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DESIGN FEASIBILITY ANALYSIS OF FIBER REINFORCED COMPOSITE ARMY --ETC(U)
JUN 79 E G SMITH, G BOURLAND, R N RAINEY DAAG46-78-C-0069
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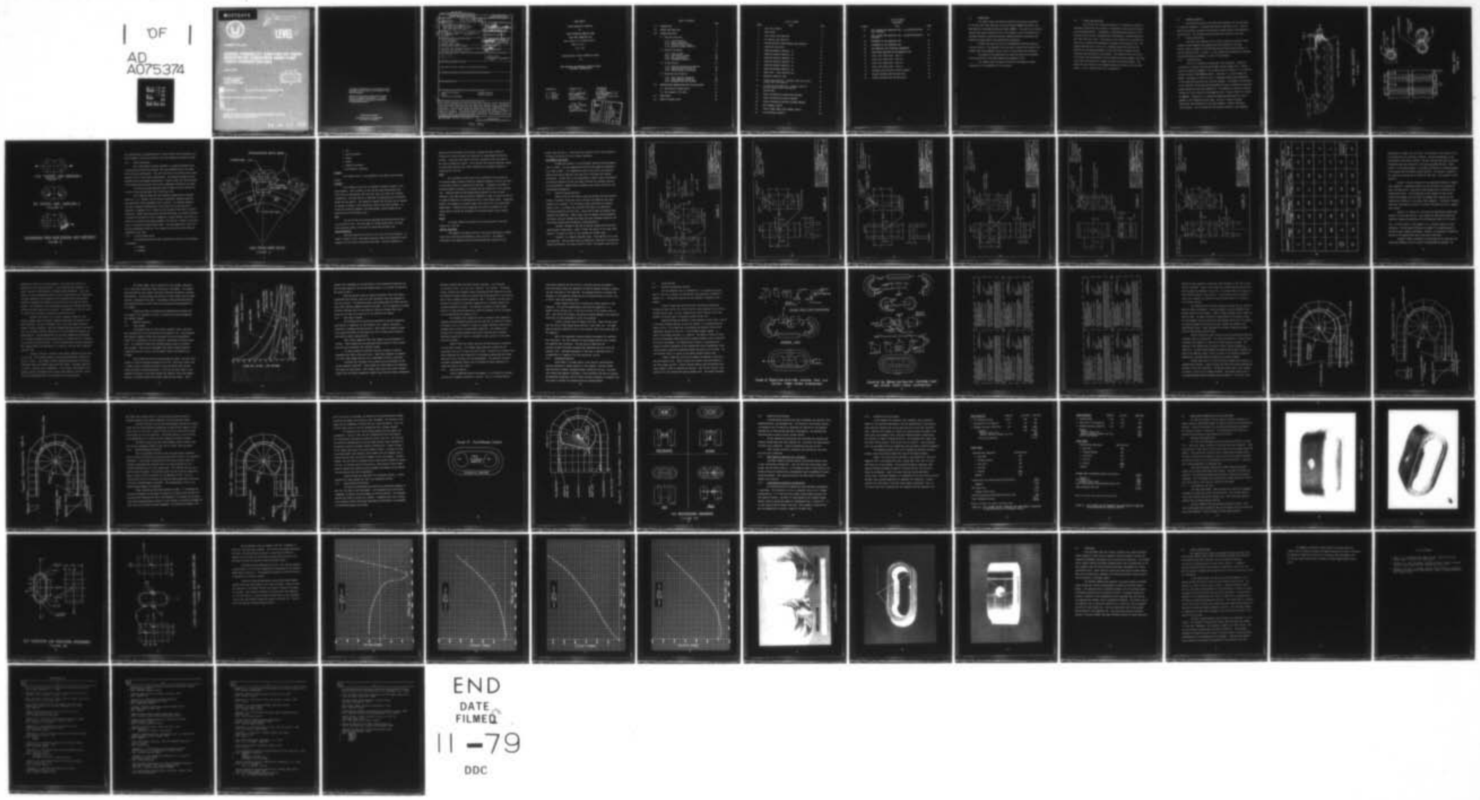

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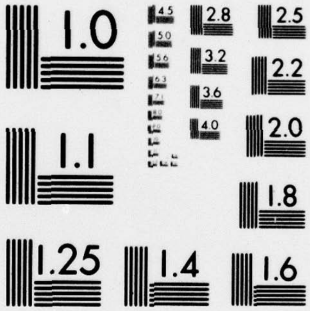
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This report documents the baseline definition, material, design, and manufacturing analyses performed on an Army Tank Track Connector Link. Significant technical issues were identified and potential solutions recommended for further study. The selected design was chosen from a trade study of several potential concepts. These design concepts and detailed results of the trade study are presented. Structural analysis and design was performed on the selected concept to establish predicted performance. Cost analyses were also conducted to determine production costs.

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FINAL REPORT

DESIGN FEASIBILITY ANALYSIS
OF
FIBER REINFORCED COMPOSITE ARMY
TANK TRACK CONNECTOR LINK

Vought Report No. 2-53500/9R-52234

AMMRC TR 79-41

8 June 1979

Prepared Under Contract DAAG46-78-C-0069

for

ARMY MATERIALS AND MECHANICS RESEARCH CENTER
WATERTOWN, MASSACHUSETTS

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1.0 INTRODUCTION

This report covers the baseline definition and analysis performed on the Army Tank Track Connector Link under Contract DAAG46-78-C-0069 to the Army Materials and Mechanics Research Center (AMMRC). The scope of the contract required that design feasibility of an end connector link for the M60 tank be evaluated through a baseline definition, composite materials evaluation and selection, design analysis and manufacturing evaluation.

The M60 tank requires the use of approximately 1200 end connector links per vehicle. The connector links are used to connect and transfer load between track pad assemblies and are a part of the primary drive mechanism.

The purpose of the program was to study the technical and manufacturing feasibility of building composite end connector links.

This report covers the scope of activities performed by Vought Corporation in the completion of this contract.

2.0 PURPOSE AND OBJECTIVES

The utilization of composite materials in aerospace and commercial automotive applications has resulted in lightweight, high strength structure with improved durability. Consequently, advanced composite materials offer potential weight savings, improved vehicle performance, increased durability, and lower life cycle costs. The purpose of this program was to evaluate the feasibility of design and manufacture of composite end connector links. The program objective was to arrive at a suitable design which maximizes the benefits and increased performance of the vehicle while imposing minimum limitations and penalties on the customer. This objective could not be met. The existing tank end connector link was forged from high strength, low carbon, alloy steel, heat treated to increase strength and surface hardness. The weight and cost targets for the composite design were those of the existing design: 2.6 lbs. and $3.50 per link, respectively.

3.0 PROGRAM DISCUSSION

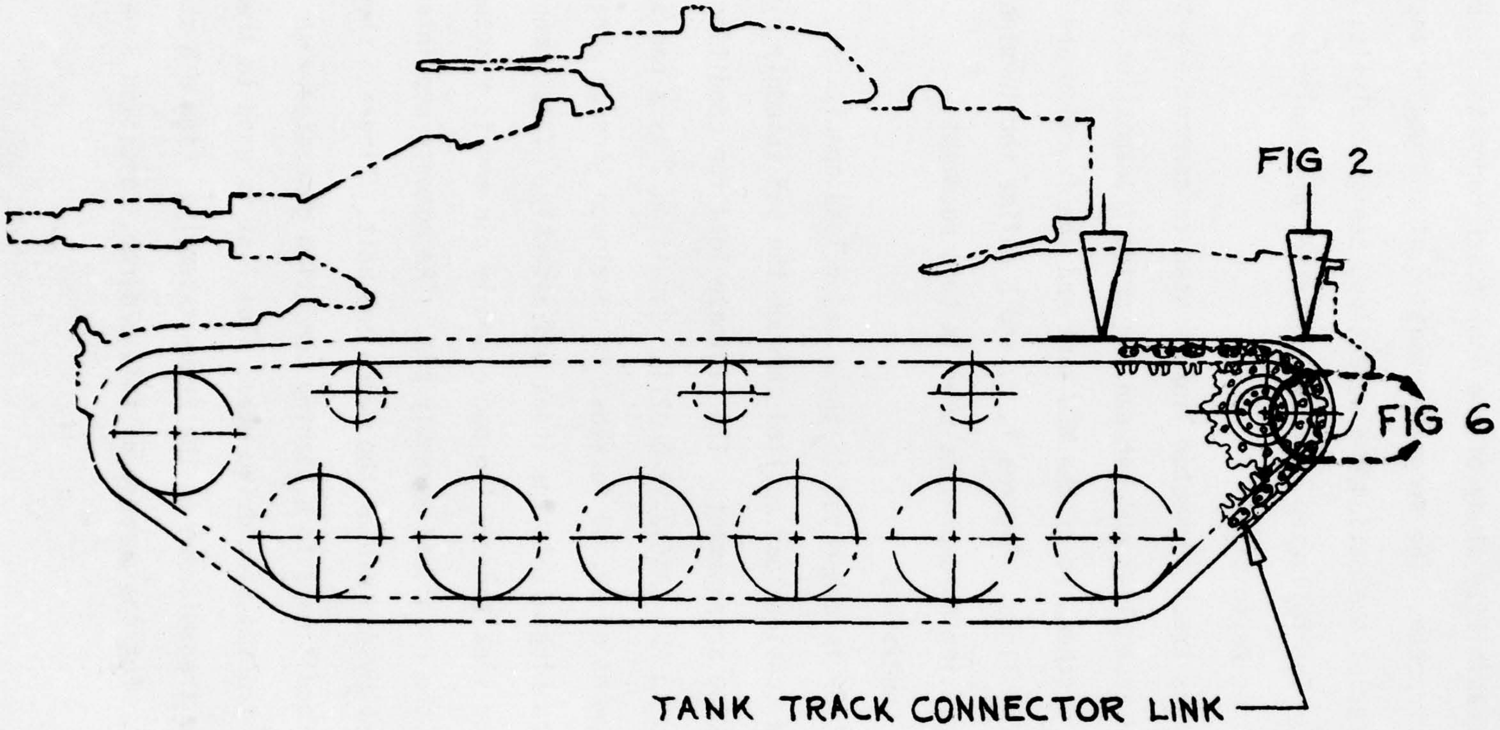
The feasibility study of the tank track connector link was performed as originally proposed. The program consisted of four major tasks: baseline definition, material evaluation and selection, design analysis, and manufacturing evaluation. The following sections describe the results of the tasks.

3.1 Baseline Definition

The tank track connector link is used to connect and transmit loads between the pad assemblies and between the drive transmission and pads. Figure 1 shows a schematic of the M60 tank and the function and locations of the end connector links. Figures 1, 2, and 5 define the terminology of adjacent, mating and connecting hardware, as used in this document.

