F and 200°F under saturated humidity conditions.

Upon completion of the three phases it is expected that the results obtained will be adequate to specify one or two superior FRP products in terms of the manufacturing process and the fiber and resin constituents. In order to facilitate the attainment of this objective, and to promote the use of the new materials, several supplementary tasks are required both before and after the three principal phases:

> If tensile strengths of the materials are to provide a meaningful measure of product improvement, it is necessary to determine the tensile strengths accurately. However, previous work in this laboratory [1,2] has shown that the end fittings for these materials, which are available commercially, are not generally capable of withstanding the tensile forces which are required to fracture these materials in a true tensile mode. Hence, there has been a need, first, to develop end fittings, for use in the laboratory, which can generate the full tensile strengths of the materials.
>
> A second task which has been pursued prior to Phase I is a study of the existing manufacturing practices for FRP rod and rope. The results of this study are required to enable potential improvements, in the manufacturing practices, to be devised. This study will also permit the identification of one or more manufacturers having the capability and the willingness to institute the improved manufacturing practices.

At the completion of the three primary phases of activity, a task will be undertaken to generate design data for the new material or materials developed in this program. These data are required in order to facilitate the use of these materials either in new systems or as replacements in existing systems.

## 3. DEVELOPMENT OF IMPROVED END FITTINGS

It has been established [2] that commercially available end fittings for FRP rod and rope are not generally capable of developing the full tensile strengths of these materials. In antenna-support applications it is not necessary that the end fittings have this capability since, in service, the guys and catenaries are loaded only to a fraction of their short-time tensile strengths. In a program such as this, however, in which there is need to measure the tensile strengths of FRP rod and rope materials, it is necessary to have end fittings which will permit the full tensile strengths of the materials to be attained.

In this task, laboratory prototypes of two new end fittings were developed which are markedly superior to any of a variety of commercial end fittings with which they have been compared. While the development of these fittings was completed in the present program, much of the basic work which went into the development was initiated or pursued in prior studies performed in this laboratory. These prior studies were carried out under the sponsorship and with the financial assistance of the Army Electronics Command, the Coast Guard, the Naval Facilities Engineering Command, Rome Air Development Center (USAF), the United States Information Agency and the National Bureau of Standards.

The basic approach to the development of improved end fittings consisted of an analytical parameter study of the problem and an experimental evaluation of trial prototype designs, which were pursued concurrently. The analytical study involved the axisymmetric, finite-element stress analysis of a broad class of end connections consisting of a metal sleeve joined to the FRP rod with a polymeric potting material. The experimental study involved the fabrication and tensile testing of prototype end fittings employing several different gripping concepts. An important aspect of this parallel analytical and experimental approach was the free transfer of newly developed information from one study to the other. During the course of the work the orientation of each study was changed to a more profitable direction based on information developed in the other study. Some aspects of the analytical study are reported in greater detail elsewhere [3].

### 3.1 Finite-Element Analysis

A new computer program was developed for the axisymmetric, finite-element stress analysis of end connections. The basic finite-element formulation used [4] was developed for the case of isotropic elastic materials. That earlier formulation has been modified in the end-fitting analysis in accordance with the assumption that the FRP rod is homogeneous and transversely isotropic as defined by five independent elastic constants. The metal sleeve and the potting compound are assumed to be isotropic elastic.

In a finite-element analysis the continuum is subdivided into a network of elements that are connected to adjacent elements only at common nodal points. Elastic displacements within the individual elements are defined by generalized functions that assure displacement compatibility along common boundaries of adjacent elements. In the end-fitting analysis elastic strains within the elements are assumed to be uniform, thus assuring displacement compatibility along common element boundaries.

Figure 1 shows a representative finite-element analysis mesh for one general class of end connections. In this case, the metal sleeve is conically tapered, and the outer end of the FRP rod is slit into quarters and spread with a conical metal wedge. Where the rod is spread by the wedge, the elastic constants for the region occupied by the spread rod are recomputed according to the volume fractions of rod material and potting compound.

In addition to generating the usual line-printer output of computed results, the computer program drives an electron-beam plotter which produces contour plots of seven different stress components and the angle of maximum principal stress, as well as a plot of the analysis mesh. As an example, Figures 2, 3, and 4 give, respectively, plots of the analysis mesh, the longitudinal normal stress and the longitudinal shear stress for the Mod 4 end fitting which will be described later.

### 3.2 Analytical Parameter Study

The linear elastic finite-element computer model was used in a parameter study of the general class of end fittings represented schematically in Figure 5. The numerals in the figure denote the eight variable parameters studied. Parameters 4 and 5 are the elastic moduli of the two potting compounds indicated.

It was assumed that the critical component of stress, with respect to tensile strength, is the peak bond-shear stress at the interface between the rod and the potting compound. This assumption was based on the fact that rod pullout was the most common failure mode observed in tensile tests of this class of fitting.

The analyses were carried out for a 1/2-in diameter FRP rod. The assumed properties of the metal sleeve and the conical wedge (not shown) were those of 7075-T6 aluminum alloy.

The general indications for the eight parameters studied are:

1. End-fitting length.--Within the range of 6 to 16 in, greater length results in significantly smaller peak bond-shear stress, but the rate of change of peak stress decreases as length increases.

2. Potting thickness at inner end of fitting.--Within the range of 0.24 to 0.48 in, greater thickness results in significantly smaller peak bond-shear stress, but the rate of change of stress decreases as thickness increases.

3. Sleeve thickness at inner end of fitting.--Within the range of 0.02 to 0.25 in, greater thickness results in slightly greater peak bond-shear stress.

4. Elastic modulus of inner potting compound.--Within the range of 40000 to 316000 $lbf/in^2$ , greater stiffness of potting compound results in significantly greater peak bond-shear stresses. This is true whether a single potting compound or a combination of two different compounds is used.

5 & 6. Elastic modulus and length of outer potting compound.--A combination of two potting compounds having different elastic moduli produces two bond-shear stress peaks (one at the inner end of each potting compound). If Parameters 4, 5 and 6 are proportioned so as to make the two stress peaks approximately equal, the peak stress is significantly less than for the case of a single potting material.

7 & 8. Potting thickness and sleeve thickness at the outer end of the fitting.--Parameters 7 and 8 have a relatively small direct influence on the peak bond-shear stress.

The two most significant findings of this parameter study are:

1. The potting compound should have a relatively low modulus of elasticity, i.e., it should be flexible.

2. The potting compound layer should be relatively thick.

Both of these findings appear to be entirely logical but they were not intuitively obvious prior to the parameter study. In particular, it is known that adhesives with high bond strengths generally have relatively high moduli of elasticity, and that adhesives generally exhibit higher bond strengths when applied in thin layers. However, the parameter study showed that a flexible, thick potting compound allows the tensile load to be transferred from the fitting to the rod gradually, over a long length, without developing a high peak bond-shear stress at the inner end of the fitting. Thus, a flexible, thick potting compound performs better in this application than a stiff, thin potting compound which may have a greater bond strength.

### 3.3 Selection of Potting Compound

On the basis of previous work in this laboratory, the selection of an appropriate potting compound was focused on a single series of formulations. These consist of a 100-percent-reactive epoxy resin adhesive and an activator. The system requires a 2-h cure at 165°F. The two components may be combined in different resin/activator ratios to provide different mechanical properties. The designations and some of the properties for several mixture ratios are given in Table 1.

A simple, shear-type end fitting was designed and fabricated to evaluate the relative pullout shear strengths of the several CW potting compounds. This fitting, called the Mod 3, is shown in Figure 6. It consists of a cylindrical metal sleeve which is attached to an FRP rod with a thick layer of potting compound.

A series of twelve tensile tests was performed using 1/2-in diameter, high-strength FRP rod. All twelve specimens failed by rod pullout and the results are given in Table 2. Although there is great scatter in these data, the relatively high strengths of the specimens with the most flexible potting compound are significant. These results support the analytical parameter study which showed that a more flexible potting compound produces significantly lower peak bond-shear stresses. Finite-element analyses of the Mod 3 fitting indicate that the peak bond-shear stress with the most flexible C2W3 potting compound is only 47 percent of the corresponding stress with the stiff C3W2 compound.

Table 1 - Mechanical Properties of CW-Series Potting Compounds

| | Resin/activator ratio | | | |
|---|---|---|---|---|
| | 2:3 | 1:1 | 3:2 | 2:1 |
| Designation | C2W3 | C1W1 | C3W2 | C2W1 |
| Bond strength [a], $lbf/in^2$ | 2450 | 3280 | - | - |
| Compressive strength [a], $lbf/in^2$ | 32200 | 20700 | - | - |
| Elongation [a], percent | 8.0 | 7.0 | - | - |
| Elastic modulus [b], $lbf/in^2 \times 10^{-5}$ | 0.51 | 2.75 | 3.16 | - |

[a] According to the manufacturer.

[b] From compressive tests on 0.5-in diameter specimens performed in this laboratory.

Table 2 - Tensile Tests with Mod 3 Fittings on 1/2-in FRP Rod

| Test No. | Potting compound [a] Designation | Potting compound [a] Elastic modulus $lbf/in^2$ | Maximum load lbf |
|---|---|---|---|
| 71169 | C2W3 | $0.51 \times 10^5$ | 19850 |
| 71170 | C2W3 | 0.51 | 15500 |
| 71171 | C2W3 | 0.51 | 18650 |
| Average: | | | 18000 |
| 71166 | C1W1 | 2.75 | 12200 |
| 71167 | C1W1 | 2.75 | 8500 |
| 71168 | C1W1 | 2.75 | 19250 |
| Average: | | | 13300 |
| 71172 | C3W2 | 3.16 | 8000 |
| 71173 | C3W2 | 3.16 | 14350 |
| 71174 | C3W2 | 3.16 | 9400 |
| Average: | | | 10600 |
| 71175 | C2W1 | - | 12350 |
| 71176 | C2W1 | - | 17500 |
| 71177 | C2W1 | - | 18100 |
| Average: | | | 16000 |

[a] See Table 1.

On the basis of these results the C2W3 potting compound was selected for use in the development of improved end fittings.

## 3.4 Experimental Prototype Fittings

A variety of gripping concepts investigated prior to the analytical parameter study gave disappointing results in tensile strength tests. When the results of the parameter study became available, these early attempts were abandoned and the development effort was redirected along two parallel but differing approaches to the problem of achieving high strength in a potted end fitting. In one approach, the length of the interface is increased as a means of raising the total shear-carrying ability of the fitting. This resulted in the development of the Mod 4 fitting. In the second approach, compressive stresses are applied normal to the interface in order to enhance its shear strength. This resulted in the development of the H3M fitting. The development of these two laboratory prototype fittings are described below.

## 3.5 Design of the Mod 4 End Fitting

The Mod 4 end fitting is a shear-type potted end fitting which is, basically, a longer version of the Mod 3 end fitting which was discussed above. The Mod 4 fitting, Figure 7, consists of a 1-1/2-in diameter rod of aluminum alloy, 18-in long, which is drilled out axially to a depth of 13-in with a 3/4-in drill. This hole is then counterbored to a depth of 12-in, leaving a uniform 1/8-in wall thickness. To mount the fitting on an FRP rod, the end of the rod, after abrasive cleaning, is set into the 3/4-in hole in the base of the cavity. The rod is carefully aligned parallel and concentric with the fitting and the remaining cavity is filled with the potting compound. The fitting was designed primarily for 1/2-in diameter rod, which leaves a 3/8-in thickness of potting compound around the rod.

The first Mod 4 fittings tested were machined from a low-strength aluminum alloy and they failed, in tension, near the base of the cavity at loads between 27900 and 30250 lbf. Subsequent fittings were machined from high-strength aluminum alloys, e.g., 7075-T6, and further failures of the fitting have not been experienced.