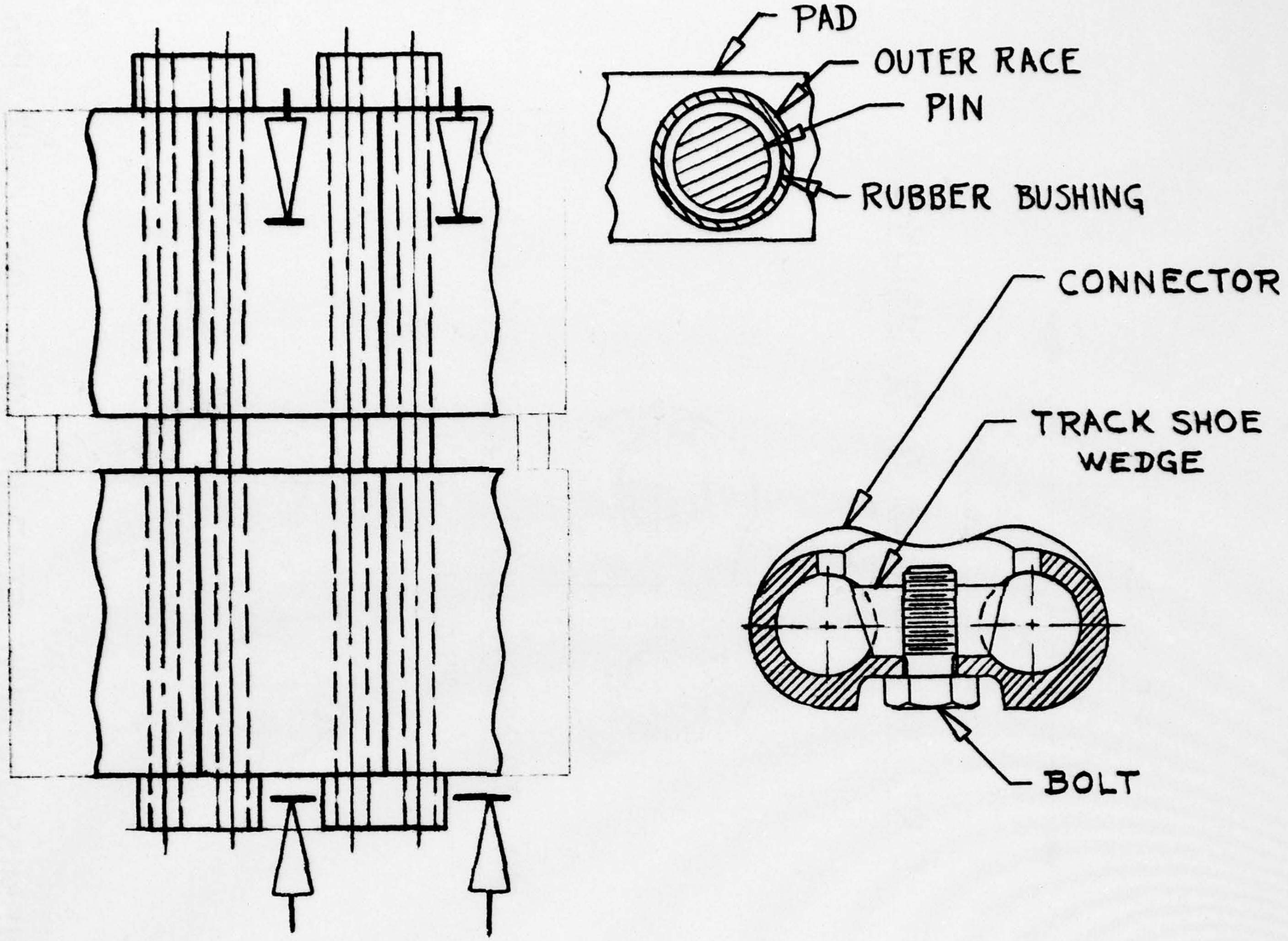
3.1.1 Load Conditions

The link is subjected to three major load conditions. Condition 1 is defined as a tension load applied through the pad assembly pins. Figure 3 shows this loading arrangement. The ultimate load for condition 1 is 11,700 lbs. and was defined in RFQ DAAG46-78-Q-0271. Condition 2 is a pad assembly pin moment. The moment of 19,000 in.-lbs. is developed through shear deformation of the rubber bushing within the track pad assembly. This moment is transmitted to the connector link through the pad assembly pin and is reacted by an opposing moment through the other pad assembly pin. The moments are internally balanced through the link by the use of the wedge and bolt. Figure 4 shows this loading arrangement. Condition 3 is a bearing condition generated when the link is engaged in the transmission drive gear. The link is used to transmit torque from the transmission to the track assembly. Figure 5 shows this load condition. For the purpose of this program, condition 3 was addressed



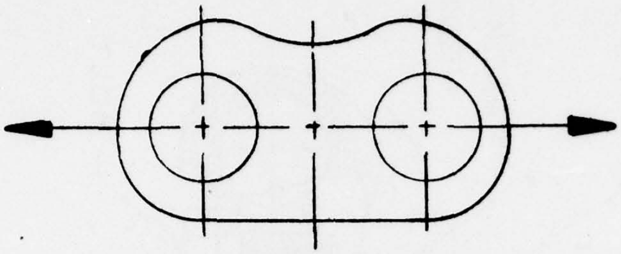
M60 TANK SCHEMATIC

FIGURE 1

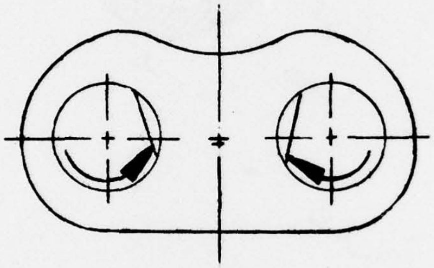


TRACK DETAIL

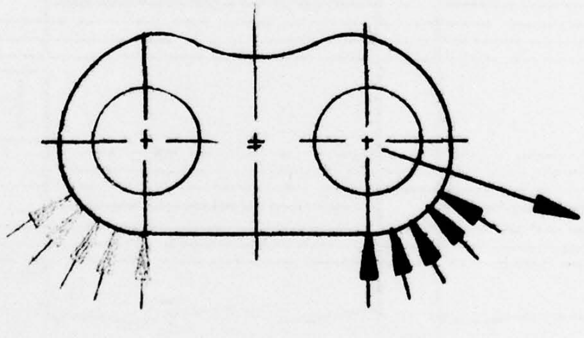
FIGURE 2



LINK TENSION LOAD CONDITION 1
FIGURE 3



PIN TORSION LOAD CONDITION 2
FIGURE 4



TRANSMISSION DRIVE GEAR BEARING LOAD CONDITION 3

FIGURE 5

only qualitatively: the determination of loads, bearing stress allowables, and wear allowables can only be defined by the final geometry and material system.

3.1.2 Design Constraints

Due to the amount of mating, adjacent, or connecting hardware used in conjunction with the end connector link, many dimensions had to be common to the existing configuration. The use of the link in the primary drive system requires that all cam surfaces be maintained. The dimension between pins was dictated by the pad assembly configuration. Figure 6 shows the link positioned in the transmission drive gear and critical dimensional constraints are shown.

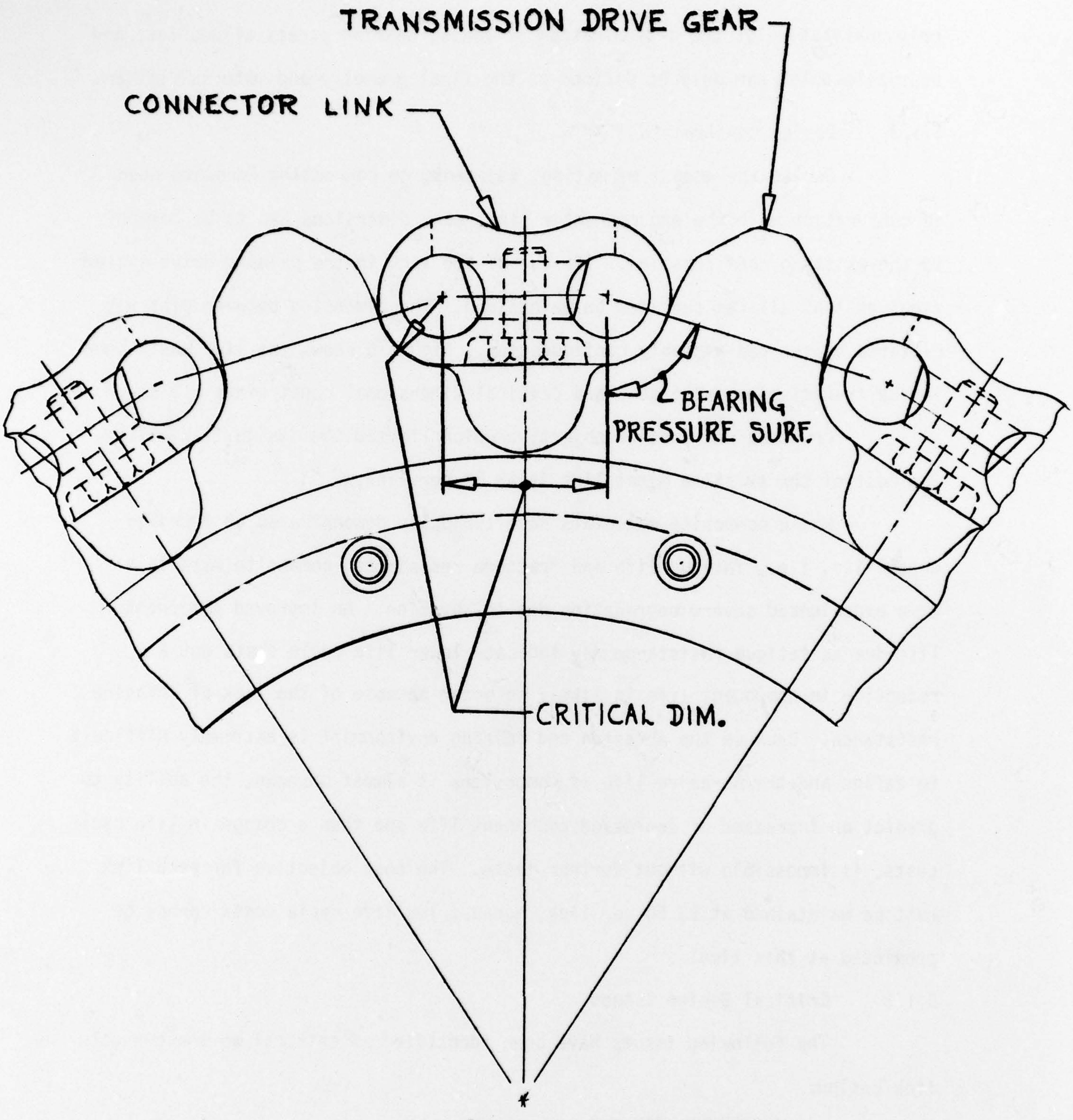
Low cost was another objective which limited the design flexibility. The cost of the existing metal link is $3.50 per link.

While composite materials have typically demonstrated an improved durability, i.e., fatigue life and fracture resistance, composite materials have experienced severe degradation due to abrasion. An improved component life due to fatigue resistance may indicate lower life cycle costs but a reduction in component life is likely to occur because of the lack of abrasion resistance. Because the abrasion and bearing environment is extremely difficult to define and the abrasive life of composites is almost unknown, the ability to predict an increased or decreased component life and thus a change in life cycle costs, is impossible without further tests. The cost objective for each link must be maintained at $3.50 per link, because low life cycle costs cannot be predicted at this time.

3.1.3 Critical Design Issues

The following issues have been identified as critical to the connector link design:

- strength
- stiffness



LINK/DRIVE GEAR DETAIL

FIGURE 6

- cost
- wear and abrasion
- impact
- weight
- chemical resistance
- environmental resistance

STRENGTH

The strength issue is self-explanatory, and need not be discussed further.

STIFFNESS

The stiffness of the link is important to maintain tension in the track assembly. Lower stiffness in the link may seem insignificant, but since there are approximately 600 links per track, the lower link stiffness is magnified. The track tension is important in keeping the track from being thrown from the vehicle. The problem of reduced link stiffness can be resolved by changing or adding a "belt tensioning" system to the track assembly. By solving the stiffness problem in the above manner, design freedom can be granted to the link stiffness issue.

COST

The cost of the link has been discussed and the objective has been set at $3.50 per link. This cost does not include installation, but these costs should be similar to the costs of installing the metal link.

WEAR AND ABRASION

Wear and abrasion are critical to the life of the end connector. As shown in Figures 5 and 6, high bearing pressure loads can be expected to occur between the link and the transmission drive gear. The drive mechanism is exposed to the environment which further increases the wear problem by allowing dirt, sand, and other grit materials to lodge between the bearing surfaces. Lubricants would add only minimal protection since they would be worn away or washed off rapidly. Since the wear and abrasion conditions cannot be sufficiently defined, this effort addresses only conceptual methods of increasing the link life.

IMPACT

One consideration which led to the initiation of this program was the improved damage tolerance offered by composite hardware to blast, ballistic, or high energy impact as experienced by the Army. A composite link offers a promising method to improve the survivability and reliability of the connector link. Composite materials have demonstrated potential for use as armor; Reference 1 describes testing which was conducted in order to assess the ability of composite materials to withstand ballistic or high energy impact. Composites, however, are damaged at low energy impact levels which will not significantly damage metal. Therefore, while composites may offer an advantage for high energy impact, they may be susceptible to low energy impact such as ground debris.

WEIGHT

The weight objective has been set at less than that of the metal forged link, 2.60 lbs.

CHEMICAL RESISTANCE

The chemical environment which the link may be subjected to includes diesel fuel, and other petro-chemicals, fuels, and oils. The chemical resistance of the composite can be tailored through the selection of the proper fiber and matrix. Since most fiber materials resist these chemicals, the matrix selection will be of primary importance.

ENVIRONMENTAL RESISTANCE

The M60 tank operates in an environment ranging from approximately -40°F to +120°F. Hot soak temperatures may drive the composite temperature to as high as 200°F. This temperature range is well within the operating range of most matrix materials with some loss of stiffness and strength encountered. The M60 tank is also operational in humid tropical environments so moisture absorption and the associated stiffness and strength reduction must be considered. Reduced design allowables were used to account for this environmental degradation.

3.1.4 Baseline Concept Selection

Based on the critical design issues and guidance from the technical monitor, five major issues were used to evaluate the composite tank track connector link concepts. The five major issues, which were all weighted equally, were: (1) weight, (2) structural efficiency, (3) durability, (4) manufacturability, and (5) cost. Issues such as wear and abrasion were combined with durability. Other issues, such as chemical and environmental resistance, were not included since they are matrix dominated properties and most design concepts were not material system sensitive.

Figures 7 through 12 show the six design concepts which were evaluated through a trade study. Figure 13 shows the results of the trade study. Concept 5, as shown in Figure 11, was selected for further study.