### 3.6 Experimental Stress Analysis of the Mod 4 End Fitting

A tensile specimen was fabricated by mounting two Mod 4 fittings on a length of 1/2-in diameter, high-strength FRP rod using the C2W3 potting compound. The specimen was instrumented with twenty-six resistance strain gages and subjected to six cycles of tensile loading. The loading sequence was 0-2500-0-10000-0-10000-0-22000-0-23250-0-30100 (failure) lbf. Seventeen strain gages were located on the surface of one end fitting and the remaining nine gages were mounted on the FRP rod adjacent to that fitting. Twenty-two gages were oriented in the longitudinal direction and nine of these were grouped in sets of three and spaced 120° apart to detect eccentricity. Four gages were oriented in the circumferential direction. The 7075-T6 aluminum alloy sleeve was filled, to within 0.6 in of the inner end, with the potting compound.

Figures 8 and 9 are plots of longitudinal strain on the surface of the instrumented fitting as predicted by the linear elastic finite-element analysis and as measured by the strain gages. The individual data points indicate the strains measured during the initial application of the particular load indicated. The vertical lines in Figure 9 indicate the spread in strain data for subsequent loading cycles. The major part of the spread is due to residual strain present in the specimen at the beginning of Load Cycles 3 and 5. These two cycles were applied less than one hour after completing Load Cycles 2 and 4, (which had maximum values of 10000 lbf and 22000 lbf, respectively) and the strain gages had not been reset to zero. There is good agreement between the linear elastic analysis and the experiment at 1000 lbf load during the first cycle, but there is progressively poorer correlation at higher loads.

The rate of change of surface strain with respect to distance along the fitting is approximately proportional to the rate of transfer of load in shear through the potting compound. That is, the slope of a smooth curve fitted to a set of strain data points in Figures 8 or 9 would be approximately proportional to the bond-shear stress acting at the surface of the rod. This interpretation of the data suggests that, at the higher loads and for the greater part of the potted length of the rod, the bond-shear stress acting on the rod was roughly uniform. This apparent degree of uniformity of bond-shear stress is believed to be a major factor contributing to the relatively high strength of the Mod 4 type fitting when used with the flexible C2W3 potting compound.

### 3.7 Tensile Tests with Mod 4 End Fittings

The performance of the Mod 4 end fitting was evaluated by means of tensile tests on two commercially available FRP rod materials of 1/2-in diameter. Both are fabricated from unidirectional, continuous, E-glass roving and a polyester resin matrix. The individual glass fibers are 0.00051 in in diameter (Type K). The manufacturing process for one of these materials, Material E, results in the formation of an integral gel coating of the matrix material on the outer surface of the rod. The resin system of the second material, Material N, is reported by the manufacturer to be an "epoxy-modified" polyester. Material N rod is coated with epoxy that is heavily loaded with titanium dioxide for resistance to weathering and ultraviolet radiation. Thickness of the coating is 0.005 to 0.015 in.

The results of twenty tensile tests using Mod 4 fittings on 1/2-in diameter Materials E and N rods are given in Table 3. The low-modulus C2W3 potting compound was used on all specimens. Two of the seventeen Material E specimens failed in the free length at loads of 32850 and 31500 lbf. The other fifteen Material E specimens failed by pullout with the failure located principally at the interface between the rod and the potting compound. The average maximum load for all of the Material E specimens was 30100 lbf, which is more than 90 percent of the loads attained by the specimens which failed in their free lengths. This indicates that the full tensile strength of Material E is approached with the Mod 4 fittings.

The average maximum load for three specimens of 1/2-in Material N with Mod 4 end fittings was only 20100 lbf. Failure here was also by pullout but in this case the failure was within the rods with several of the outer layers of glass fibers being sheared off.

A comparison of these results with those obtained with commercial end fittings [2] reveals that the Mod 4 end fitting is clearly superior to the commercial types for Material E. For Material N the performance of the Mod 4 fitting is equal to that of the commercial types although it does not, apparently, allow the full tensile strength of Material N to be approached.

### 3.8 Further Research on Mod 4 End Fittings

Several approaches were explored in an attempt to improve the performance of the Mod 4 fitting on Material N. In the first of these approaches the effects of increasing the relative size of the Mod 4 fitting were examined. In order to avoid the expense of machining larger fittings an initial test series was carried out using the standard Mod 4 fitting on Material N rods of smaller diameters, i.e., 3/8 and 1/4 in. The results of these tests are given in Table 4. These results show that one of the 1/4-in diameter specimens did, indeed, fail in the free length. This suggests the possibility that a larger end fitting of the Mod 4 type would more nearly approach the full tensile strength of 1/2-in Material N rod.

Accordingly, a scaled-up version of the Mod 4 was designed and several such fittings were fabricated. These have an overall length of 24 in, a potted length of 18 in, an outer diameter of 2 in and a wall thickness of

Table 3 - Tension Tests with Mod 4 End Fittings on 1/2-in FRP Rod. Potting compound: C2W3.

| Test No. | Material | Maximum load lbf | Failure |
|---|---|---|---|
| 71182 | E | 31350 | (a) |
| 71183 | E | 32850 | (b) |
| 71184 | E | 25750 | (a) |
| 81242 | E | 27000 | (a) |
| 81243 | E | 28600 | (a) |
| 81244 | E | 32600 | (a) |
| 81245 | E | 29600 | (a) |
| 81246 | E | 29000 | (a) |
| 81247 | E | 31800 | (a) |
| 81248 | E | 32750 | (a) |
| 81249 | E | 30950 | (a) |
| 81250 | E | 31100 | (a) |
| 81251 | E | 31500 | (a) |
| 91261 | E | 23250 | (c) |
| 101315 | E | 30100 | (a) |
| 101333 | E | 31850 | (a) |
| 101404 | E | 31500 | (b) |
| Average: | | 30100 | |
| 81240 | N | 23700 | (a) |
| 81241 | N | 17850 | (a) |
| 91263 | N | 18900 | (a) |
| Average: | | 20100 | |

(a) Pullout.

(b) Failure in the free length.

(c) Pullout; potting compound did not appear to have been adequately cured.

Table 4 - Tensile Tests of Small-Diameter Material N Rods with Mod 4 Fittings.

| Test No. | Nominal rod diameter | Maximum load | Nominal maximum stress | Failure |
|---|---|---|---|---|
| | in | lbf | $lbf/in^2$ | |
| 91262 | 3/8 | 13100 | 119000 | (a) |
| 92266 | 3/8 | 9800 | 89000 | (a) |
| 92264 | 1/4 | 3000 | 61000 | (a) |
| 92265 | 1/4 | 7550 | 154000 | (b) |

[a] Pullout.

[b] In the free length.

Table 5 - Evaluation of Other Potting Compounds with 1/2-in FRP Rod.

| Test No. | Rod material | Potting compound[a] | Maximum load | Failure |
|---|---|---|---|---|
| | | | lbf | |
| 101400 | E | PC23 | 22900 | (b) |
| 101402 | E | PC8 | 16000 | (c),(b) |
| 101401 | E | PB5 | 12850 | (b) |
| 101405 | N | PB5 | 7650 | (b) |

[a] PC23 is a flexible epoxy laminating resin which is prewarmed and mixed in the ratio 2 parts resin to 3 parts hardener. PC8 is a two-component, 100-percent solids, liquid epoxy pouring compound with a prescribed mixture. PB5 is a two-component, flexible, polysulfide adhesive with a 1:1 prescribed mixture requiring extensive mixing.

[b] Pullout.

[c] Bond between potting compound and fitting failed at 1500 lbf, then potting compound was gripped directly.

0.25 in. Two tensile tests were performed using these fittings on 1/2-in diameter rod of Material N. The results showed no improvement over those obtained with the standard Mod 4 fitting and this approach has not been pursued further.

A second approach which was explored involved an attempt to find a potting compound which is superior to C2W3. Four tensile tests involving three promising potting compounds were carried out using Mod 4 end fittings and 1/2-in diameter FRP rod. The results, Table 5, indicate that none of these compounds performs as well as C2W3.

In the third approach, wedges were driven into the ends of Material N rods prior to potting in Mod 4 fittings. This was done in an attempt to achieve a degree of mechanical locking which would enhance the pullout strength. Two tests culminated in pullout failures at loads not markedly different from those attained without the wedges.

Several numerical experiments were conducted on the computer in an effort to obtain a greater understanding of the process of load transfer from the end fitting, through the potting compound, to the rod. This effort indicated the feasibility of incorporating the nonlinear properties of polymeric potting compounds into the finite-element analysis. It was found that a relatively coarse finite-element mesh can give sufficiently accurate linear solutions for bond-shear stress and surface strain, and that a series of these linear solutions could be used in a direct-iterative procedure to approximate nonlinear response. This type of nonlinear analysis has been used in this laboratory to study composite-reinforced cutouts in metal sheet [5]. However, it was determined that this approach could not be effectively pursued within the resources available on the present program.

### 3.9 Development of the H3M End Fitting

Since the Mod 4 end fitting was found to be incapable of developing the full tensile strength of Material N, it was decided to investigate the performance of compression-type, rather than shear-type, end fittings for this material. Accordingly, a series of tension tests was performed using two different compression-type potted end fittings. One of these is a commercially available fitting and the other was developed in this laboratory in an earlier program.

The Type R/P end fitting, Figure 10, is a commercially available, basket type, potted, compression fitting which is intended primarily for synthetic ropes. The conical basket, or potting head, is fitted with a yoke and bail for attachment to thimble-eye type hardware. To mount the Type R/P fitting on an FRP rod, a fluted, cruciform wedge (Fig. 11) is first driven axially into the end of the rod. (These metal wedges are available from the manufacturer of Material N.) The inner surface of the potting head is treated with an epoxy-release agent, then the rod is alined parallel and concentric with the fitting, which is then potted and cured. The release agent permits the potted material to slide relative to the potting head, and under tensile loads the potted end seats tightly into the conical potting head. This seating process develops significant radial compressive stresses in the potted end which enhance the strength of the bond between the rod and the potting compound. The release agent also facilitates removal of the potted material for reuse of the fitting.

The NBS aluminum block end fittings, Figure 12, were developed in an earlier investigation [1]. These are 2-5/8 x 3-1/4 x 6 in long and are machined from 2024-T4 aluminum-alloy stock. Each block is split in half longitudinally and bolted together, and then a conical section is machined out. For use with 1/2-in FRP rod the conical section is 2-1/4 in in diameter at the large end, tapering to a short cylindrical section 5/8 in in diameter. The wedging and potting procedures for these fittings are the same as those described above for the Type R/P end fittings.

These two types of fittings were used in a series of eight tensile tests on 1/2-in Material N in an earlier study [1]. For those tests conical wedges (Fig. 11) and C1W1 potting compound (Table 1) were used. Except for one test in which the rod pulled out of the fitting prematurely, all of the specimens failed at loads between 20500 and 22300 lbf by pinching off at the fitting due to the radial compressive stresses.

Four additional tensile tests of 1/2-in Material N were performed in the present investigation using these two types of end fittings. In these tests the cruciform wedges were used. The C2W3 potting compound was used for two of the specimens on the basis of the analytical parameter study. PC8 potting compound (Table 5) was selected for the other two specimens because of its high compressive strength. The results of the tests are given in Table 6. These results show that the aluminum block end fitting is capable of developing the full tensile strength of Material N rod and verified that the C2W3 potting compound is apparently the best of those which have been tried. The maximum load in Test No. 101411 is the highest ever achieved in this laboratory on 1/2-in Material N at room temperature.

The aluminum block end fitting was subsequently redesigned in a cylindrical, one-piece configuration, and assigned the laboratory designation H3M. See Figure 13. These changes were made in order to reduce the cost of the fitting and to facilitate its use in the testing machine which is being employed for the tensile tests in this investigation. The changes have no apparent effect on the performance of the fitting.

Two more tensile tests were performed to examine the relative performances of the conical wedge and the fluted, cruciform wedge when used with the H3M end fitting. For these tests 1/2-in Material E rod and C2W3 potting compound were employed. The specimen with the cruciform wedges failed in its free length at 33450 lbf. This is the highest breaking load ever achieved in this laboratory on 1/2-in Material E rod. The specimen

Table 6 - Tensile Tests of 1/2-in Material N with Compression-Type Potted End Fittings.

| Test No. | End fitting | Potting compound | Maximum load lbf | Failure |
|---|---|---|---|---|
| 101408 | R/P | PC8 | 21950 | (a) |
| 101410 | R/P | C2W3 | 21000 | (a) |
| 101409 | Al block | PC8 | 24350 | (b) |
| 101411 | Al block | C2W3 | 26050 | (b) |

(a) Initiated in the end fitting.