Concept 1 is a typical composite layup. Plies would be cut to near net dimensions. Each ply would then be worked over a male tool to achieve the proper configuration, and excess material trimmed. The assembly would then be

NOTES:

1. FABRICATE FROM GLASS/EPOXY FABRIC - ONE PIECE COCURED PART.
2. FILL WITH GLASS/EPOXY RANDOM FIBER.
3. WEIGHT = .63#

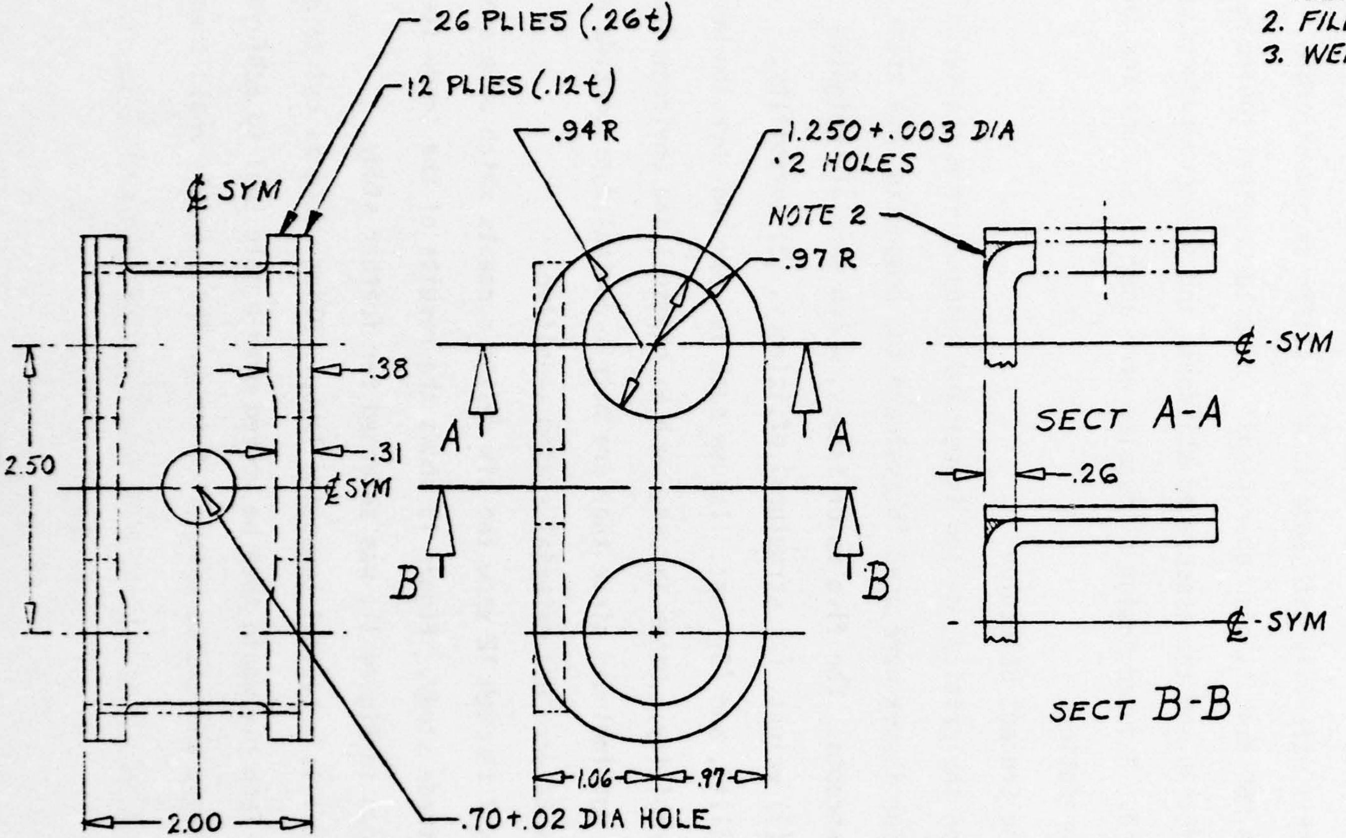


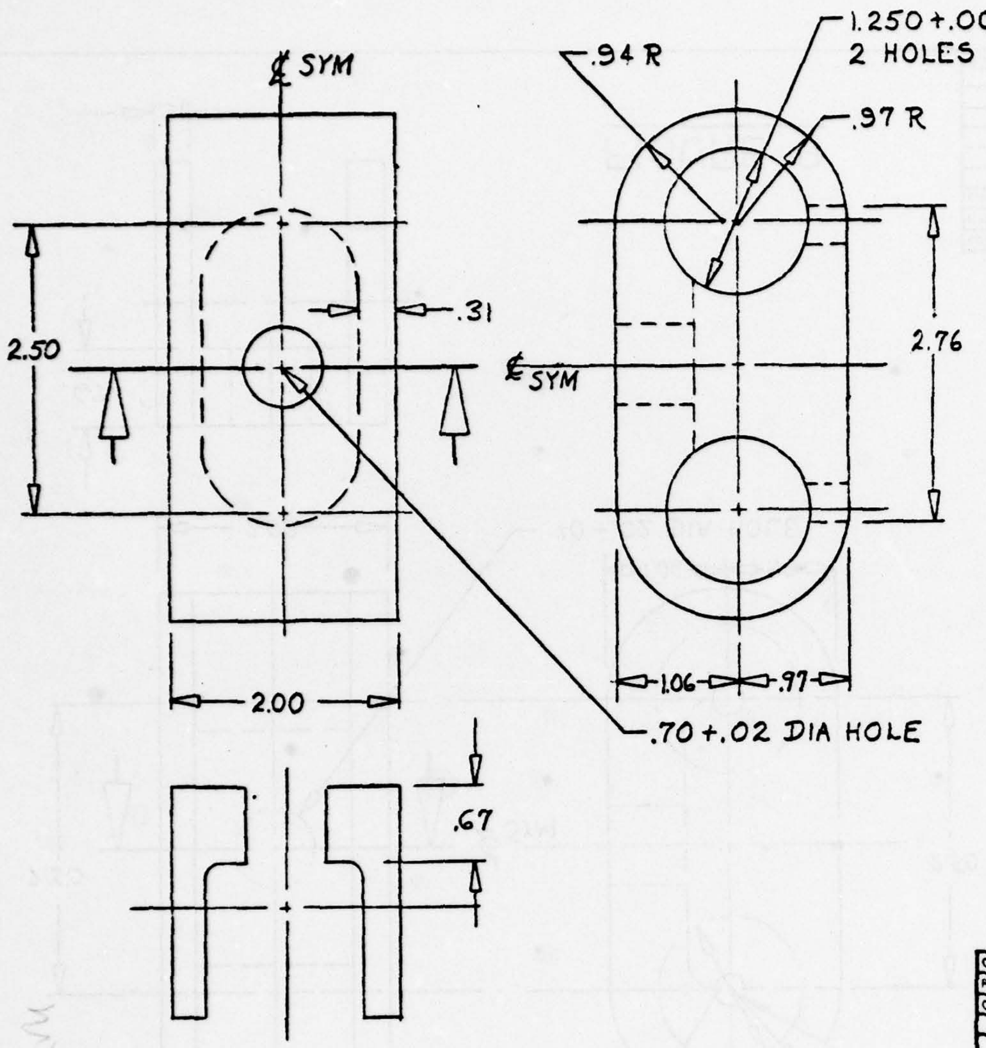
FIGURE 7

CONTR NO.
PREP RAINEY 1-23-
CHKD
DESIGN GROUP NAME ADVANCED COMPOSITES

VOUGHT CORPORATION
Post Office Box 225907
Dallas, Texas 75265

CONNECTOR
ADVANCED COMPOSITE #1

SIZE
FSCM NO. 80378
DWG NO. FIGURE 7
REV
SCALE 1/1
SHEET



NOTES:
1. FABRICATE FROM GLASS/EPOXY RANDOM FIBER - ONE PIECE PRESS MOLDED PART.
2. WEIGHT = .73 #

FIGURE 8

CONTR NO.
PREP RAINEY 12/4/[illegible]
CHKD
DESIGN GROUP NAME
ADVANCED COMPOSITES

VOUGHT CORPORATION
Post Office Box 225907
Dallas, Texas 75265

CONNECTOR
ADVANCED COMPOSITE #2

SIZE 1/17 FSCM NO. 80378 DWG NO. FIGURE 8 REV
SCALE 1/1 SHEET

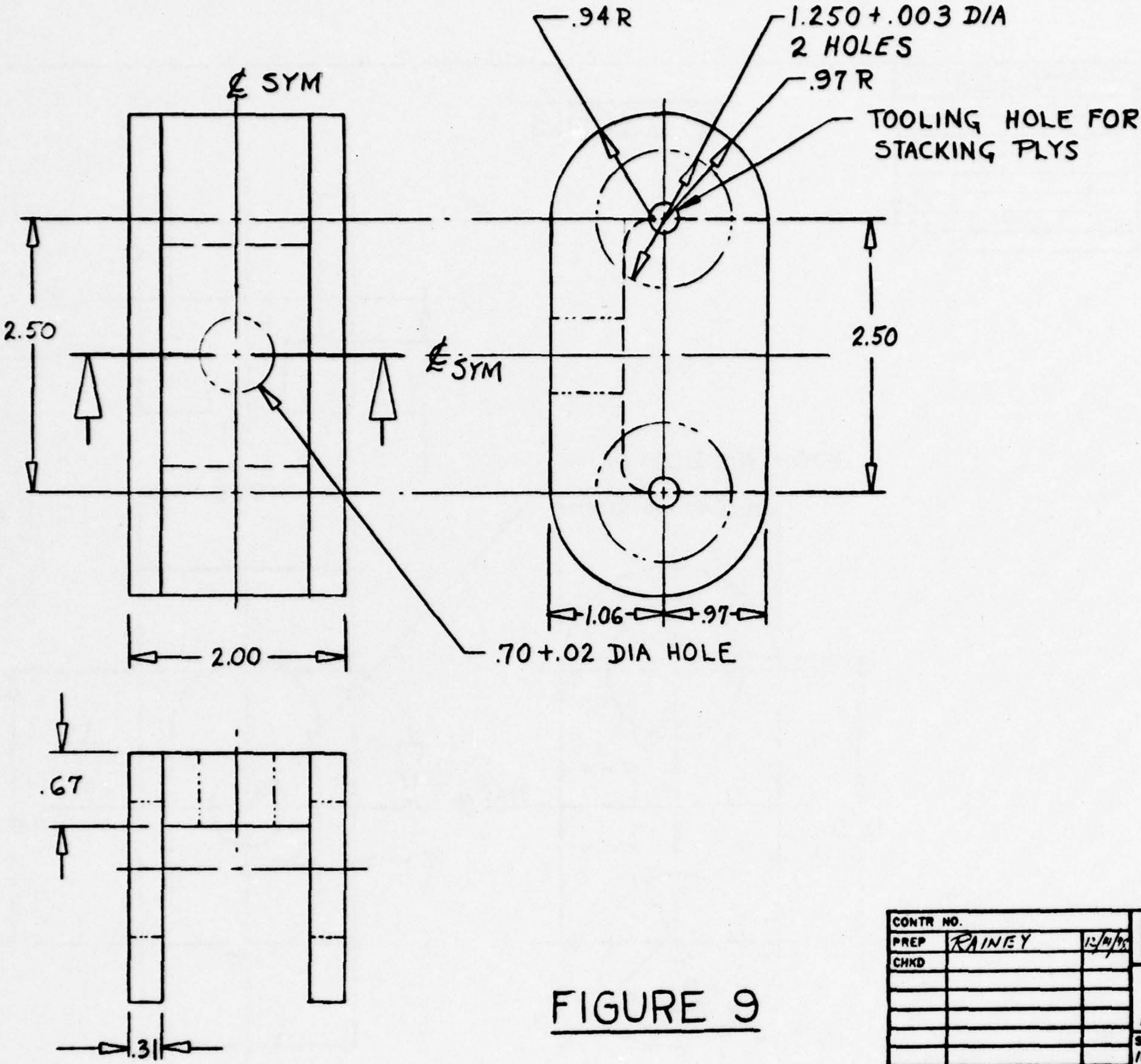


FIGURE 9

NOTES:

1. FABRICATE FROM GLASS/EPOXY FABRIC-
ONE PIECE COCURED PART OF
STACKED PLIES.

2. WEIGHT = .92#

CONTR NO.
PREP RAINEY 12/4/75
CHKD
DESIGN GROUP NAME
ADVANCED COMPOSITES

VOUGHT CORPORATION
Post Office Box 225907
Dallas, Texas 75265

CONNECTOR
ADVANCED COMPOSITE #3

SIZE 11/17 FSCM NO. 80378 DWG NO. FIGURE 9 REV
SCALE 1/1 SHEET

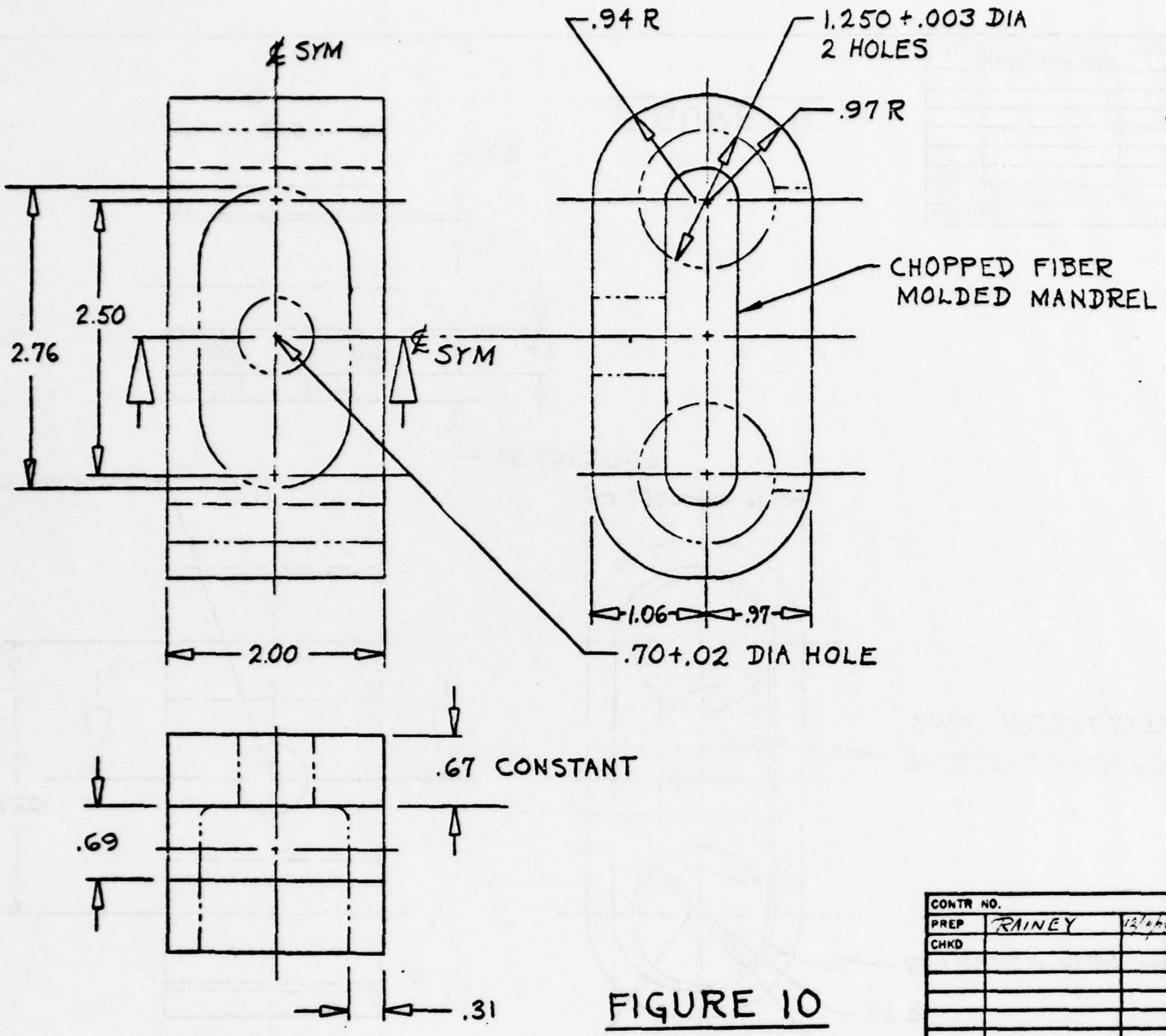


FIGURE 10

NOTES:

1. FABRICATE FROM GLASS/EPOXY TAPE WRAPPED AROUND A CHOPPED GLASS/EPOXY MANDREL.
2. WEIGHT = .73 #.

CONTR NO.
PREP RAINEY 12/4/7
CHKD

DESIGN GROUP NAME
ADVANCED COMPOSITES

VOUGHT
CORPORATION
Post Office Box 225907
Dallas, Texas 75265

CONNECTOR
ADVANCED COMPOSITE #4

SIZE 11/17
FSCM NO. 80378
DWG NO. FIGURE 10
REV
SCALE 1/1
SHEET

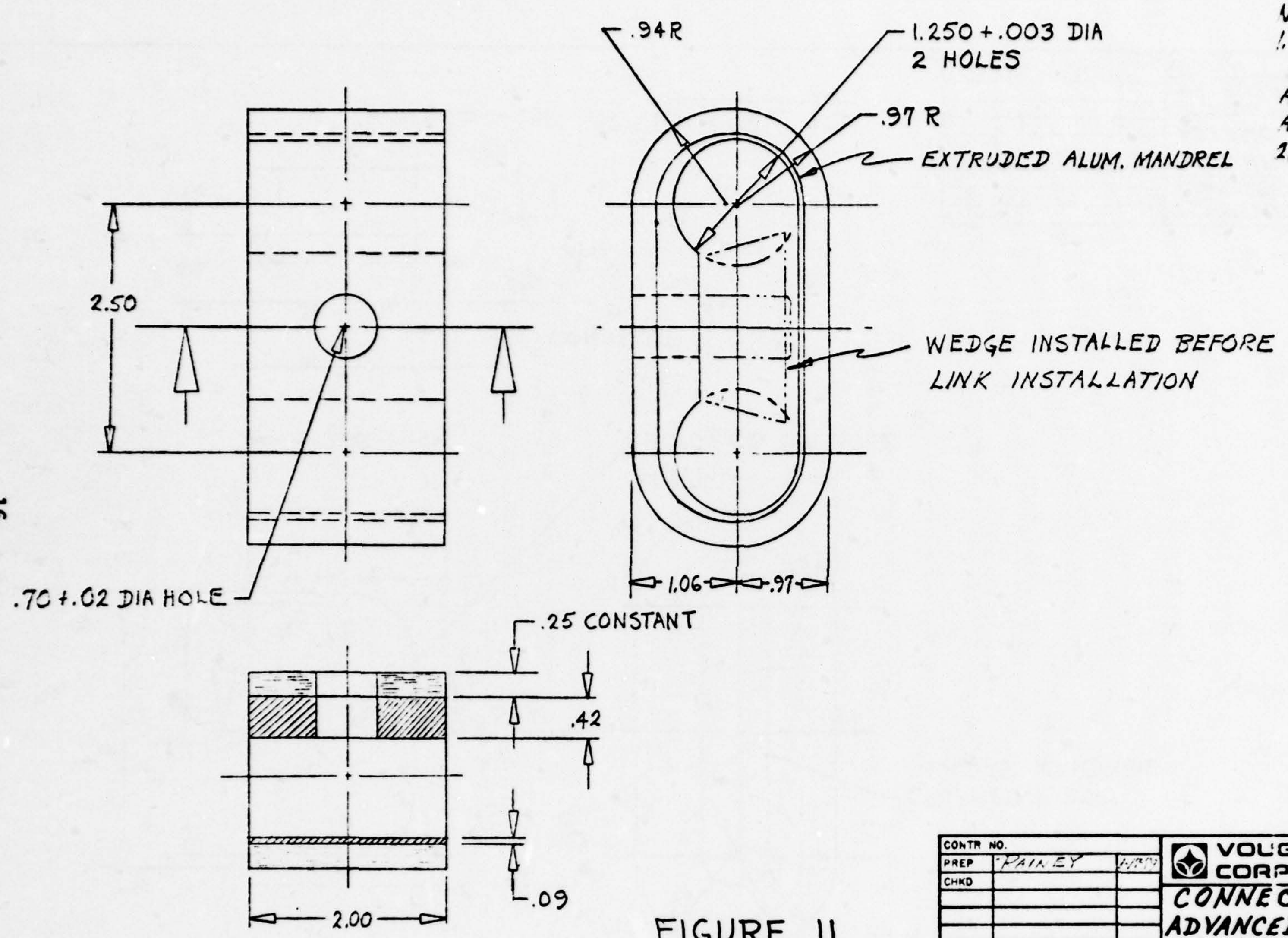
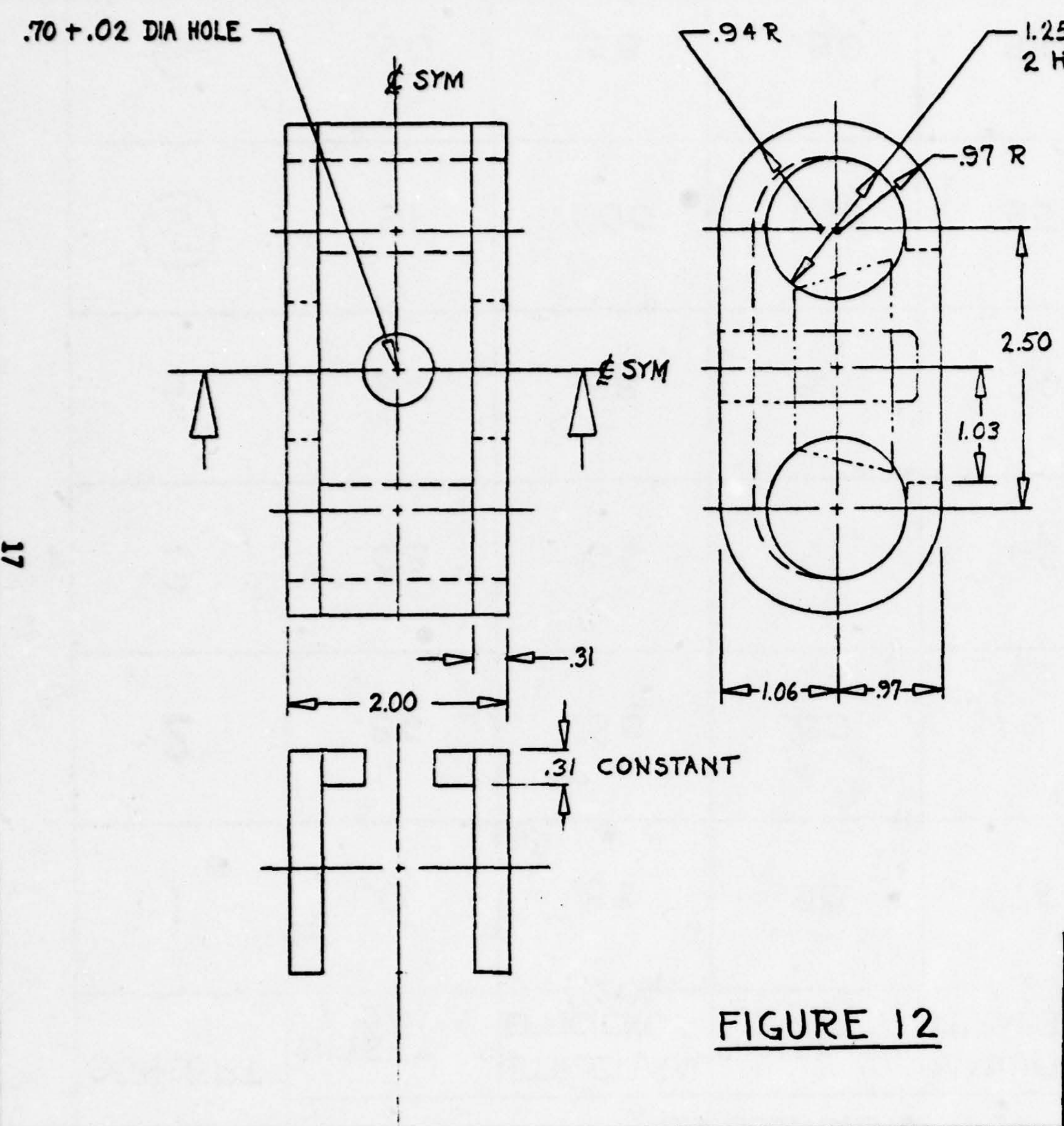


FIGURE 11

NOTES:
1. FABRICATE FROM GLASS/ EPOXY TAPE WRAPPED AROUND AN EXTRUDED ALUM. MANDREL.
2. WEIGHT = .69#

CONTR NO.
PREP PAINEY
CHKD
DESIGN GROUP NAME
ADVANCED COMPOSITES

VOUGHT CORPORATION
Post Office Box 225907
Dallas, Texas 75265
CONNECTOR
ADVANCED COMPOSITE #5
SIZE
FSCM NO. 80378
DWG NO. FIGURE 11
REV
SCALE 1/1
SHEET



NOTES:
1. FABRICATE FROM GLASS/EPOXY FABRIC - TWO PIECES BONDED TOGETHER.
2. WEIGHT = .33

FIGURE 12

CONTR NO.		
PREP	MAINEY	[illegible]
CHKD		
DESIGN GROUP NAME ADVANCED COMPOSITES		

VOUGHT CORPORATION
Post Office Box 225907
Dallas, Texas 75265

CONNECTOR
ADVANCED COMPOSITE #6

SIZE	FSCM NO.	DWG NO.	REV
	80378	FIGURE 12	
SCALE 1/1		SHEET	

TRADE STUDY ~ TANK CONNECTOR LINK

CONCEPT	EVALUATION					SELECTION	
	WEIGHT (.20)	STRUCTURAL EFFICIENCY (.20)	DURABILITY (.20)	MANUFAC-TURABILITY (.20)	COST (.20)	TOTAL POINTS	RATING
1	1.0	.83	.90	.75	.72	.84	3
2	.86	.58	.80	1.0	.96	.84	4
3	.68	.66	.91	.65	.67	.71	6
4	.86	.88	.96	.90	.97	.91	2
⑤	.91	1.00	1.00	.95	1.00	.97	1 SELECTED CONCEPT
6	.90	.58	.80	.85	.90	.81	5

FIGURE 13

transferred to a female tool and cured. The advantage of this method is that ply orientation can be tailored as desired. The main disadvantage is the large amount of hand labor involved. The fact that each part must be produced individually does not provide for a low cost mass-producible part. While concept 1 is the lowest weight, its structural efficiency is penalized because of the complex load distribution around the hole. The concept is subject to poor abrasion resistance due to fraying of fiber ends. This concept is quite expensive.

Concept 2 utilizes injection or bulk compression molding of chopped fiber composites. Injection molding is by far the lowest cost approach to track link fabrication. High rates of mass production are achievable with minimum manual labor. The disadvantage of this approach is that initial tooling and equipment costs are high, and chopped fiber systems lack the strength and stiffness of a continuous fiber composite. The weight, structural efficiency, and durability factors all reflect the penalty paid for a chopped fiber system.