(b) In the free length.

with the conical wedges pulled out of the end fitting at 32900 lbf. On the basis of these results it was decided to continue using the cruciform wedges, which are available commercially at less cost than the conical wedges, which had been manufactured in-house.

# 4. INDUSTRIAL SURVEY

The objectives of this task were twofold:

(1) To learn the fundamentals of the pultrusion process as it is used in American industry for the manufacture of FRP rod and rope materials, in order to identify individual operations which may need improvement.

(2) To identify some pultrusion manufacturers with both the capability and the interest in working with this laboratory toward the development of an improved pultrusion manufacturing process for FRP rod or rope.

A notice was placed in the Commerce Business Daily [6] inviting interested manufacturers to respond. Fourteen responses were received. On the basis of these responses plus prior contacts, thirteen firms were surveyed, nine by means of on-site visits and the remainder by correspondence and telephone discussions. The on-site visits involved inspections of the pultrusion facilities plus discussions of possible means for improving them.

At the time this survey was carried out, it was found that there were no firms with the capability for manufacturing 1/2-in FRP rope in production quantities*. It was decided, therefore, to pursue this program in terms of FRP rod. Seven of the thirteen firms were identified as having the capability to manufacture 1/2-in FRP rod in production quantities.

## 4.1 The Pultrusion Process

The pultrusion process for FRP rod has been described in the literature [7, 8, 9]. For completeness, the basic features of this process are reviewed here. Figure 14 is a schematic of the process which illustrates several features that are common to most manufacturers. It should be noted, however, that no two manufacturers were surveyed whose processes were identical.

On the left of the figure, the glass rovings are drawn from a creel in which are mounted dozens of bales or spools of roving. The rovings are guided down into the resin tank where the individual fibers are wetted with the matrix resin. Following this, the impregnated mass is drawn through one or more guides and bushings which give the material its desired cylindrical shape. Finally, the rod is cured in a heated die system. On the right of the figure is the pulling mechanism which gives the process its name and which supplies the considerable force that is required. The final product is either cut to desired lengths or coiled, and allowed to cool.

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*This is no longer the case.

# 5. OPTIMIZATION OF THE MANUFACTURING PROCESS

## 5.1 Evaluation of Product Characteristics

A series of laboratory tests and inspection procedures was devised in order to evaluate certain important physical characteristics of FRP rod products. Some of these tests and procedures are applicable to available products, and were used to identify those characteristics which appear to be deficient and which could, potentially, be upgraded by appropriate modifications of the manufacturing process. Some of these tests and procedures are primarily applicable to the experimental FRP materials which are to be fabricated in this program, and are intended to indicate the degree of improvement, in product characteristics, which is achieved through various process modifications. The tests and procedures are outlined below.

5.1.1 Dimensional Uniformity. Measurements of the average diameter, the length, and the weight of several sections of each FRP rod material are made. The densities [10] and the weights per unit length are calculated. These determinations provide an indication of the uniformity of the product.

5.1.2 Resin Content. The determination of the resin content of FRP rods is made by means of a burn-out test similar in principle to the ASTM ignition loss test [11]. This test, which is intended for use on the experimental FRP materials, involves the use of a continuous-reading scale which is enclosed in a muffle furnace. The furnace temperature is set at a value at which the organic resin matrix material is completely decomposed to volatiles. The difference between the original weight of a sample and the minimum weight achieved during heating is considered to be the resin content.

5.1.3 Fiber Distribution. Microscopic examinations of cross sections of an FRP rod provide a simple means for assessing the uniformity of the distribution of fibers in the rod. By using an image analyzing computer, a measurement of the fiber volume-fraction as a function of radial distance from the center may be obtained.

5.1.4 Fiber Straightness and Collimation. Careful examination of the surface of an uncoated FRP rod occasionally permits the paths of individual fibers to be traced for several inches or feet, before the fibers descend into the interior of the rod. In the fabrication of experimental rod materials it is intended to add a colored glass tracer strand to the reinforcing rovings on certain runs. By sectioning the rod product at discrete intervals it should be possible to follow the paths of these tracers reasonably well.

5.1.5 Fiber Wetting. When an FRP rod is properly tested in tension, such that failure initiates in the free length of the rod, the fracture generally causes all of the fibers to broom out in a rather explosive fashion. Examination of these fibers can sometimes reveal where and whether they had been adequately wetted by the resin.

A more quantitative indication of the degree of fiber wetting can, perhaps, be made by measuring the corona inception voltage on rod samples which have been saturated with water. This approach is based on the premise that absorbed water will migrate to fiber/resin interfaces which are not thoroughly adhered. The following test procedure has been suggested [12] for some of the experimental FRP rod materials:

(1) Cut a 1/2-in long specimen from 1/2-in diameter rod, with the ends smooth and parallel.

(2) Boil the specimen in distilled water for 2 h.

(3) Measure the electrical breakdown voltage across the parallel faces within 15 min after removal from the water, as follows:

   (a) Mount the specimen between 1-in diameter electrodes in an oil bath.

   (b) Raise the voltage across the specimen from 0 to 15 kV at a rate of 0.5 kV/sec.

   (c) Hold the voltage at 15 kV for 1 min. If failure occurs within this interval, record the failure voltage as 15 kV.

   (d) Increase the voltage further at a rate of 0.5 kV/sec to breakdown and record the breakdown voltage. (The maximum voltage from the available equipment is 50 kV.)

5.1.6 Degree of Cure. Rockwell hardness measurements are made on FRP materials as an indication of the degree of cure of the resin. For this purpose Procedure A of ASTM Designation D785-65 [13] is used. Samples are removed from several locations along the length of a rod. A minimum sample length of 2 in has been established to enable multiple measurements to be made on the same sample. Not less than five measurements are made on the cylindrical surface of each sample. Three of these are made on a single generator line. The other two measurements are made on a second generator line, 90° from the first line, at points intermediate to the first three test sites.

5.1.7 Transverse Tensile Strength. A measure of the tensile strength of the resin matrix material in an FRP rod is obtained by means of a diametral compression test. In this well-known test method for brittle materials [14], a cylindrical disk-shaped specimen is compressed diametrically between two flat platens. Under the proper conditions [15] the test culminates in a tensile fracture along the loaded diameter, and the transverse tensile strength $\sigma_u$ of the rod is calculated from the relation

$$\sigma_u = \frac{2P}{\pi D t}$$

where P is the compressive load at fracture, D is the diameter of the disk and t is its thickness. The transverse tensile strength of the rod is considered to be indicative of the tensile strength of the resin matrix material assuming, of course, that the influence of the glass fibers on the transverse strength is not significant.

Disk specimens, approximately 1/4-in thick, are sliced from 1/2-in diameter FRP rods using a water-cooled, diamond cutoff saw. Care is taken during this cutting process to prevent fraying of the edges. The coolant is carefully blotted from the disks which are then allowed to dry, under ambient laboratory conditions, for at least 24 h prior to testing. The diameter and thickness of each specimen is measured, and the specimen is mounted, on edge, in a compression subpress [16] which is then loaded to fracture of the disk in a universal testing machine. A fractured specimen in the subpress is shown in Figure 15.

## 5.2 Deficiencies in Existing Products

Some of the tests and procedures described above were applied to commercially available FRP rod products obtained from five different manufacturers. The following list of product deficiencies were found to be present, in varying degrees, in all of the products.

1. Fibers are not uniformly distributed throughout the cross-section of the rod.
2. Fibers are not thoroughly wetted by the resin.
3. Microscopic voids exist in the matrix.
4. Fibers are not straight.
5. Fibers are not axially oriented.
6. Resin is incompletely cured.

These deficiencies are discussed below together with proposed modifications to the manufacturing process which may help to overcome these deficiencies.

5.2.1 Deficiency No. 1. Photomicrographs, such as that shown in Figure 16, clearly reveal that the fibers are not uniformly distributed throughout the cross section of a rod. Instead, they seem to be bunched together in clusters with resin-rich areas between them. It may be speculated that each cluster corresponds to the ends of a single roving. If this is, indeed, the case then it might be possible to achieve a more uniform distribution by pultruding a larger number of rovings having a lower end count (i.e., fewer strands per roving) or, perhaps, by using fibers of larger diameter.

5.2.2 Deficiency No. 2. Examination of the fibers in a rod which had been fractured in tension reveals that many fibers do not appear to have been wetted by the resin. Numerous modifications to the manufacturing process may be proposed which offer promise of facilitating wetting. For example:

a. Use a better coupling agent on the fibers.
b. Use untwisted rovings. (The rovings, as they are drawn out of bales or off of spools, usually have a certain amount of twist which inhibits the flow of resin to the individual fibers.)
c. Lengthen the resin tank or reduce the pulling speed to provide more wetting time.
d. Preheat the rovings before they enter the resin tank, to drive off surface moisture.
e. Agitate the resin tank and/or the rovings passing through the tank.
f. Add a wetting agent to the resin system.

5.2.3 Deficiency No. 3. Photomicrographs made under high magnification frequently show apparent voids adjacent to individual fibers. This tends to confirm the above observations regarding incomplete wetting. However, apparent microscopic voids are also occasionally observed in the matrix at locations apart from fibers. It is speculated that these voids may be created by volatilization of one or more components of the resin system under the heat of the curing operation. A remedy for this deficiency would probably require an additive or other modification to the resin system.

5.2.4 Deficiency No. 4. Examinations of fibers on the surfaces of FRP rods reveals that the fibers are not straight but follow a rather wavy path. This condition is obviously not conducive to achieving a uniform distribution of load among the fibers in a tensile application. This may be another manifestation of the fact that the rovings are twisted initially. It is also believed that this deficiency could be remedied, to some extent, by pretensioning the rovings before they go into the shaping and curing dies.

5.2.5 Deficiency No. 5. This deficiency is related to the previous one. Examination of surface characteristics, particularly on broken rods, reveals that the individual fibers are not alined with the direction of the rod. Deviations of 10 to 20° are not uncommon. In this situation rods are clearly unable to demonstrate maximum tensile strength. It is speculated that this condition could be improved by providing better collimation for the rovings. That is, it is believed that better alinement could be achieved if the rovings were guided in a straight or conical path from the creel to the dies, rather than forcing them to travel down into the resin tank and then up again to the dies.

5.2.6 Deficiency No. 6. Hardness measurements on FRP rods have been made, both before and after post-curing operations. In all cases the post cure produced an increase in hardness. This is taken to mean that the rods, in the as-received condition, were not fully cured. A fully cured rod should exhibit no significant increase in hardness during post curing. Perhaps the manufacturing process for FRP rods should include a post-curing operation prior to shipment.

## 5.3 Manufacture of Experimental Materials

A Request for Proposals (RFP) was prepared for the procurement of experimental FRP rod materials, pultruded with improved manufacturing processes. The number of potentially beneficial modifications to existing manufacturing processes, which are mentioned above, is greater than that which could properly be investigated within the resources available to this program. Nevertheless, a discussion of all of these modifications was included in the RFP, which invited potential subcontractors to exercise ingenuity in proposing improved manufacturing processes for the pultrusion of the experimental materials.

On the basis of the Industrial Survey, the RFP was issued to four firms which were considered to have both the capability and the interest to work with this laboratory toward the improvement of the manufacturing processes for 1/2-in FRP rod. Additional proposals were solicited via an announcement in the Commerce Business Daily [17]. Proposals were received from three firms and the subcontract was awarded to one of these.

The subcontract calls for the manufacture of fourteen runs of 1/2-in FRP rod using E-glass roving (Table 7) and a polyester resin matrix. The polyester (Table 8) is the isophthalic equivalent of an orthophthalic resin frequently used by the subcontractor. The processing conditions for the first eleven runs were designed, by a statistical techique, to facilitate evaluation of the effects of nine different processing parameters. The processing conditions for Runs 1 through 11 are given in Table 9. The processing conditions for Runs 12, 13 and 14 will be selected at a later date. A colored tracer strand will be incorporated into most of the runs to ease the problem of determining fiber straightness and alinement.