Concept 3 is similar to 1, but plies are preplied and stacked independently for the sides and cap. This reduces the layup time slightly but extensive trimming and machining of the finished part would still be necessary. As with concept 1, this concept is not a feasible approach to mass production. The structural efficiency of concept 3 is reduced because of the matrix shear transfer requirement. Concept 3 is rated weak in durability because of the exposed fiber ends in the area of high wear.

Concept 4 offers an approach to solving many of the structural and durability problems, as well as some of the manufacturing problems. By wrapping the fibers on a pre-cast mandrel, a more efficient structure is obtained for most loading conditions. From a manufacturing standpoint, it permits the use of tape winding or filament winding techniques. These techniques are low cost approaches which are easily convertible to mass production. The major drawback of this approach was the secondary machining operations required to complete the connector link and the lack of a good pin bearing surface. The thickness of the reinforcement required also imposed processing difficulties which could drive the cost up. The durability of the link would be significantly improved by eliminating exposed fiber ends.

Concept 5 was similar to 4 in that it employs filament or tape winding, however, many of the major drawbacks associated with concept 4 have been eliminated. The major difference lies in that the integral wrapping mandrel is made of aluminum. While the aluminum adds some weight to the overall link, the improved structural efficiency of this configuration minimizes any weight penalty. The aluminum mandrel has two major manufacturing advantages: (1) it reduces secondary machining operations to a minimum and (2) it provides an excellent pin bearing surface. With the aluminum mandrel being an extrusion, this concept permits the fabrication of a feasible, low cost, mass producible connector link.

Concept 6 utilizes a "bracelet" type central laminate with cap plies on each side. This assembly would be cured using matched metal compression molds in a press. This concept requires sophisticated expensive tooling and some manual labor for preform shaping and mold loading. Secondary machining is required to reach final configuration. This concept, like concept 3, has severe structural limitations due to matrix shear transfer, and like 1 and 3, has fiber ends exposed which are susceptible to abrasive erosion.

The rating system used to evaluate the link concepts employed a 0 to 1 scale with 0 being the lowest rating and 1 the highest. The concepts were evaluated for cost, weight, structural efficiency, durability, and manufacturability. The best concept was selected for each category and the others rated as a percentage of the best. The category ratings were multiplied by the weighting factors (0.20 for each) and the average rating determined for each concept.

Ratings were made by Engineering and Manufacturing personnel and the average of all responses was used in selecting the baseline composite end connector concept.

3.2 Material Evaluation

3.2.1 Fiber Systems

The standard group of fiber systems, graphite, Kevlar, and glass, were evaluated for use on the Army Tank Track Connector Link. Both aerospace and industrial grades of fibers were evaluated for cost and performance. Figure 14 is a compilation of fiber supplier's projections of future prepreg costs. All composite systems were estimated based on epoxy or polyester resin systems. Exact costs are dependent upon future assumed production volumes which may be in error, but the general trends are expected to be accurate.

Since weight and cost are being evaluated as equals, the glass fiber systems are the most attractive because of low cost. While only E-glass tape is shown, E-glass or industrial grade S-2 glass roving may offer the most viable production reinforcing materials. The price for glass fibers is not expected to decrease in the future because the industry, unlike the graphite industry, is presently mature and already producing high volumes. Fabric

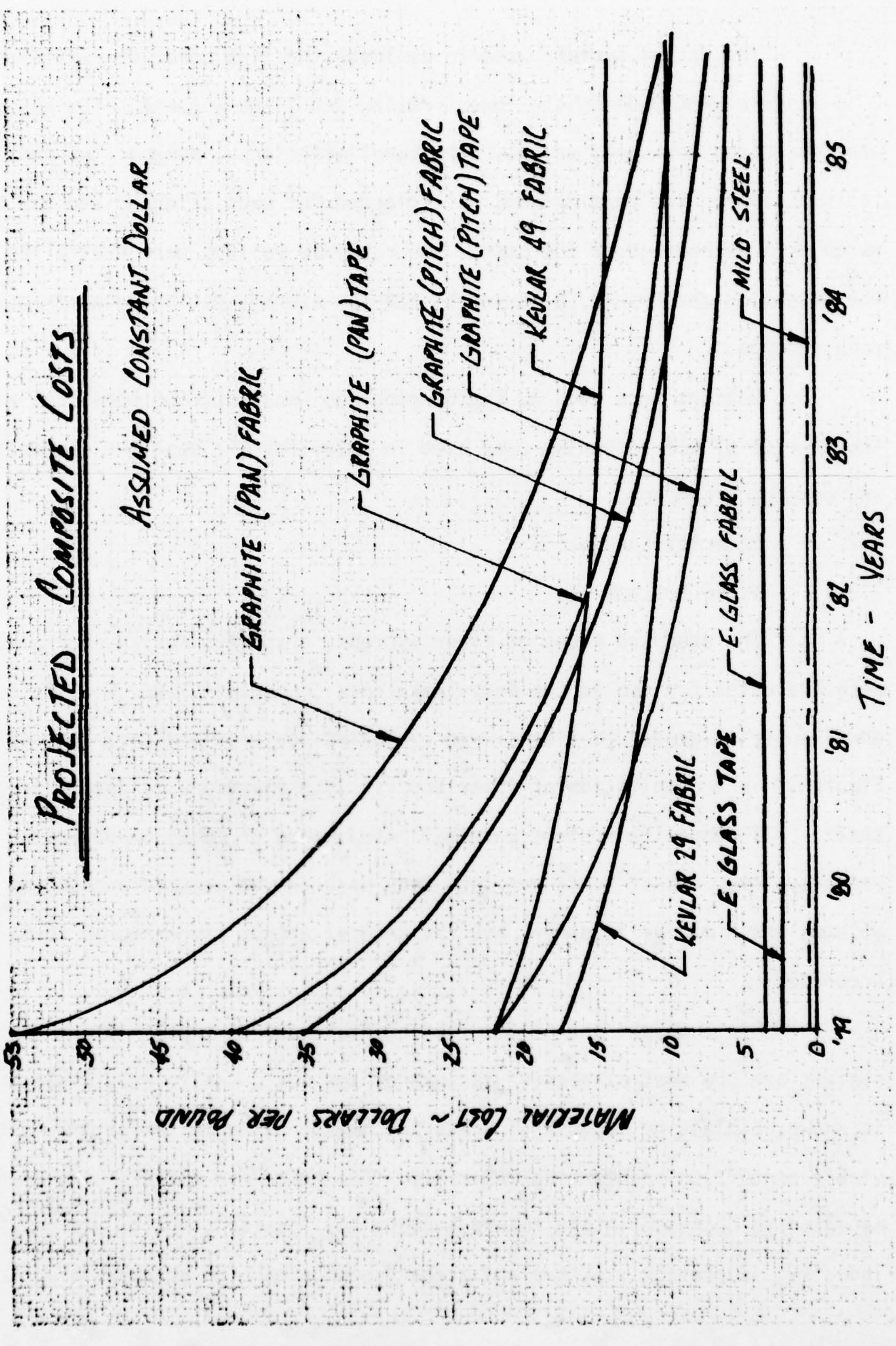

PROJECTED COMPOSITE COSTS
ASSUMED CONSTANT DOLLAR
GRAPHITE (PAN) FABRIC
GRAPHITE (PAN) TAPE
GRAPHITE (PITCH) FABRIC
GRAPHITE (PITCH) TAPE
KEVLAR 49 FABRIC
KEVLAR 29 FABRIC
E-GLASS TAPE
E-GLASS FABRIC
MILD STEEL
MATERIAL COST ~ DOLLARS PER POUND
53
50
45
40
35
30
25
20
15
10
5
0
'79
'80
'81
'82
'83
'84
'85
TIME - YEARS

FIGURE 14

systems add no advantage to link fabrication in the selected configuration and they are more expensive, due to high weaving costs, so no further consideration was given to fabric.

While the general trend for graphite and Kevlar fiber costs shows a significant price decline, they still add significant costs when compared to the glass systems. The graphite systems, both polyacrylonitrile (PAN) and pitch base, offer improved toughness and wear resistance. The low compressive strength of Kevlar indicates that its use should be limited to extreme fibers only. Kevlar was not used in the analysis of the selected link concept.

3.2.2 Resin Matrix Systems

The following resin systems were evaluated for possible production applications of composites for the connector link: epoxies, polyesters, vinylesters, urethanes and metal matrices. While there are numerous polymer resin systems available on the market which fall in these broad categories, most exhibit similar characteristics.

Metal matrix composites offer high chemical and environmental resistance. These systems were not evaluated further because of their present high cost and no definable cost reduction trends.

The epoxy systems are typically the most resistant to chemical degradation but require long cure cycles. Epoxy resin prepregs are produced on a high volume production basis and a large amount of data is available.

Polyester and vinylester resin systems are also prepreged in high volume production quantities. These systems are used primarily for automotive and industrial applications. Both systems offer rapid cure (under 3 minutes) capabilities but exhibit properties slightly lower than their epoxy counterparts.

30

Vinylester systems offer excellent fatigue resistance. The vinylester and polyester resins are also less expensive than epoxies. The design concept selected uses filament winding technology and PPG Industries has done considerable filament winding of polyester and vinylester/glass in the development of their automotive grade composite, "XMC." At present, the data base is limited for polyester or vinylester composites but is growing rapidly with increased automotive interest. The chemical resistance of these polymer families is lower than the epoxies but should be adequate for the environment to be encountered by the connector link.

The urethane resin systems are new to continuous fiber composites. Urethane and polyurethane have been used for some time in industrial products. At present, only U.S. Polymeric is known to prepreg continuous fibers with a urethane resin, and only in experimental quantities. The urethane resin systems offer increased toughness and possible improved wear resistance. Additional research will have to be devoted to these resins to verify their ability to perform.

Epoxies offer the largest data base and best mechanical properties over the other systems. The filament wound production concept does not necessitate the use of a rapid cure resin system. The ability to filament wind epoxy composites and the availability of glass/epoxy prepreg tape and roving make their use on the Army link very advantageous. The chemical resistance and known environmental effects can be evaluated for epoxy systems but is beyond the scope of this effort.

3.2.3 Wear and Abrasion

With an undefined abrasion environment, it is difficult to evaluate the ability of composite materials to survive. But it is believed that an unprotected composite may not survive in the harsh abrasion environment a tank experiences without the employment of specific methods designed to improve the wear resistance of the composite. One approach would be to increase the toughness of the composite through the use of improved fibers and resins, such as Kevlar fibers and urethane resin.

Another approach would be to increase the surface hardness of the composite. This may be accomplished by hard particle deposition, i.e., deposit silicon carbide, etc., on the outer surface of the laminate prior to cure. Upon curing the laminate, the particles become embedded in the composite. Testing has not been performed to verify this approach.

Finally, coatings could be added to the link. These coatings could take the form of flame sprayed metal particles, metal shims, etc. The added material would be expected to carry little load but resist the surface wear of the composite.

Each of the approaches discussed above has potential for improving wear resistance. The first approach of using tougher materials may increase the composite wear resistance. The hard particle deposition and coatings increase the weight, manufacturing complexity and cost of the end connector link. Continued development in this area is necessary prior to incorporation of a composite link into operational service.

3.2.4 Recommended Materials

Glass fibers in an epoxy matrix in the form of a unidirectional tape was selected for further analysis in this program. The glass fibers offer excellent strength, reasonable weight savings and low cost. The epoxy resin offers high chemical resistance, a large available data base for physical and mechanical properties, and are readily available prepregs at reasonable cost. The system is suitable for wrapping around an aluminum mandrel.

3.3 Design Analysis

3.3.1 Baseline Configuration Analysis

The end connector link, as configured, is a glass/epoxy-aluminum hybrid. The link is subject to three primary load conditions as defined in Section 3.1.1. The bearing condition was not defined or analyzed in this program.

Figure 15 shows the strain and stress distribution through the thickness of the link for the critical section when subjected to the 11700 lb. ultimate tension load. For this condition the critical section is the area adjacent to the bolt hole in the center section of the link.

Applying Nuismer and Whitney's stress fracture criteria (Ref. 2 and 3) to the glass laminate adjacent to the hole, results in a strength reduction factor of 0.45. At ultimate load, the aluminum has attained initial yield immediately adjacent to the hole, if the extruded integral mandrel is made of low strength aluminum, i.e., 6061-T6. The margin of safety on yield would be considerably higher should high strength aluminum, such as 7075-T731, be used for the mandrel. An aluminum yield criteria is used because the effects of plastic deformation of the aluminum and elastic deformation of the glass presents a problem of complexity beyond the scope of this program. The link fracture load is in excess of the design ultimate tension load.

Figure 4 shows the external pad assembly pin moments as applied to the end connector link. Figure 16 shows the internal load distribution on the link, wedge, and bolt. Certain internal bearing load distributions have been assumed in order to complete the analysis. The critical section is the center of the link through the wedge attachment bolt. The torque introduced

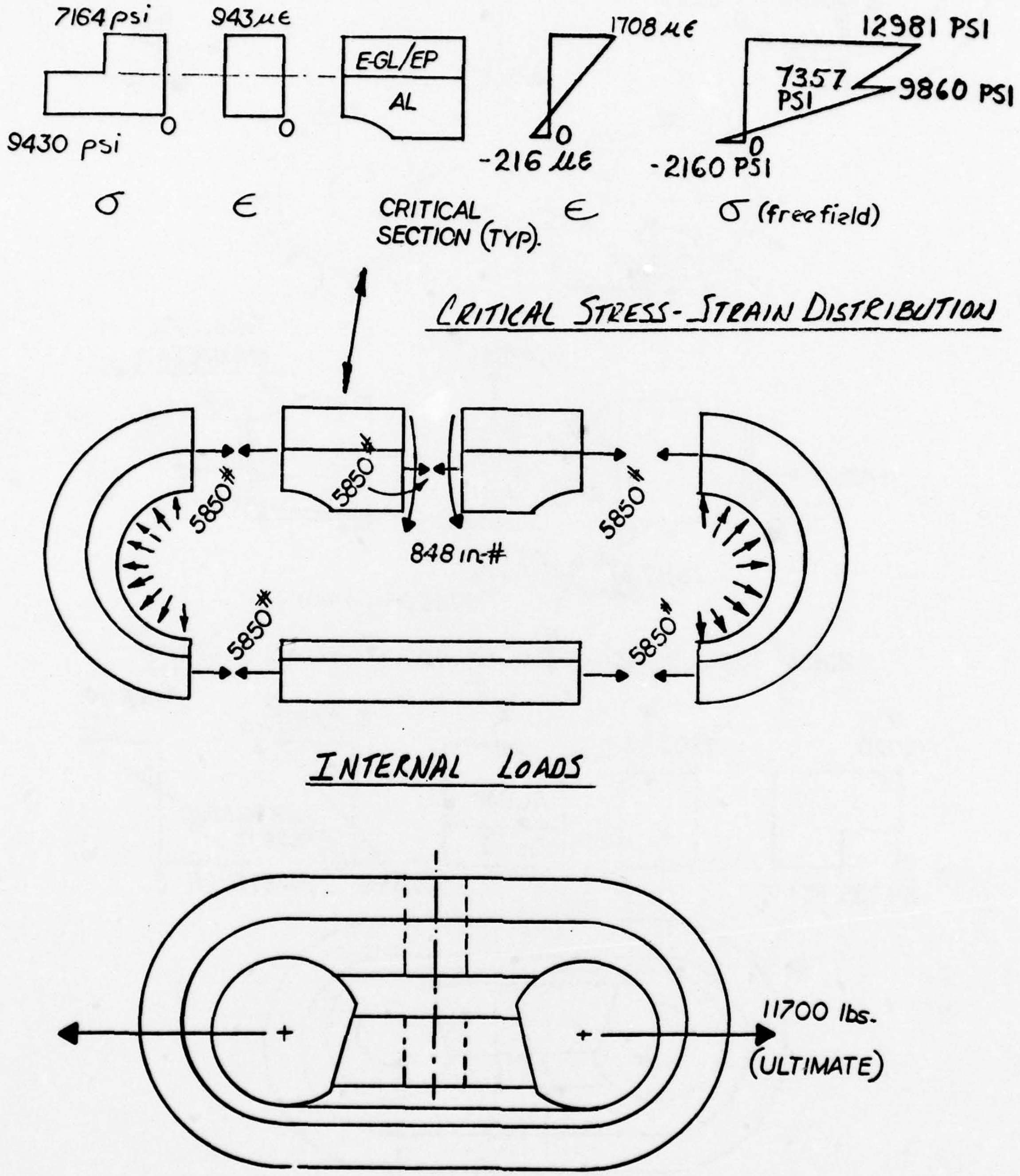


FIGURE 15. TENSION LOAD CONDITION - INTERNAL LOADS AND CRITICAL STRESS-STRAIN DISTRIBUTION

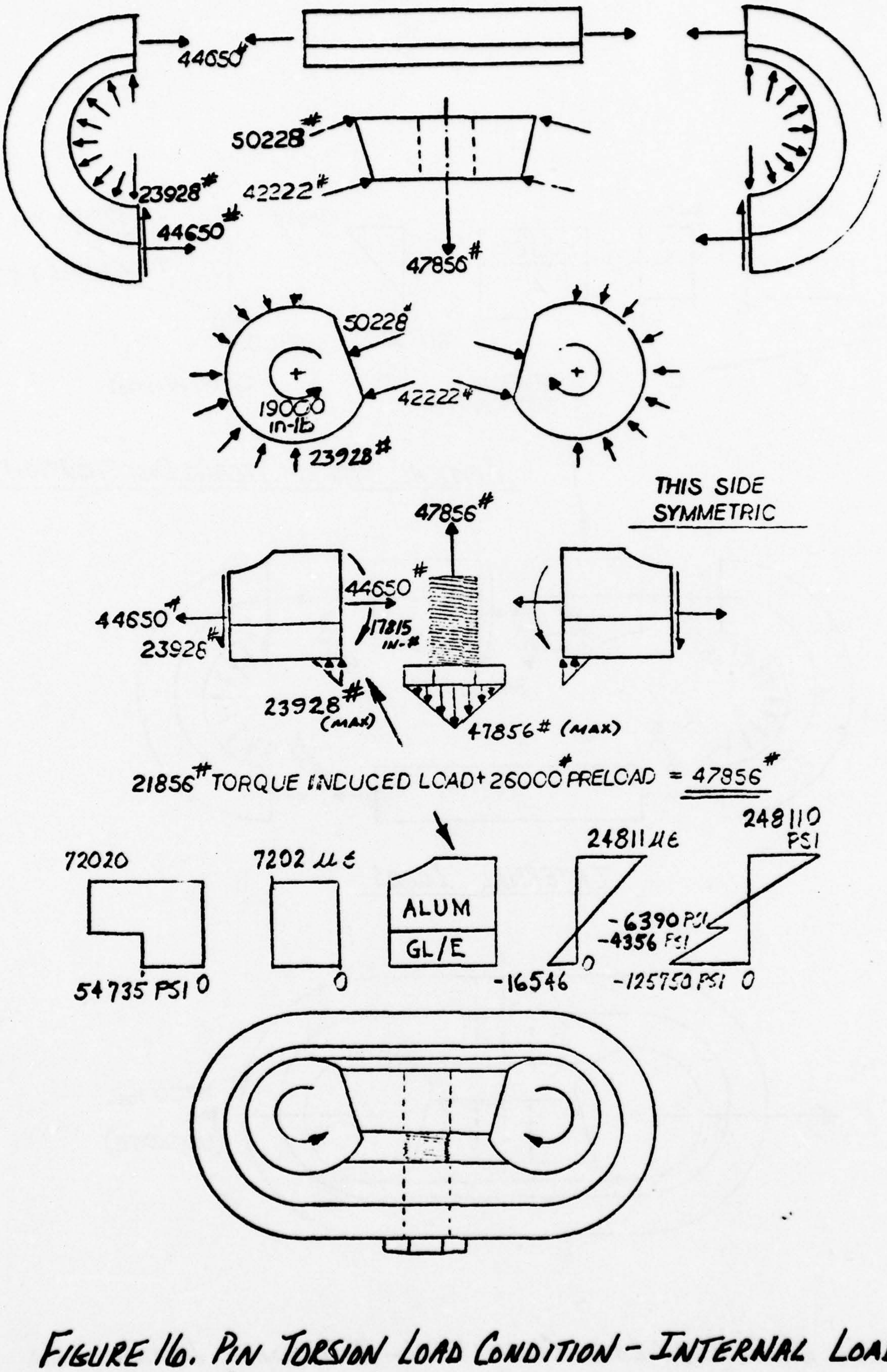


FIGURE 16. PIN TORSION LOAD CONDITION - INTERNAL LOADS AND CRITICAL STRESS-STRAIN DISTRIBUTION

Army Materials and Mechanics Research Center,
Watertown, Massachusetts 02172
DESIGN FEASIBILITY ANALYSIS OF
FIBER-REINFORCED COMPOSITE ARMY
TANK TRACK CONNECTOR LINK
E. G. Smith, G. Bourland, R. N. Rainey and
O. L. Mijares,
Vought Corporation, Dallas, Texas 75265

Technical Report (AMMRC TR 79-41), June 1979
64 pp – illus-tables, Contract DAAG46-78-C-0069
D/A Project IL162105AH84, AMCMS Code
612105.11.H84, Final Report, September

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through the pins generates a large bolt load sufficient to fail the critical section in bending. Figure 16 also shows the critical section stress distribution through the thickness of the link. The stress levels are in excess of the ultimate strength of the aluminum. It was expected that the bondline shear stress between the aluminum and glass laminate would be in excess of its ultimate strength.

The conclusion drawn from this analysis was that the link would not meet the design requirement. A check was made by running a NASTRAN finite element solution to the problem. Figure 17 shows the model used to check the analysis made. The model consisted of quadrilateral and triangular plates with rod elements used to transfer the load between the pin and link elements. The bondline between the aluminum and glass laminate was modeled using quadrilateral plates. Loads introduced to the model simulated the wedge reaction load and bolt reaction load.

Figure 18 shows the input loads and stress distribution through the thickness at the link centerline. The stress distribution is shown as being continuous even though it is discrete for hybrid material systems. The stresses in the aluminum were in excess of their ultimate strength (F_{tu} = 72000 psi). The bond stress between the aluminum and the glass laminate was shown to be 26500 psi, which is well in excess of the ultimate strength of commercially available adhesives (≈5000 psi lap shear strength).

Another model was run in which the glass laminate was replaced by a graphite/epoxy laminate. Figure 19 shows the stress distribution through the thickness at the link centerline. The maximum stress level of the aluminum was again in excess of its ultimate strength. The maximum stress level of the graphite/epoxy-aluminum laminate bond was 30550 psi. This stress level