## 5.4 Mechanical Testing Equipment

The mechanical properties of the experimental materials will be evaluated by means of room temperature tensile tests, at both normal and high loading rates, and by stress-rupture tests, at 160 and 200°F, under saturated humidity conditions.

The tensile tests at normal rates will be performed in a 100000-lbf capacity, horizontal, hydraulic, universal testing machine [20]. A

Table 7. -- Characteristics of Glass Fiber Rovings[a]

Type: E-glass, continuous.

Fiber diameter: K (0.00052 in, nominal).

Fibers per strand: 400, nominal.

Roving yield:

| End count[b] | Nominal yield yd/lb |
|---|---|
| 30 | 123±6 |
| 60 | 61.5±3.1 |

Type of binder: Silane (proprietary formulation).

Percent of binder: 0.55±0.15, by weight of glass.

Tensile strength[c]: > 200,000 $lbf/in^2$

[a] According to the manufacturer.

[b] Number of strands per roving.

[c] Per ASTM Designation D-2343 [18].

Table 8. -- Characteristics of Isophthalic Polyester Resin[a]

| | |
|---|---|
| Monomer: | Styrene, approximately 30 percent. |
| Viscosity: | 23-27 poises at 77°F. |
| Specific gravity: | 1.12 - 1.13 at 77°F. |
| Reactivity: | Medium |
| Cure data[b]: | |
| Gel time: | 3-4 minutes. |
| Time to peak: | 4.5 - 5.5 minutes. |
| Peak temperature: | 390-410°F. |

[a] According to the manufacturer, for matched-metal-die molding applications.

[b] Per SPI procedure [19].

Table 9. -- Processing Conditions for Runs 1 through 11

| Run No. | Preheat roving | Twisted roving | End count | Added tension | Wetting agent[a] | Length of resin tank | Ultrasonic agitation | Colli-mation | Post cure |
|---|---|---|---|---|---|---|---|---|---|
| 1 | No | Yes | 60 | No | No | Std | No | No | No |
| 2 | Yes | Yes | 60 | No | No | Std | No | No | No |
| 3 | Yes | Yes | 60 | No | Yes | Long | Yes | No | No |
| 4 | Yes | Yes | 30 | Yes | Yes | Std | No | No | No |
| 5 | Yes | Yes | 30 | Yes | No | Long | Yes | No | No |
| 6 | Yes | No | 60 | Yes | No | Long | No | No | No |
| 7 | Yes | No | 60 | Yes | Yes | Std | Yes | No | No |
| 8 | Yes | No | 30 | No | Yes | Long | No | No | No |
| 9 | Yes | Yes | 30 | No | No | Std | Yes | No | No |
| 10 | Yes | Yes | 60 | No | No | Std | No | Yes | No |
| 11 | Yes | Yes | 60 | No | No | Std | No | No | Yes |

[a] Polycaprolactone, added to resin system.

crosshead speed of 0.75 in/min will be used. The tensile tests at high rates will be performed in a programmable, servo-controlled, electro-hydraulic, dynamic testing machine [20]. The peripheral apparatus needed to carry out the latter tests has not yet been assembled.

The stress-rupture tests will be performed in six creep-testing machines that were designed and are being assembled for this task (Fig. 17). Each of these machines has a load capacity of 30000 lbf, which is applied by dead weights acting through a 100:1 compound lever system. Specimens up to 9 ft long, including the end fittings, can be accommodated. The overall height and length of each machine are approximately 7 ft and 12 ft, respectively.

Each creep-testing machine is equipped with an environmental test chamber for providing the required temperature and humidity conditions. The chambers are cylindrical in shape, consisting primarily of a 10-in diameter asbestos-cement pipe, 4 ft long, with transparent plastic windows at the ends. Each chamber contains a brass tube which extends nearly the full length of the chamber. The purpose of the tube is to provide more uniform temperature distribution on the specimen, which passes concentrically through the tube. The ends of the specimen, including the end fittings and the pull rods, remain outside of the chamber.

Heat is supplied to each chamber by twelve quartz-tube, infra-red lamps which surround the brass tube. Each lamp has a capacity of 500W at 120V. The temperature distribution in the chamber is adjusted by regulating the power to the lamps. The test temperature is maintained with an electronic temperature controller.

Each chamber is furnished with an air-powered mist generator to provide the required saturated humidity conditions. The rate of water consumption is adjusted by regulating the air flow rate to maintain a light film of condensation on the windows of the chamber.

## 5.5 Preliminary Tests and Results

To establish suitable values for the initial processing conditions for the experimental FRP rods, the subcontractor manufactured and furnished a preliminary run of 6-ft long, 1/2-in diameter FRP rods, designated Run 0. The processing conditions for these rods are given in Table 10. The Shore D Durometer hardness for all of these rods was reported, by the subcontractor, to be in the range 91.0 to 94.5 and the glass content was estimated at 71.9 percent by weight.

Most of the rods were carefully weighed and measured in this laboratory and the densities were calculated. These calculations showed that the density was not significantly affected by the three processing parameters that were

Table 10. -- Processing Conditions for Run O.

No. of rovings: 22, 60-end twisted.

Preheat: 255-260°F.

Ambient rh: 60-63 percent.

| Specimen No. | Resin[a] | Pulling speed[b] in/min | Die temperature °F | Post cure[c] | Colored tracer |
|---|---|---|---|---|---|
| 01A | I | 9 | 325 | Yes | No |
| 01B | I | 9 | 325 | Yes | No |
| 01C | I | 9 | 325 | No | No |
| 01D | I | 9 | 325 | No | No |
| 02A | I | 12 | 350 | Yes | No |
| 02B | I | 12 | 350 | Yes | No |
| 02C | I | 12 | 350 | No | No |
| 02D | I | 12 | 350 | No | No |
| 03A | O | 9 | 340 | Yes | Yes |
| 03B | O | 9 | 340 | Yes | Yes |
| 03C | O | 9 | 340 | No | Yes |
| 04A | O | 12 | 365 | Yes | Yes |
| 04B | O | 12 | 365 | Yes | Yes |
| 04C | O | 12 | 365 | No | Yes |
| 04D | O | 12 | 365 | No | Yes |

[a] Medium reactivity polyester. I, isophthalic; O, orthophthalic.

[b] Indicative of wetting time.

[c] 16 h at 275°F.

varied, i.e., type of polyester resin, pulling speed, and post cure. The density of all of the rods was 0.070 $lb/in^3$, within one percent. This is comparable with other, commercially available, FRP rod products [2].

The surface hardness and the transverse tensile strength were also measured on most of the rods. The results of these measurements are given in Table 11. Although these data are sparse and incomplete they provide some indication of the effects of the process parameters. Changing from an orthophthalic to an isophthalic polyester resin produces an increase of roughly 25 percent in the hardness but, surprisingly, an equivalent decrease in the transverse tensile strength. Raising the pulling speed from 9 to 12 in/min also increases the hardness and decreases the transverse tensile strength, but the magnitude of these changes is small and probably not significant. Adding a post cure produces the most significant change, an increase of approximately 35 percent in both the hardness and the transverse tensile strength.

It is, perhaps, noteworthy that the transverse tensile strengths of these rods are considerably less than those of other, commercially available, FRP rod products. The transverse tensile strengths of three other pultruded rod products were found to be in the range 2200 to 3300 $lbf/in^2$.

A series of tensile tests was performed to determine which of the end fittings would perform best on this material. These tests were carried out on several of the rods from Run 0, plus one additional rod (designated 00) which had been selected at random from the subcontractor's stockpile. The results of these tests are given in Table 12. Comparing the results of the first three tests listed with those of the last five shows that the H3M end fitting is superior to the Mod 4 end fitting for this material, and confirms, once again, that the C2W3 potting compound performs better than the PC8 potting compound in this application. Of the five specimens tested with the H3M end fitting and C2W3 potting compound, none pulled out of the fitting, three failed in the free length and two failed in tension in the end fitting at loads which appear to be very close to the full tensile strengths of the materials.

While not statistically significant, the results of the last five tests, in comparison with Table 10, also suggest that neither pulling speed nor post curing affects tensile strength to any meaningful degree, and that a specimen (03A) manufactured with the orthophthalic resin has slightly less tensile strength than those manufactured with the isophthalic resin.

Since the end fittings in stress-rupture tests need not be capable of withstanding the full tensile strength of the material, four short-time stress-rupture tests were performed to evaluate the suitability of commercially available end fittings for this work. These tests were carried out under saturated humidity conditions. The specimens were maintained at the test temperature and humidity for one hour prior to the application of load.

Table 11. -- Physical Properties of Run O Specimens

| Specimen No. | Average diameter in | Density $lb/in^3$ | Weight lb/ft | Rockwell hardness $R_E$ | Transverse tensile strength $lbf/in^2$ |
|---|---|---|---|---|---|
| 01A | ---- | ---- | ---- | -- | ---- |
| 01B | 0.5015 | 0.0697 | 0.165 | 62 | 1375 |
| 01C | ---- | ---- | ---- | -- | ---- |
| 01D | 0.5008 | 0.0698 | 0.165 | 46 | 1320 |
| 02A | 0.5019 | 0.0696 | 0.165 | -- | 1500 |
| 02B | 0.5016 | 0.0696 | 0.165 | 61 | 1470 |
| 02C | 0.5006 | 0.0699 | 0.165 | -- | 1020 |
| 02D | 0.5020 | 0.0695 | 0.165 | 50 | 1450 |
| 03A | 0.4983 | 0.0705 | 0.165 | -- | 1800 |
| 03B | 0.5010 | 0.0698 | 0.165 | -- | 1870 |
| 03C | 0.4979 | 0.0707 | 0.165 | 31 | 1630 |
| 04A | 0.5018 | 0.0695 | 0.165 | 54 | 1920 |
| 04B | 0.5002 | 0.0700 | 0.165 | -- | ---- |
| 04C | 0.5008 | 0.0699 | 0.165 | 56 | 1780 |
| 04D | 0.4978 | 0.0707 | 0.165 | 33 | 1540 |

Table 12. -- Results of Preliminary Tensile Tests

| Specimen No. | End fitting | Potting compound | Free length in | Maximum load lbf | Failure |
|---|---|---|---|---|---|
| 00 | Mod 4 | C2W3 | 22 | 19100 | (a) |
| 01A | Mod 4 | C2W3 | 59 | 22450 | (a) |
| 03B | H3M | PC8 | 57 | 21850 | (a) |
| 01B | H3M | C2W3 | 57 | 28100 | (b) |
| 01D | H3M | C2W3 | 57 | 28250 | (c) |
| 02B | H3M | C2W3 | 58 | 28050 | (c) |
| 02D | H3M | C2W3 | 51 | 28150 | (b) |
| 03A | H3M | C2W3 | 58 | 27200 | (b) |

[a] Pullout.

[b] Failure in free length.

[c] Failure in end fitting.

The test results are given in Table 13. These results indicate that the Type R/P end fitting with the C2W3 potting compound is adequate for this application. The results also suggest that the rods fabricated with the isophthalic resin are more resistant to stress rupture than the rod (04C) fabricated with the orthophthalic resin, and that the stress-rupture strength is greater at 160°F than at 200°F.

## 6. PLANS

The following summarizes the projected activities during the second year of effort on each of the three principal phases of this program:

Phase I - Experimental FRP rod materials, pultruded in accordance with specified modified manufacturing processes, will be procured and laboratory tested. Recommendations for an improved manufacturing practice for FRP rod will be formulated.

Phase II - Experimental FRP rod materials, fabricated with one or more potentially superior fiber-reinforcing materials, will be procured and laboratory tested. The degree of improvement which is achieved, relative to glass-reinforced rod materials, will be assessed.

Phase III - Plans will be made for the procurement of experimental FRP rods, fabricated with two or three potentially superior polymeric matrix materials.

* * * * * *

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Table 13. -- Results of Preliminary Stress-Rupture Tests[a]

| Specimen No. | End fitting[b] | Test temperature °F | Tensile load lbf | Time to rupture h | Failure |
|---|---|---|---|---|---|
| 01C | R/P | 200 | 13000 | 0.27 | (c) |
| 04C | R/P | 200 | 12000 | 0.03 | (c) |
| 02C | R/P | 200 | 11000 | 1.6 | (c) |
| 02A | R/V | 160 | 11000 | 4.2 | (d) |

[a] All tests performed under saturated humidity conditions.

[b] Type R/P end fittings used with C2W3 potting compound and cruciform wedges. Type R/V end fitting is a mechanical, wedge-type, compression fitting.

[c] Failure in free length, in the test chamber.

[d] Failure in the end fitting.

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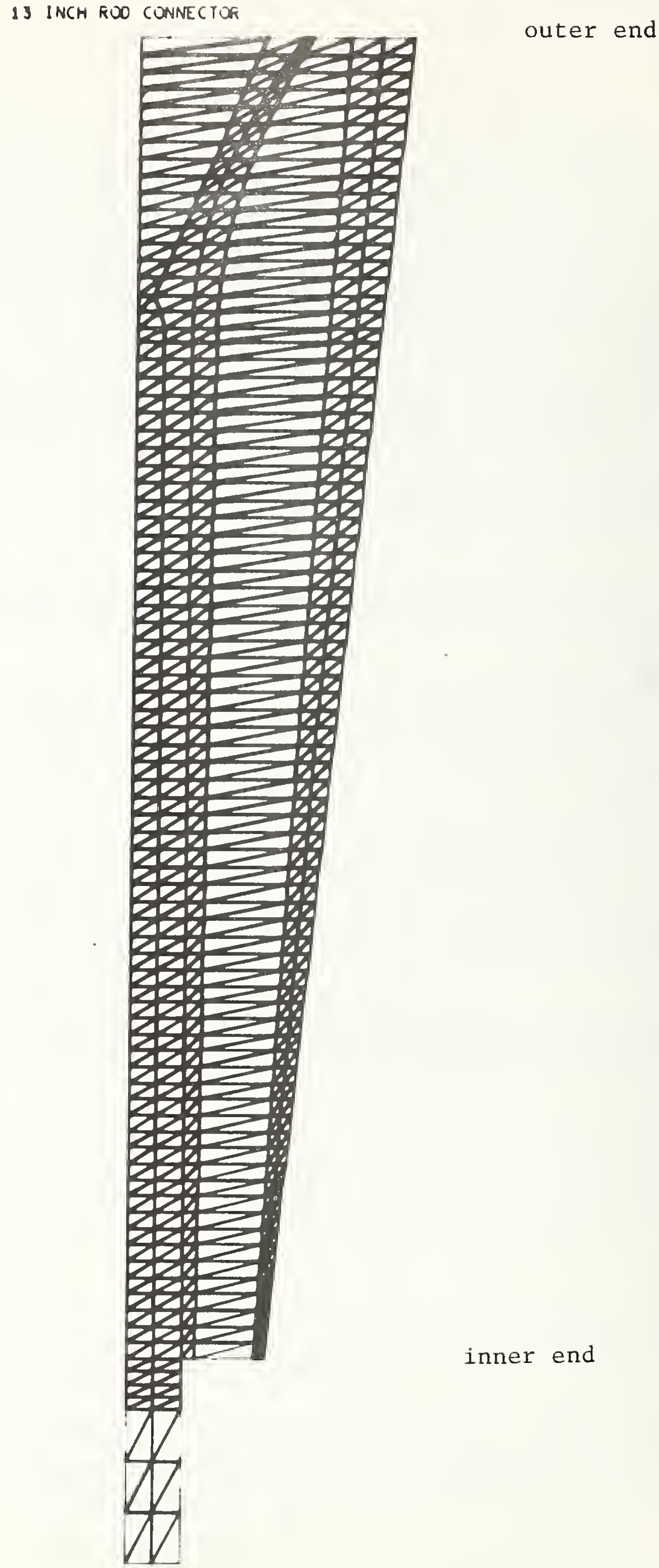
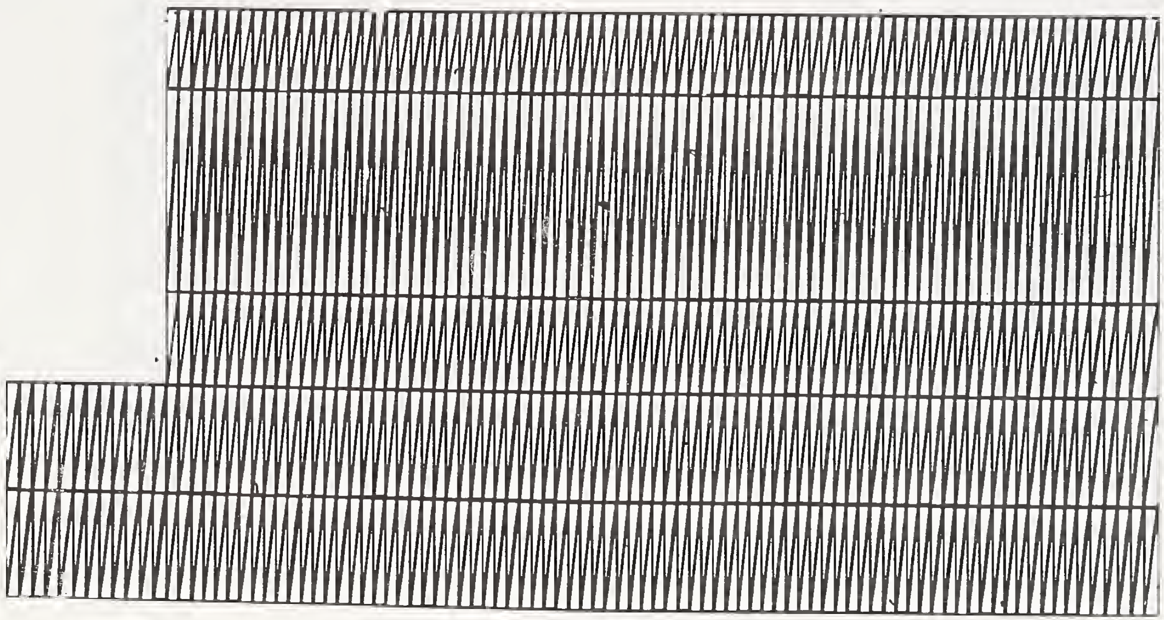



Figure 1 - Representative finite-element mesh for one general class of end fittings.

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| ENDFIT LENGTH | 12.400 | | ADH LENGTH | 11.4, 12.40 | | ROD RADIUS | .260 | | MAY 24, 1972 | |
| ENDFIT THICK. | .100 | | ADH THICK. | .365, .115 | | Z-LOAD | 25000. | | | |
| E11, ROD | .70000000+07 | | E22, ROD | .20760000+07 | | E, METAL | .10300000+08 | | V12, METAL | .330 |
| V12, V13, ROD | .253 | | G12, ROD | .78580000+06 | | E, ADHES | .51000000+05 | | V12, ADHES | .350 |



FINITE ELEMENT MESH

SCALE RATIO 10

Figure 2 - Finite-element mesh for a Mod 4 end fitting.

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| ENDFIT LENGTH | 12.400 | ADH LENGTH | 11.4, 12.40 | ROD RADIUS | .260 | MAY 24, 1972 | |
| ENDFIT THICK. | .100 | ADH THICK. | .365, .115 | Z-LOAD | 25000. | | |
| E11, ROD | .70000000+07 | E22, ROD | .20760000+07 | E, METAL | .10300000+08 | V12, METAL | .330 |
| V12, V13, ROD | .293 | G12, ROD | .78580000+06 | E, ADHES | .51000000+05 | V12, ADHES | .350 |

0006 0006

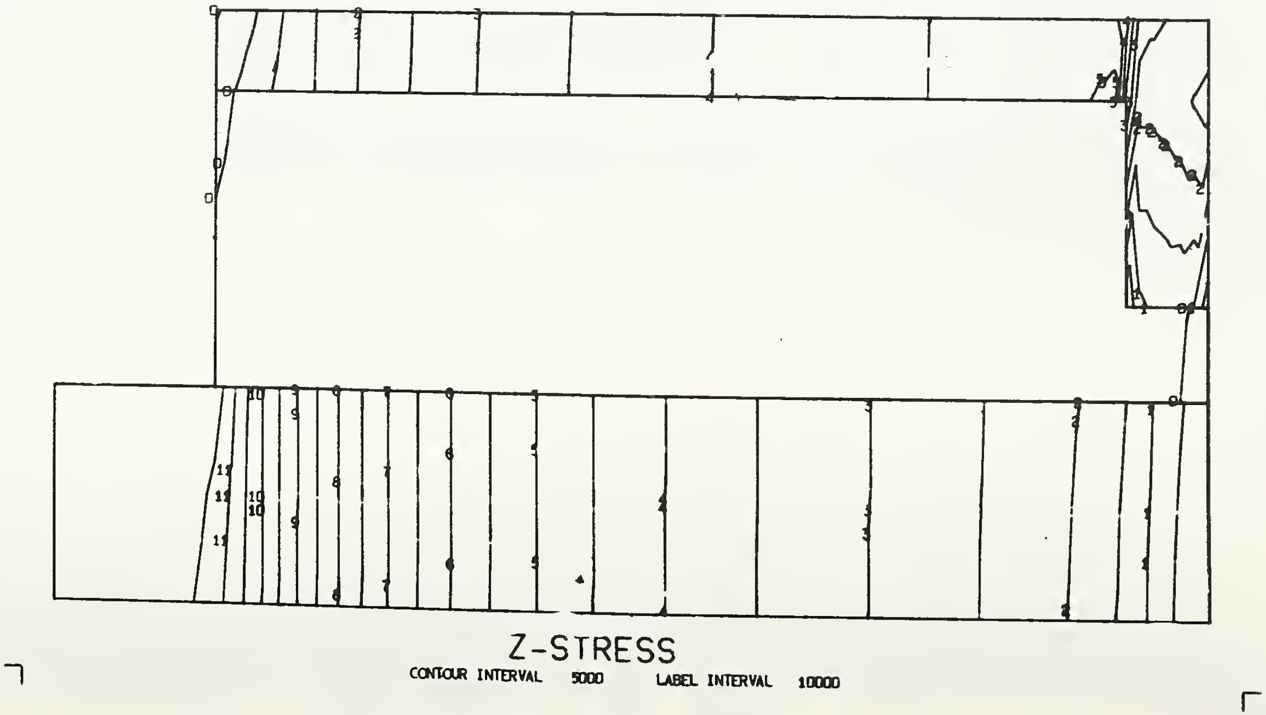



Figure 3 - Contour plot of the longitudinal normal stress in a Mod 4 end fitting.