FIGURE 17. NASTRAN MODEL

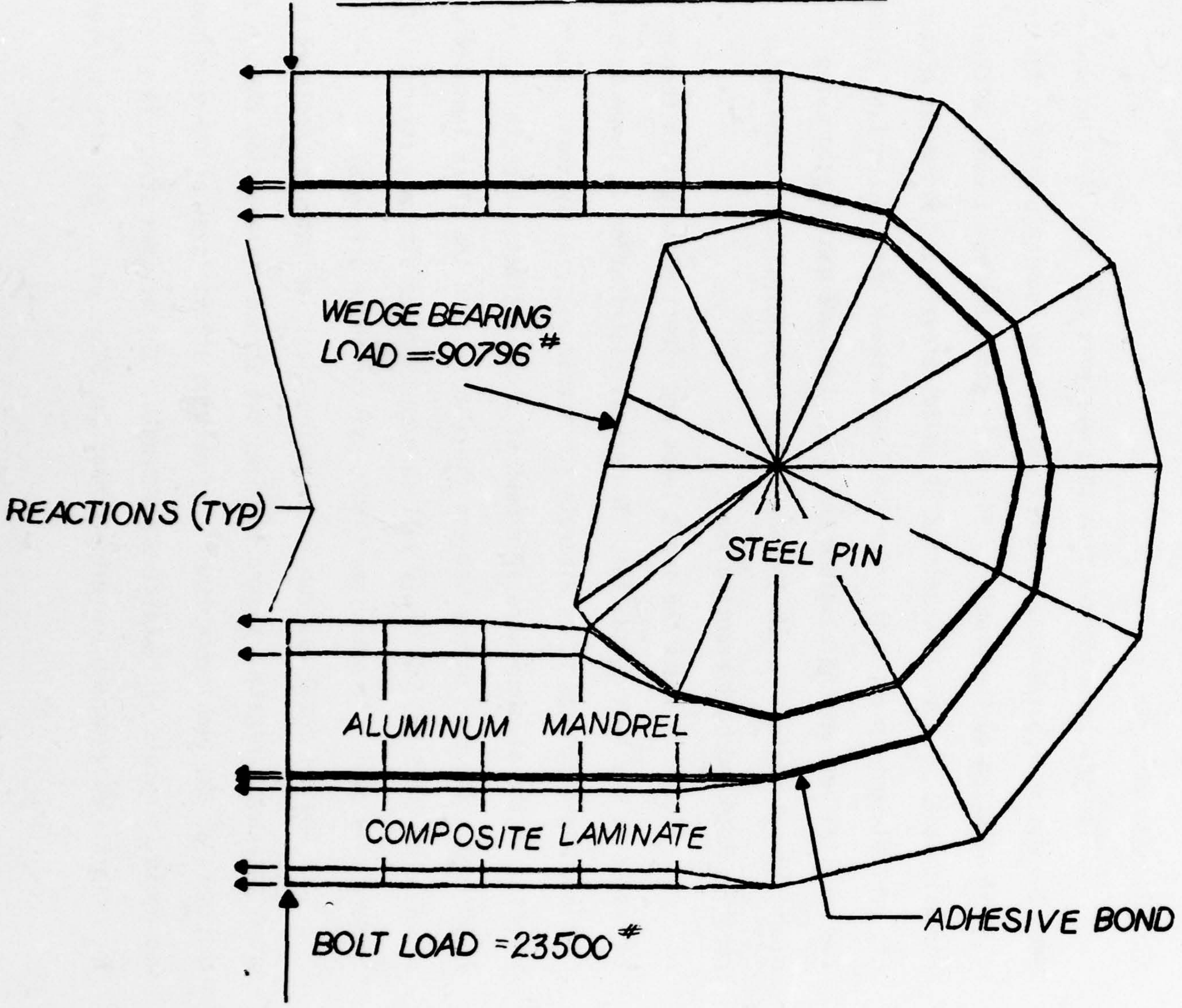


FIGURE 18. STRESS DISTRIBUTION E-GL/EP-AL

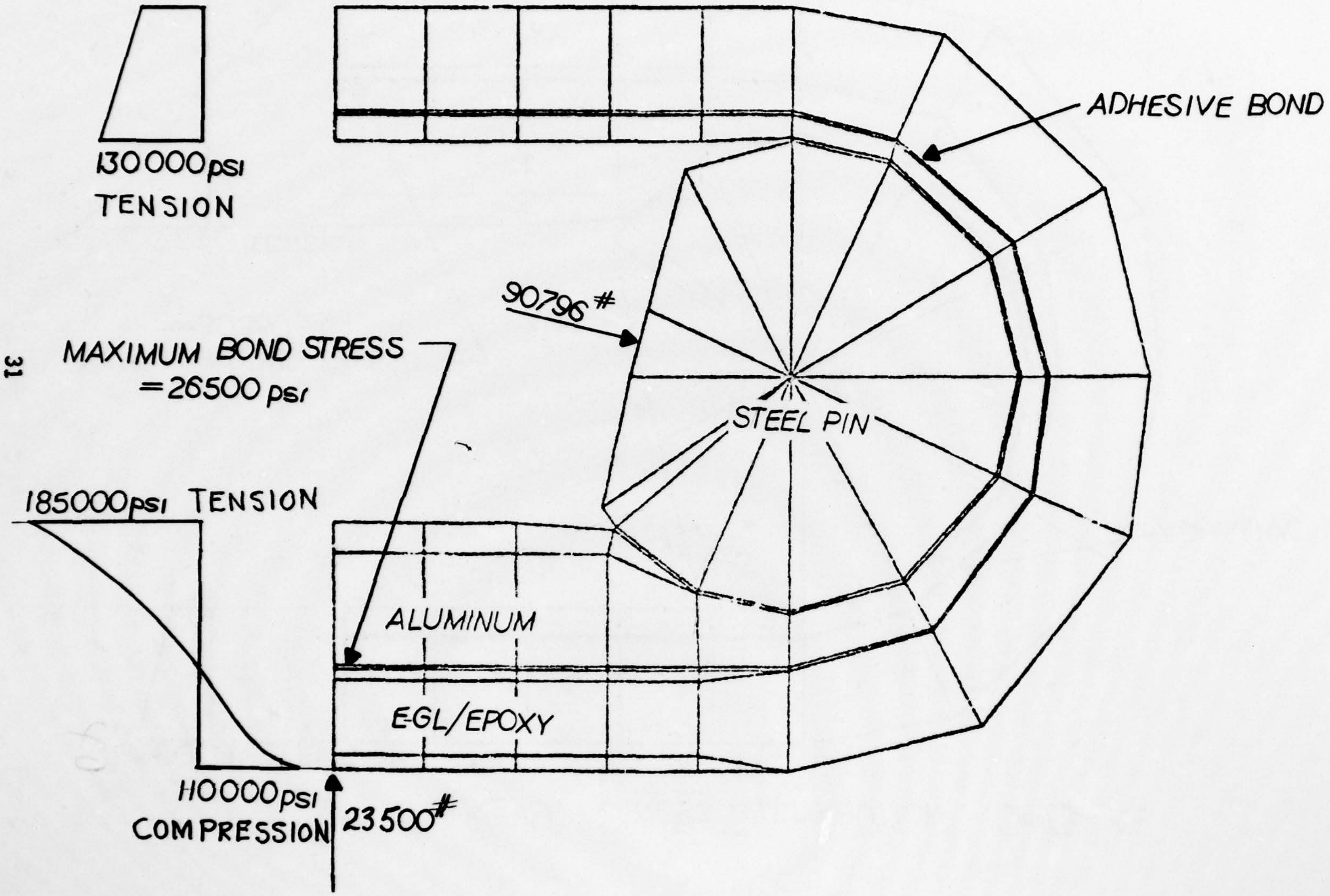
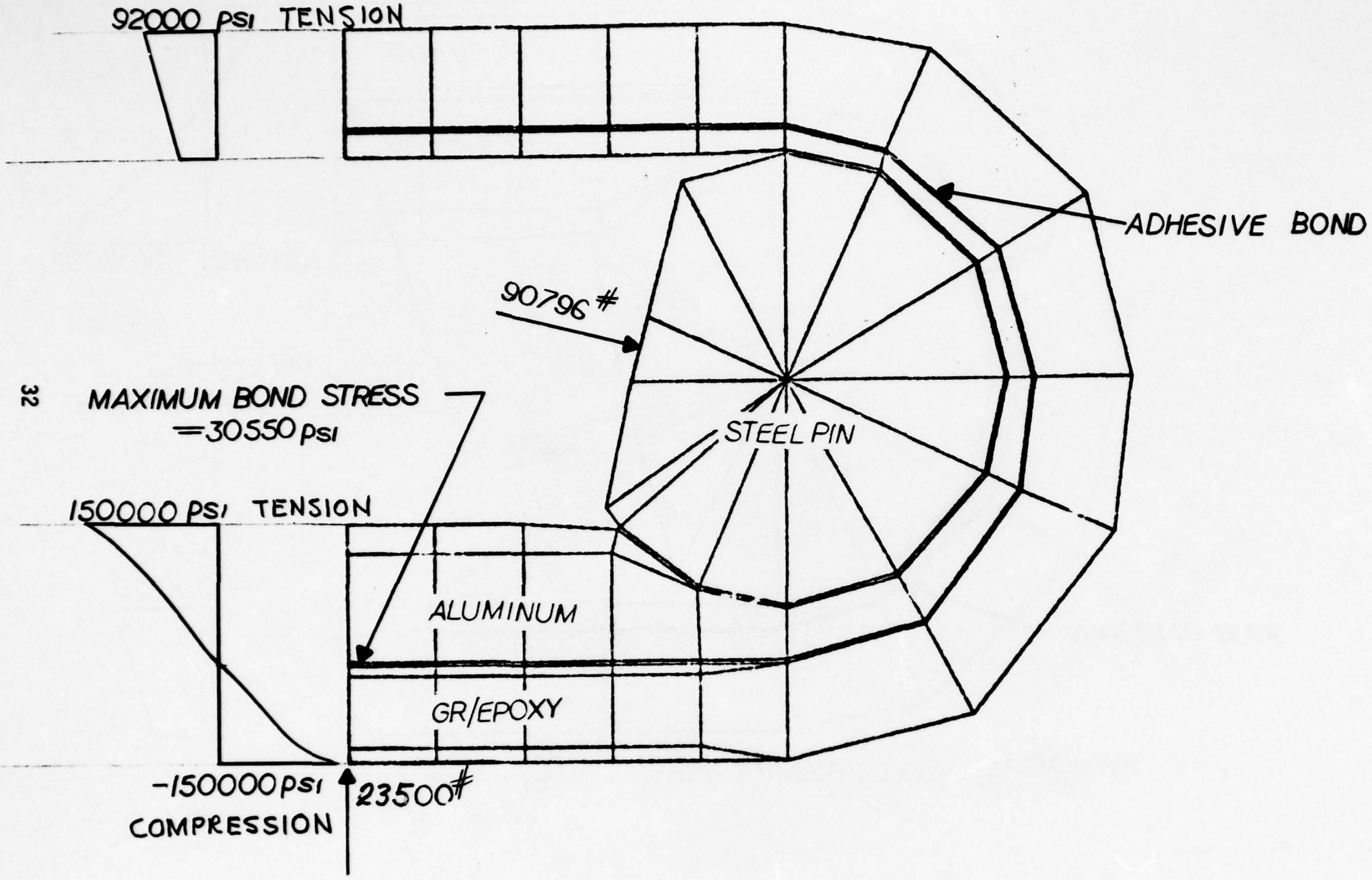


FIGURE 19. STRESS DISTRIBUTION GR/EP-AL



was higher than the bond stress of the glass/epoxy-aluminum laminate as expected, because of the larger difference in discrete material moduli.

The model was again run with the graphite/epoxy laminate and aluminum except that the plate elements representing the bondline were removed to simulate a failure of the bond. Figure 20 shows the stress distribution through the thickness at the link centerline. The maximum stresses in both aluminum and graphite/epoxy are in excess of their respective ultimate strengths.

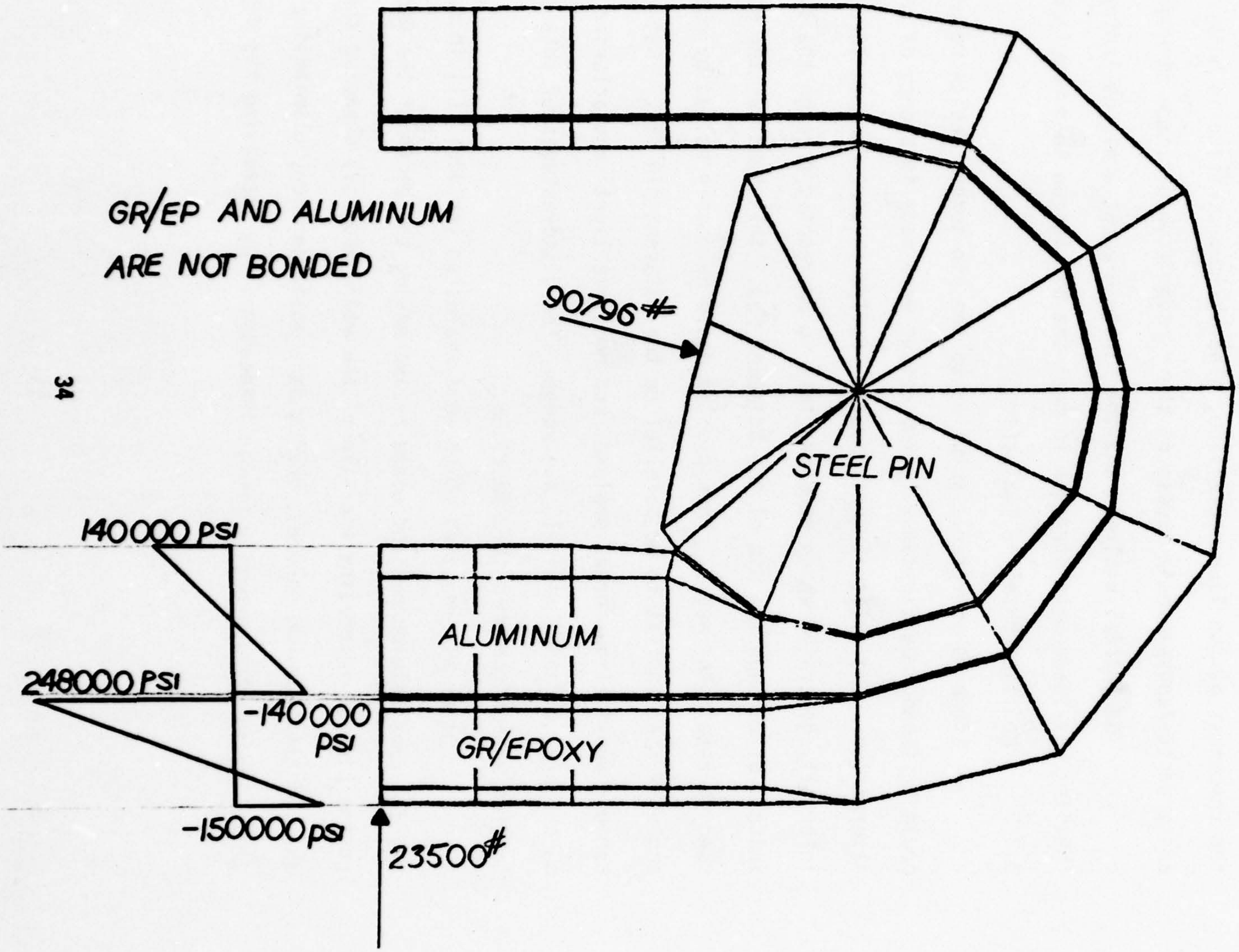
The initial analysis and the finite element analyses indicate that the link has inadequate strength to meet the pin torque load requirement.

3.3.2 Modified Baseline Evaluation

Since no acceptable solution to the pin torque design requirement could be found, modifications to the design were made in search of an acceptable alternative. The original configuration failed to work because loads were internally generated which required them to be reacted through the link, instead of through the pin of the adjacent pad. This load was the bolt load used to retain the wedge. This problem could be easily solved by changing the angle of the pin flat to be parallel to the adjacent pin flat. But this concept would allow for no preload, and required tight manufacturing tolerances on the pin, extruded mandrel, and wedge. The disadvantages of this pin retention method rendered it unfeasible.

Other alternatives which were evaluated include: (1) increasing the bearing area between pin and wedge by increasing the depth of the machined flat on the pin and increasing the size of the wedge and, (2) changing the configuration of the aluminum mandrel, making it a solid section, eliminating the wedge and bolt. The first alternative proved inadequate. By increasing the depth of the

FIGURE 20 STRESS DISTRIBUTION GR/EP-AL UNBONDED



GR/EP AND ALUMINUM
ARE NOT BONDED

pin flat and size of the wedge, the centroid of the bearing pressure changed, increasing the moment arm by which to react the moment. The increase in the moment arm was inadequate to relieve the bolt load sufficiently. Also, the torsional shear stress in the pin exceeded the pin's ultimate strength.