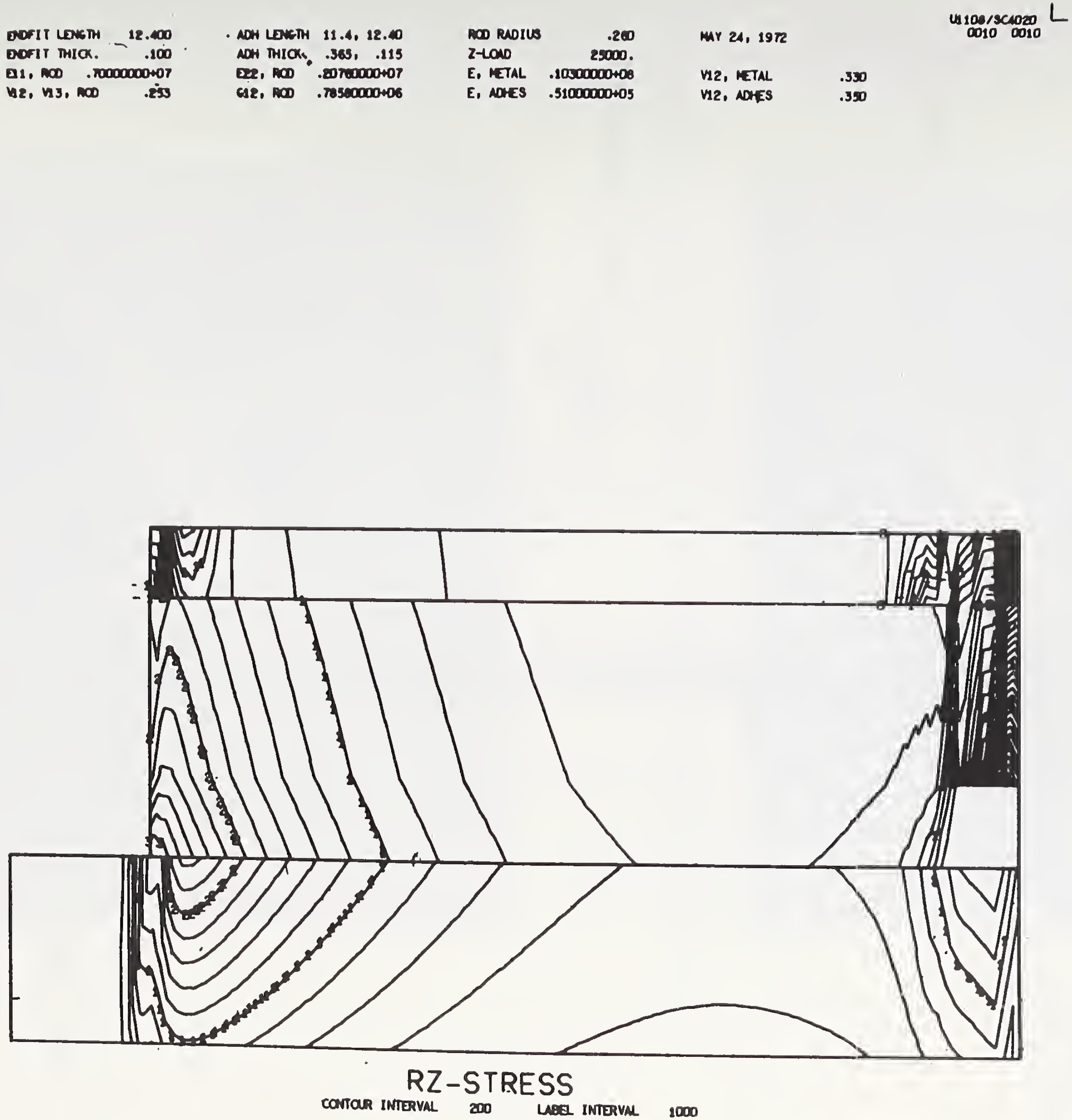



Figure 4 - Contour plot of the longitudinal shear stress in a Mod 4 end fitting.

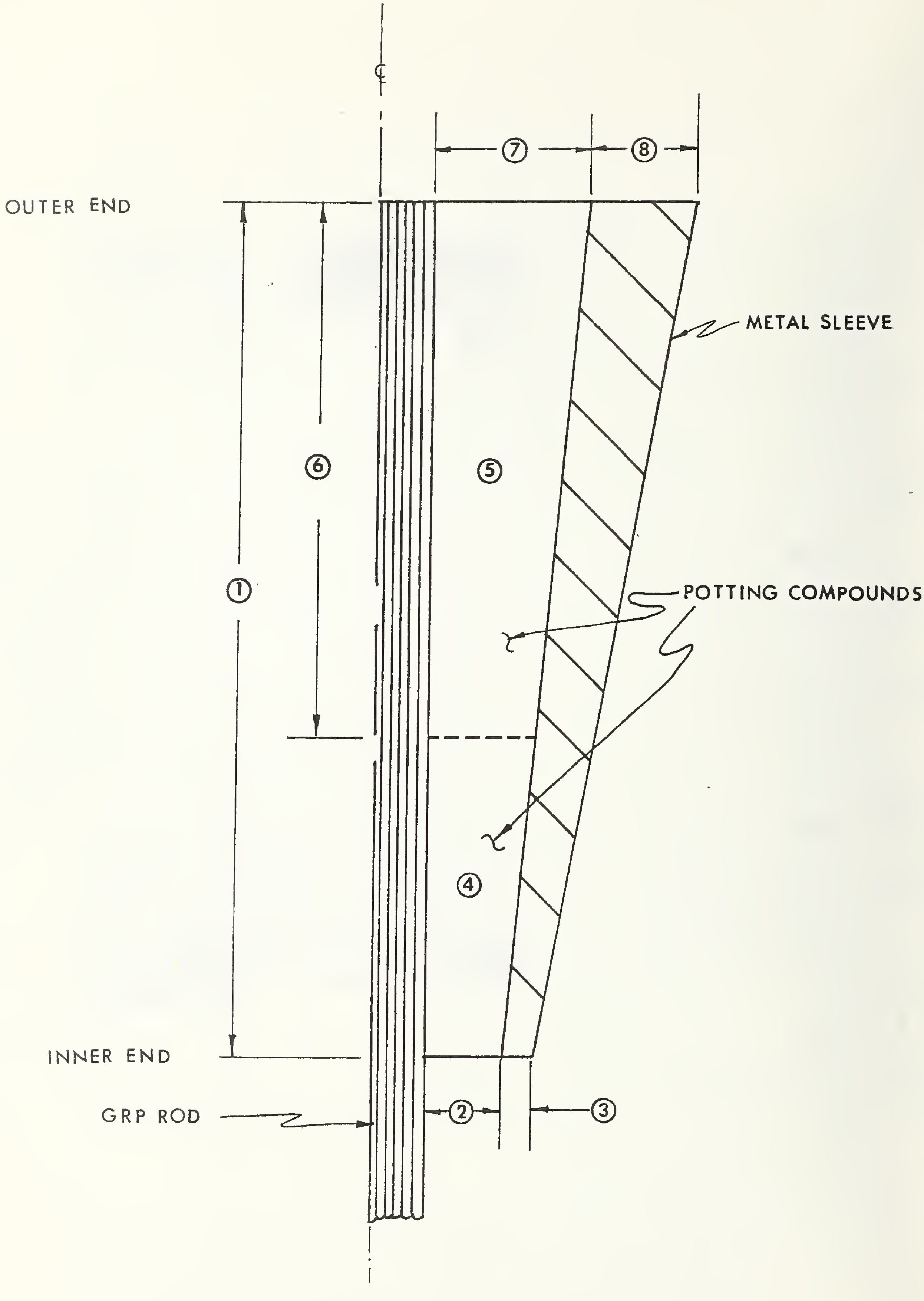



Figure 5 - Parameters for one general class of end fittings.

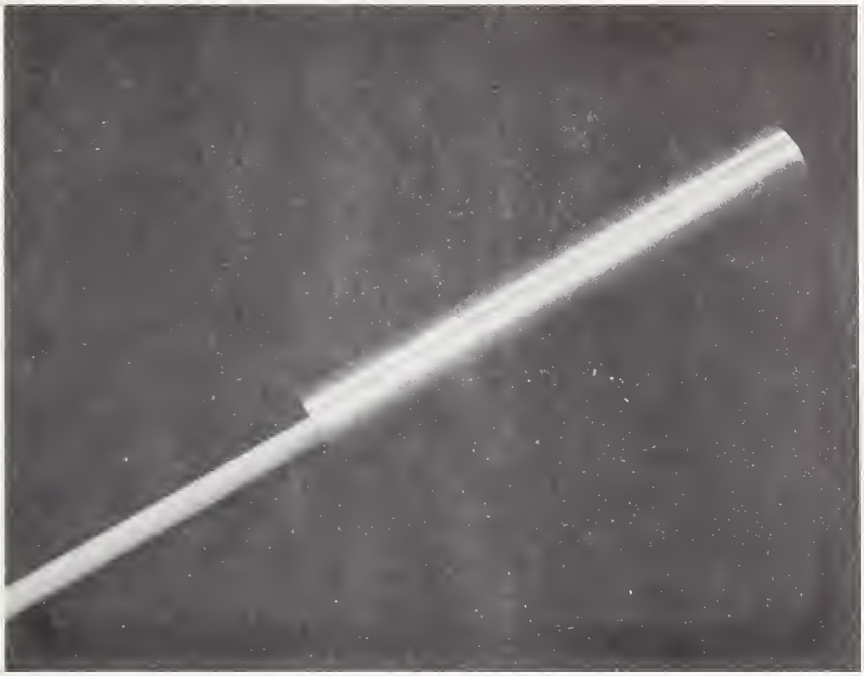


Figure 6 - Mod 3 experimental end fitting. Overall length, 12 in.

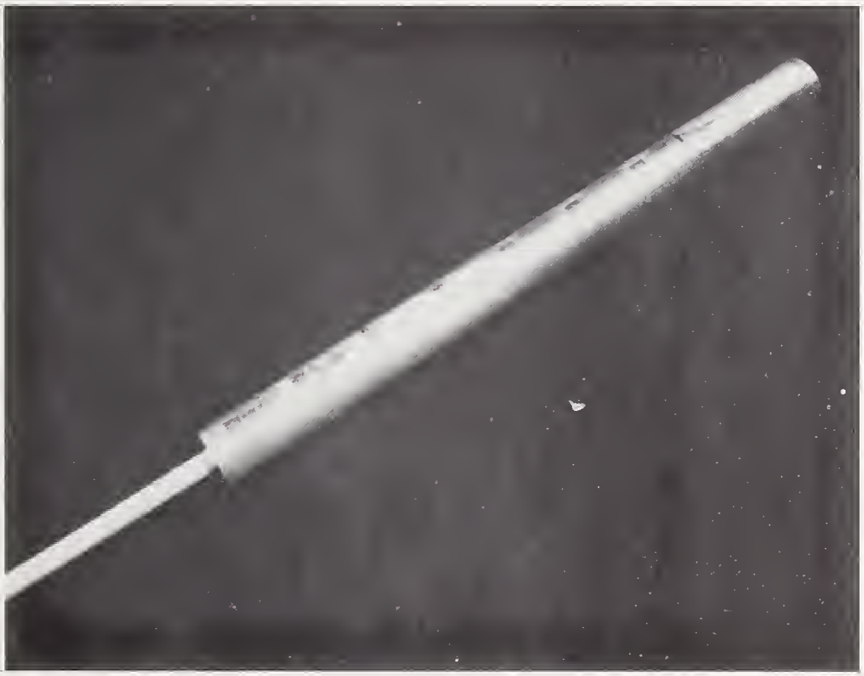


Figure 7 - Mod 4 experimental end fitting. Overall length, 18 in

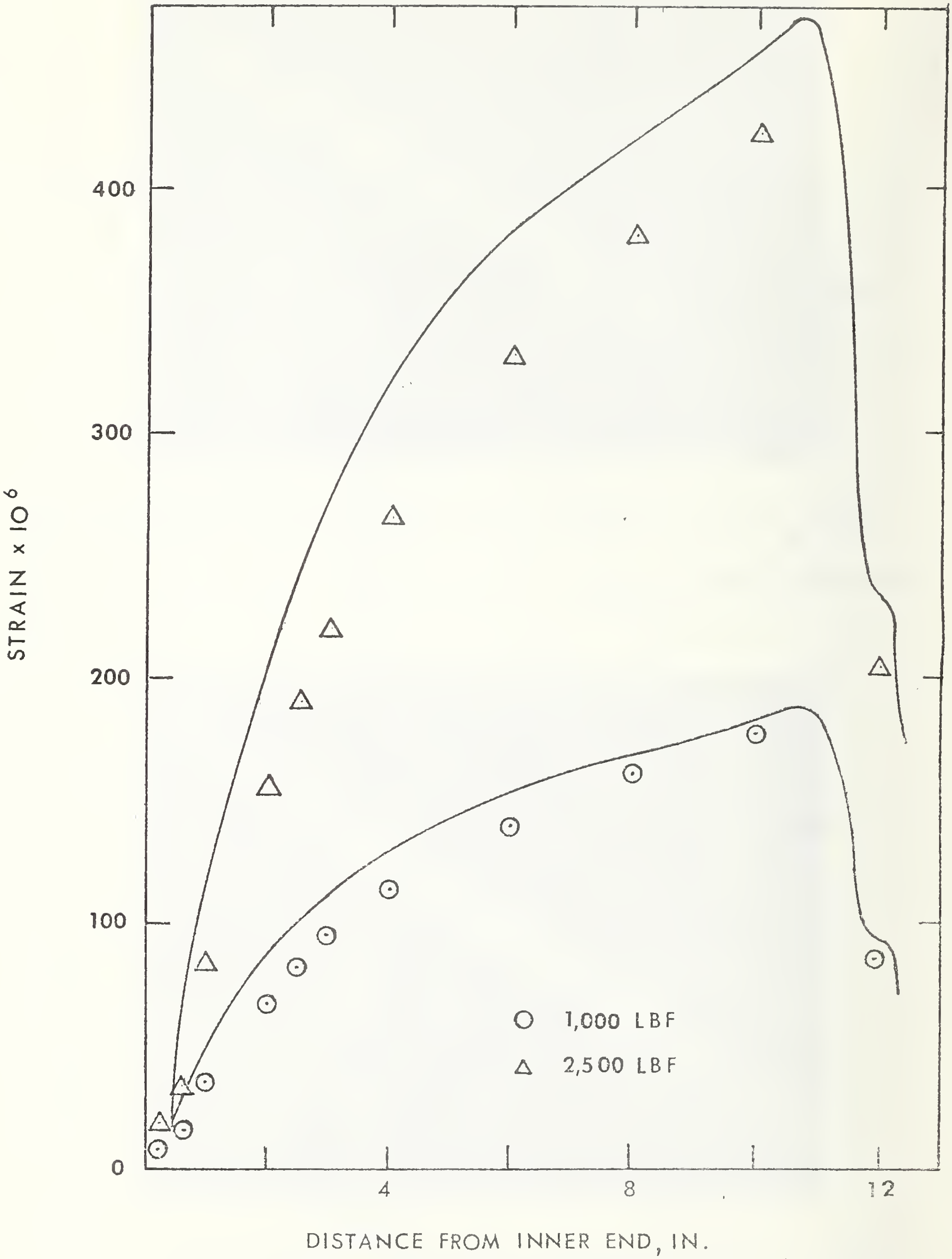



Figure 8 - Longitudinal normal strain on the outer surface of a Mod 4 end fitting, low tension loads. Points are experimental; curves are analytical.

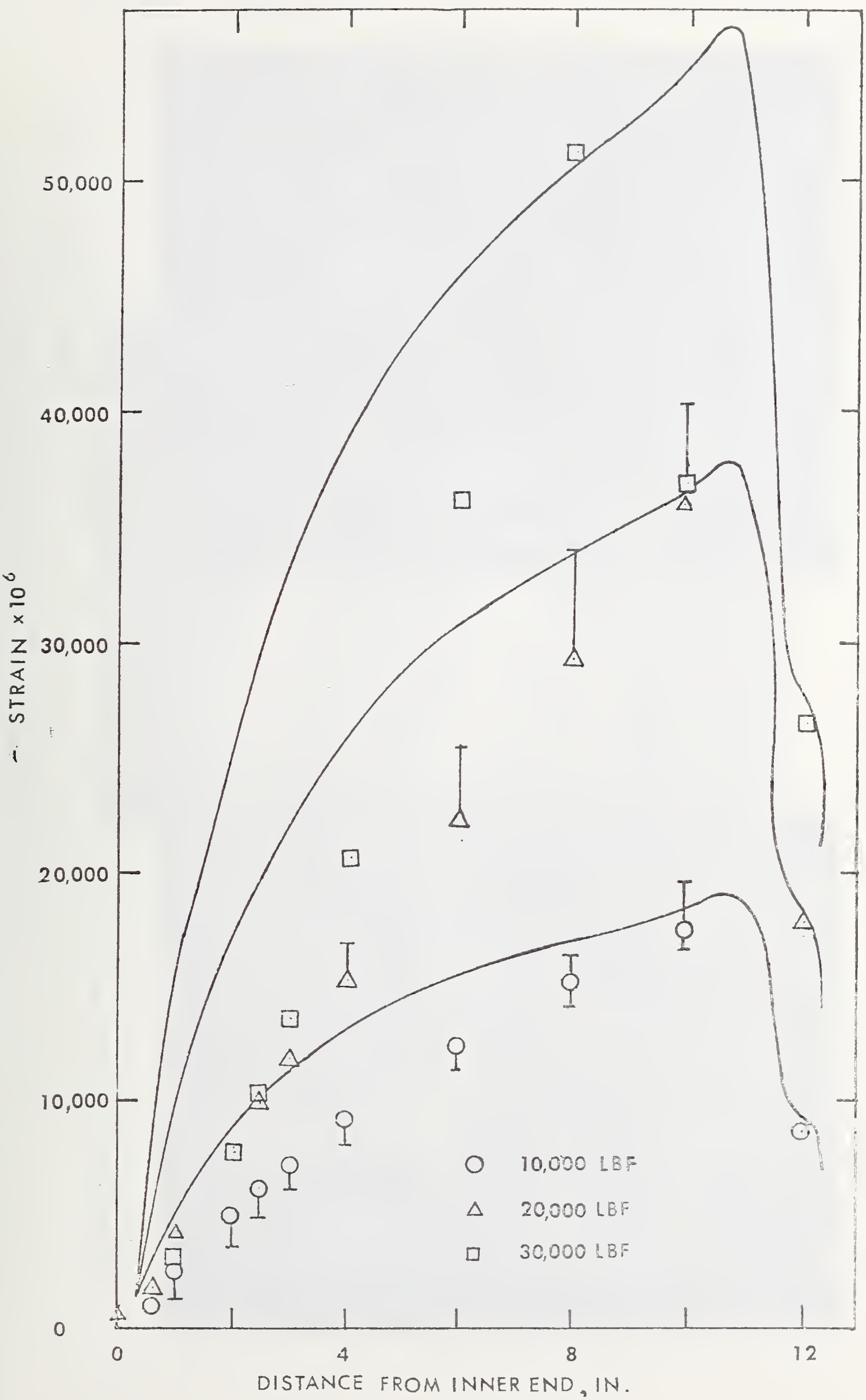



Figure 9 - Longitudinal normal strain on the outer surface of a Mod 4 end fitting, high tension loads. Points are experimental; curves are analytical.

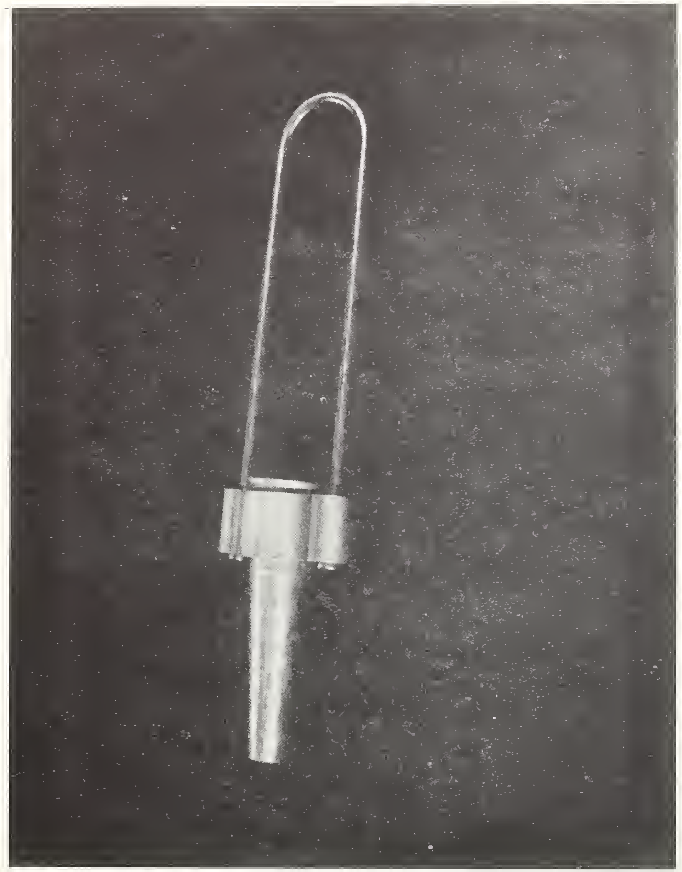


Figure 10 - Type R/P end fitting.

Figure 11 - Conical wedge (left) and fluted, cruciform wedge.

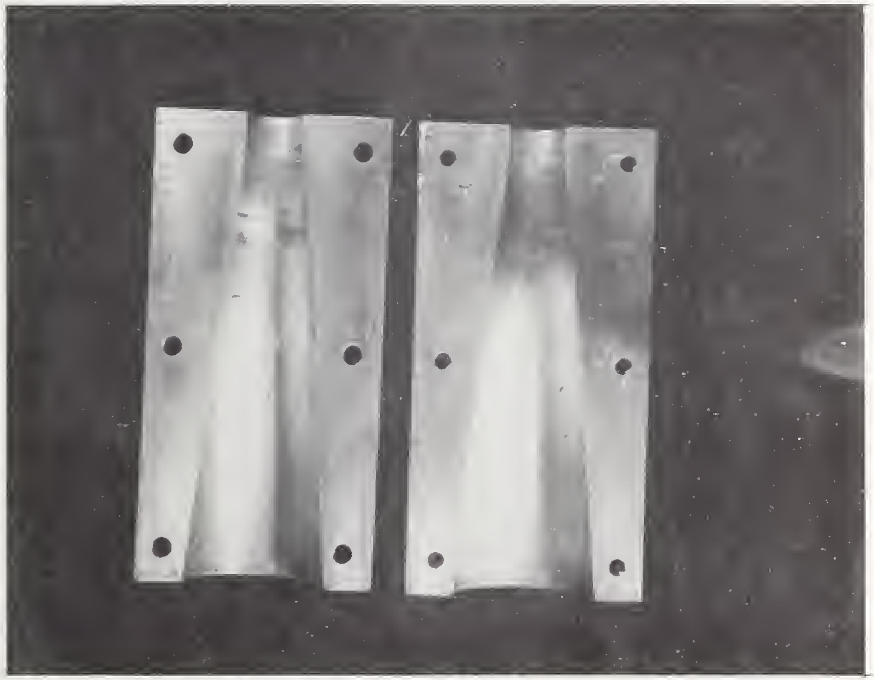


Figure 12 - Aluminum block experimental end fittings.

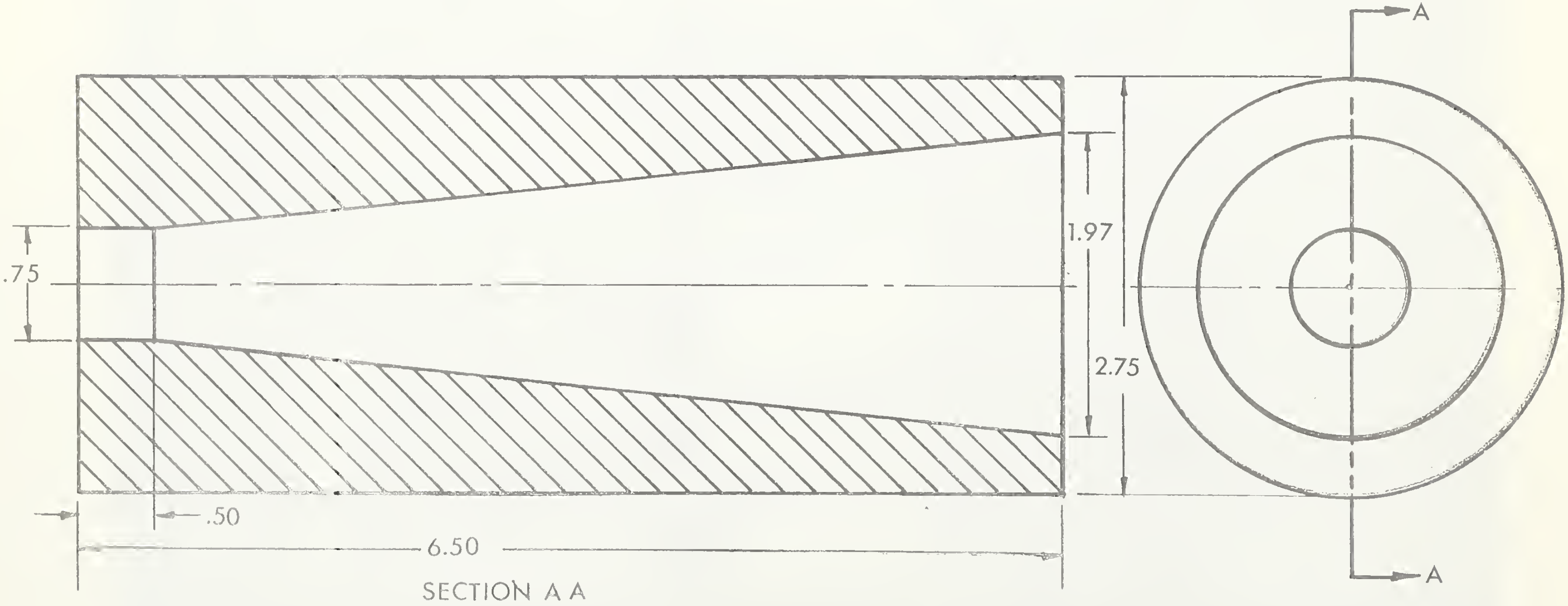



Figure 13 - H3M experimental end fitting. All dimensions in inches.

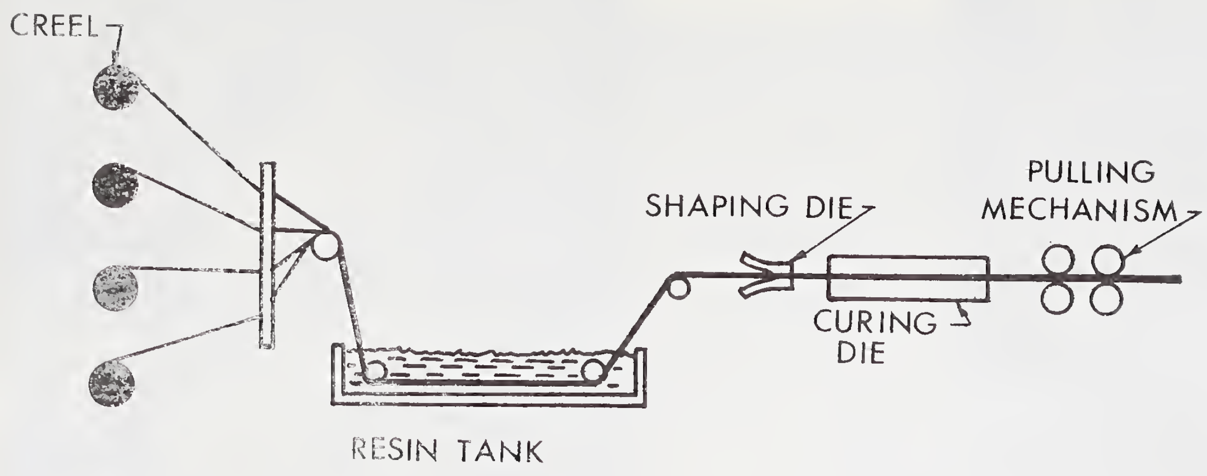



Figure 14 - Schematic representation of the pultrusion process.

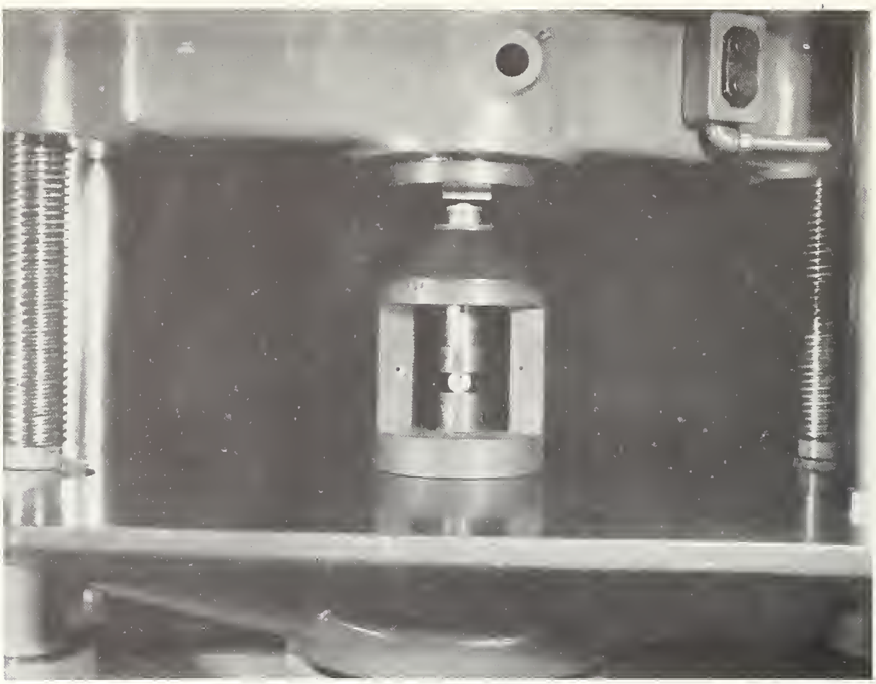


Figure 15 - Fractured disk specimen of FRP rod in subpress after diametral compression test.

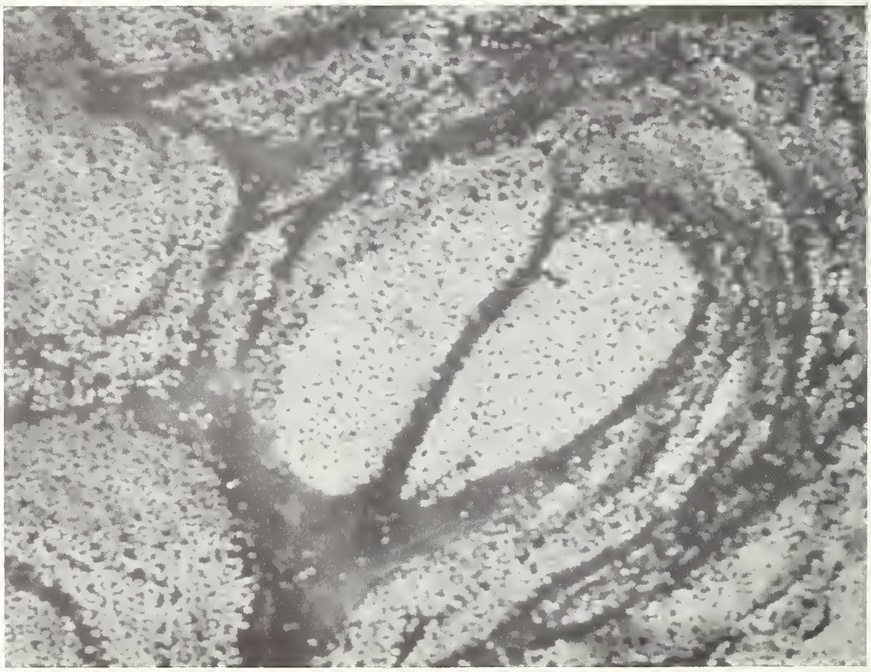


Figure 16 - Photomicrograph (X 70) of cross section of FRP rod.

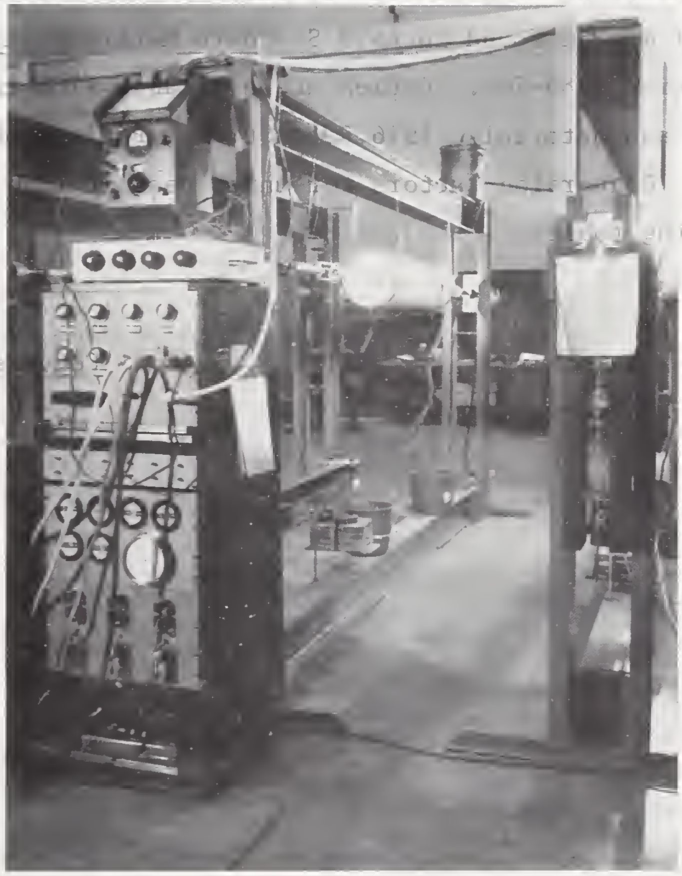


Figure 17 - One of six high-capacity creep testing machines for stress-rupture testing of long, FRP rod specimens under elevated temperature and saturated humidity conditions.

# APPENDIX

Factors for converting U. S. customary units to the International System of Units (SI) may be found in <u>ASTM Standard Metric Practice Guide</u> (ASTM Designation E380-70). Copies are available from the American Society for Testing and Materials, 1916 Race Street, Philadelphia, Pennsylvania 19103. Conversion factors for units used in this paper are given in the following table:

| Quantity | U. S. Customary Unit | SI Unit | Conversion Factor |
|---|---|---|---|
| Force | pound-force (lbf) | newton (N) | 1 lbf = 4.448 N |
| Length | inch (in) | centimeter (cm) | 1 in = 2.54 cm |
| | foot (ft) | meter (m) | 1 ft = 0.3048 m |
| | yard (yd) | meter (m) | 1 yd = 0.9144 m |
| Mass (weight) | pound (lb) | gram (g) | 1 lb = 453.6 g |
| | pound (lb) | kilogram (kg) | 1 lb = 0.4536 kg |
| Plane angle | degree (°) | radian (rad) | 1° = 0.01745 rad |
| Temperature | degree Fahrenheit (°F) | degree Celsius (°C) | °C = (5/9)(°F-32) |
| Density | $lb/in^3$ | $g/cm^3$ | $1\ lb/in^3 = 27.68\ g/cm^3$ |
| Roving yield | yd/lb | m/kg | 1 yd/lb = 2.016 m/kg |
| Speed | in/min | m/s | $1\ in/min = 4.233 \times 10^{-4} m/s$ |
| Stress | $lbf/in^2$ | $N/m^2$ | $1\ lbf/in^2 = 6895\ N/m^2$ |
| Viscosity, dynamic | poise (P) | $N{\cdot}s/m^2$ or $Pa{\cdot}s$[a] | $1\ P = 0.1\ N{\cdot}s/m^2$ |
| Weight per unit length | lb/ft | kg/m | 1 lb/ft = 1.488 kg/m |

[a] 1 pascal (Pa) = $1\ N/m^2$

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16. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)

A program was initiated to develop a non-conductive FRP rod material for use as guy lines and catenaries in large antenna systems. It is intended that the longterm structural properties of the new material, under adverse weathering conditions, be superior to those exhibited by the GRP rod and rope materials which are available at the present time. Two new end fittings for FRP rod were developed which out-perform commercially available fittings. These two fittings, which enable the tensile strengths of the rod materials to be accurately determined, include a shear-type fitting and a compression-type fitting. Deficiencies in the physical characteristics of existing GRP rod materials were identified, and modifications to the manufacturing processes were proposed to overcome these deficiencies. A subcontract was let for the manufacture of experimental GRP rods using the modified processes. A bank of six high-capacity creep testing machines was designed and is being assembled. These machines, which will accomodate long specimen lengths, are equipped with environmental chambers to permit stress-rupture testing under elevated temperature and saturated humidity conditions.

17. KEY WORDS (Alphabetical order, separated by semicolons) Composite materials; end fittings for FRP rod; environmental resistance of GRP rod; fiber-reinforced-plastic rod; glass-reinforced-plastic rod; guys, antenna; mechanical properties of GRP rod; pultrusion; reinforced plastic rod; stress-rupture of GRP rod.

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