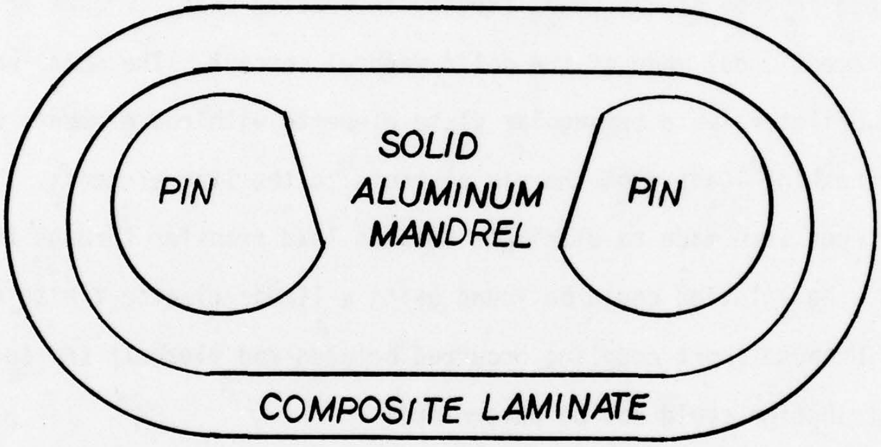
The alternative of a solid aluminum mandrel was also found to be unacceptable. Figure 21 shows the link configured with the solid mandrel. This configuration increases the weight and cost of the link. Not only does the additional aluminum add cost but the shape and mass cause the mandrel to be machined instead of extruded, further increasing cost. Figure 22 shows a finite element model made of the solid mandrel concept. The model was made using quadrilateral and triangular plate elements with rod elements used to transfer bearing loads from the pin elements to the link elements. Multiple computer runs were made to eliminate tension load transfer through the connecting rods. No solution could be found using a linear-elastic finite element analysis because short coupling occurred between rod elements and the bearing load distribution could not be determined.

Figure 23 shows four additional pin restraining concepts. Further evaluation of these concepts may lead to an acceptable solution.

3.3.3 Design Analysis Conclusions

The baseline configuration was found to be structurally adequate to meet the link tension load requirement. The configuration was structurally inadequate to restrain the pad assembly pin torsion condition. No acceptable solution was found to resolve this problem. A composite tank link is technically unfeasible unless the design requirements are modified or an acceptable pin restraining method can be found.

FIGURE 21. SOLID MANDREL CONCEPT



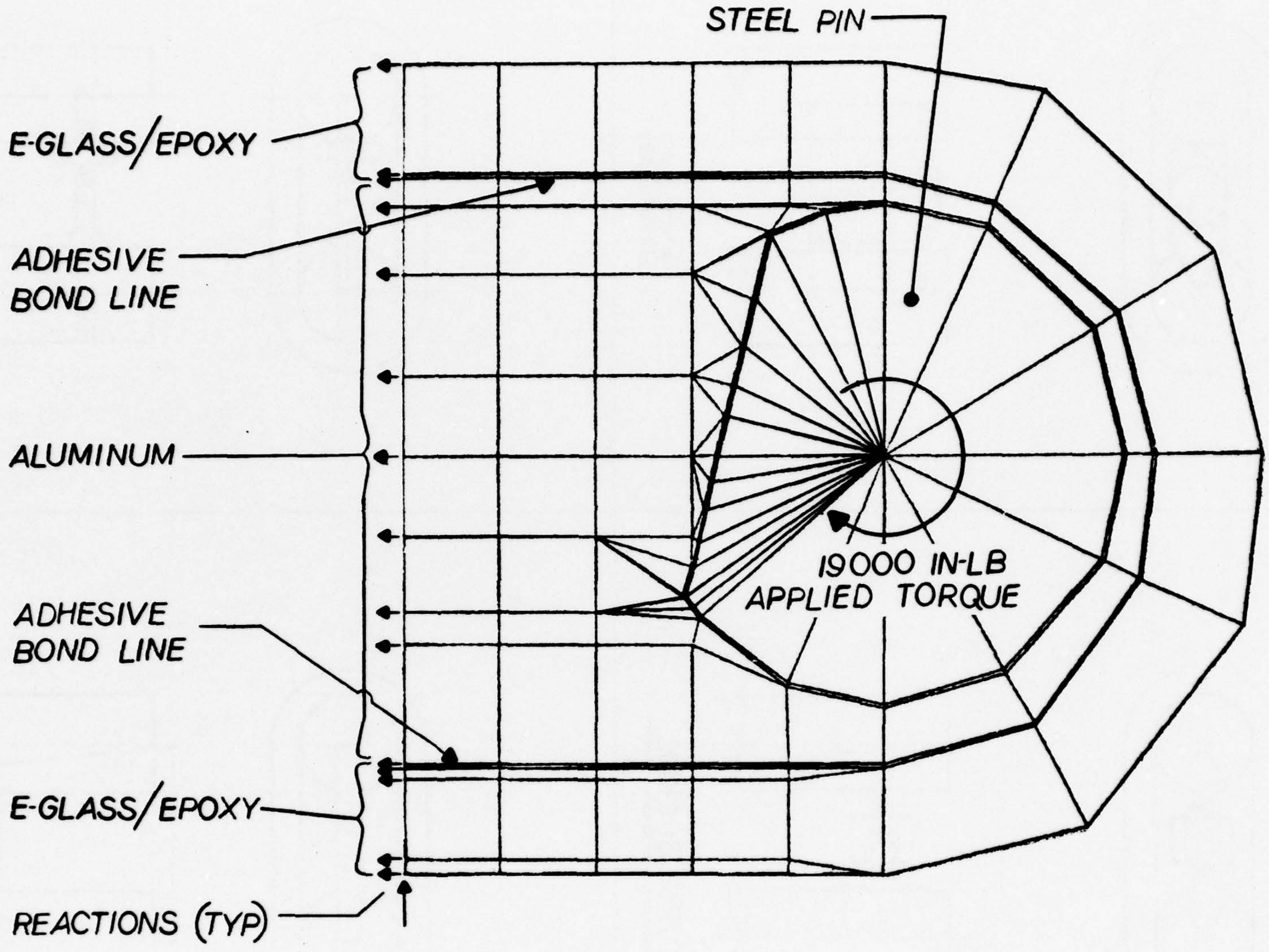
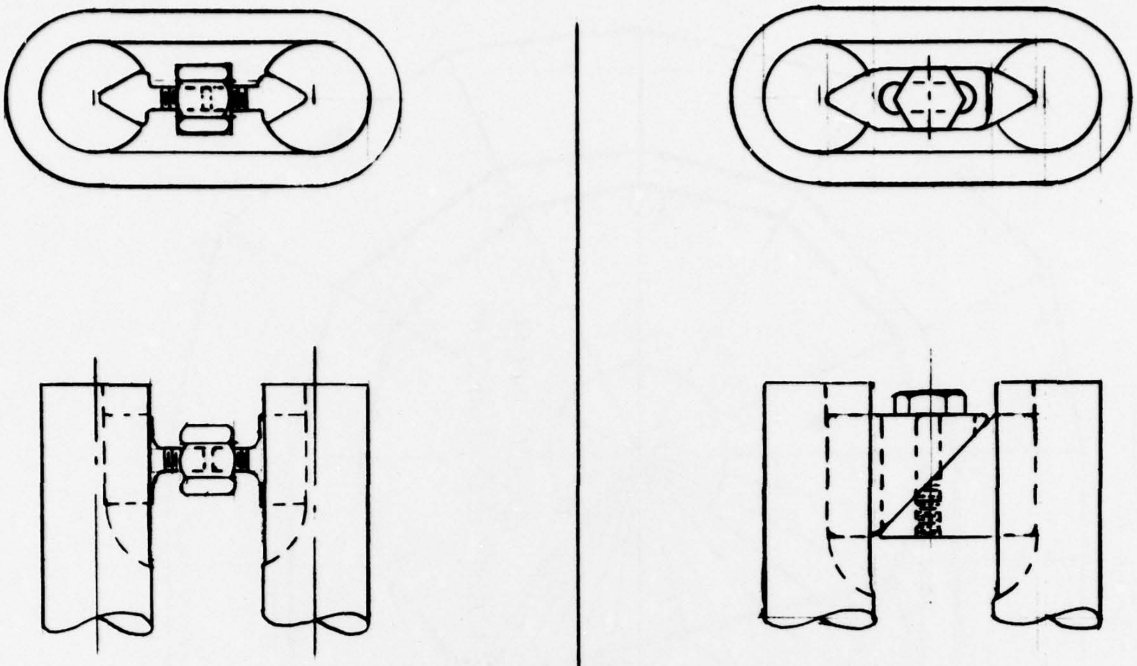
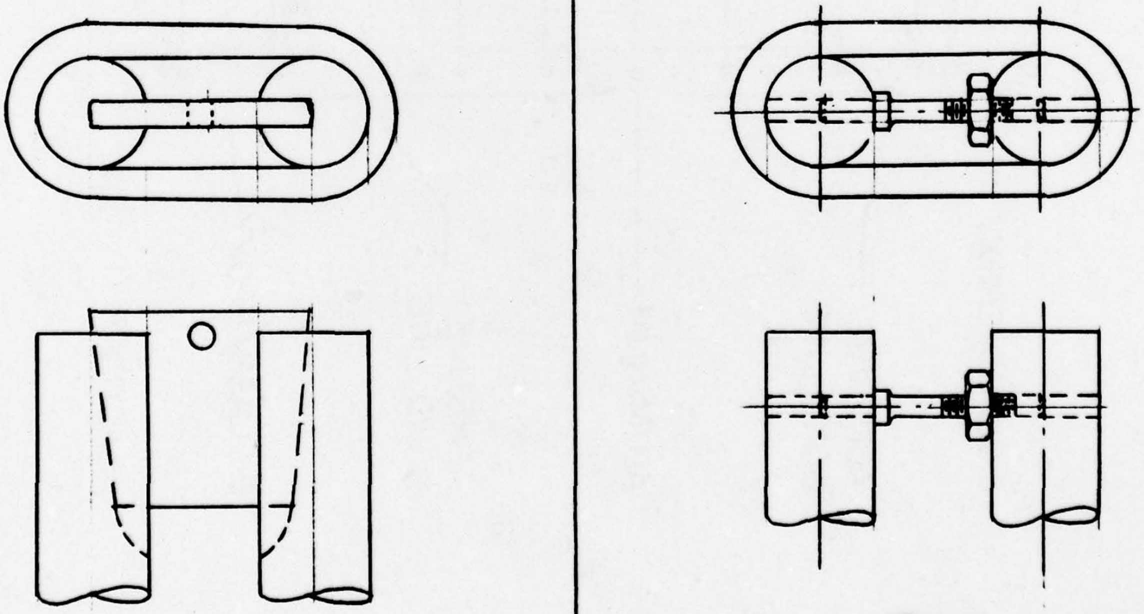


FIGURE 22. FINITE ELEMENT MODEL - SOLID MANDREL CONCEPT



TURN BUCKLE

WEDGE



KEY

BOLT

PIN RESTRAINING CONCEPTS

FIGURE 23

3.4 Manufacturing Evaluation

A manufacturing evaluation was made to determine the composite link's manufacturability and estimated cost. As discussed in the previous section, the composite link is technically unfeasible but solutions to the technical problems may be found through additional investigation. The manufacturing evaluation must be used to justify further efforts.

Various manufacturing approaches were considered for producing the selected concept under both small quantity (10 - 100 units) and large quantity (>10,000 units) production. Primary consideration was given to cost.

After careful evaluation, procedures were selected for both small and large scale production.

3.4.1 Small Quantity Production (10 - 100 Units)

Individual integral aluminum mandrels are machined from bar stock to their appropriate configuration. They are then bond clean etched, epoxy primed, and the primer cured out. A film adhesive layer is then placed on the primed surface and unidirectional preimpregnated tape circumferentially wound around the mandrel. This approach parallels the effort used to fabricate Vought's test articles.

3.4.2 Large Quantity Production (>10,000 Units)

An aluminum extrusion of appropriate cross-sectional configuration is purchased. This extrusion is cut to a convenient size to fit a filament winding machine. It is then bond clean etched, epoxy primed and cured, and film adhesive covered. The detail is then mounted on the filament winding machine, where an appropriate amount of impregnated fiber is wound on it. It is then removed from the winder, and cured. This assembly is gang drilled and cut automatically to obtain a number of finished links.

3.4.3 Manufacturing Cost Estimate

It was assumed, for purposes of this estimate, that a sufficient number of links would be fabricated so that the amortization of non-recurring costs would not increase part cost by more than 5-7% of the total recurring costs. Based on this premise, an analysis of recurring costs was made of the large scale, mass produced links, using two different material combinations. This analysis is shown in Figures 24 and 25. The estimated price ranges from $3.25 per link for option 1 to $4.34 per link for option 2. These estimated costs are considered to be cost competitive with the metallic baseline component.

No estimate was made of the cost of applying an abrasion resistant coating, since this work was beyond the scope of the present program.

Again, life cycle costs are the key to cost feasibility. While the composite link is cost competitive with a forged steel link, the life cycle costs have yet to be evaluated. As discussed previously, composites offer superior fatigue resistance to metallic structure and thus low life cycle costs can be expected. Lower life cycle costs may justify additional initial costs. Technical unknowns, as to composite's ability to resist abrasion and wear, make accurate predictions of component life impossible. Without accurate life predictions, life cycle costs cannot be predicted. Thus, no life cycle costs can be predicted for the composite tank end connector link.

DIRECT MATERIALS	COST/LB.	LB./LINK*	COST/LINK
o S-2 Fiberglass Roving	$2.55	.309	.788
o Epoxy Resin & Film Adhesive	.75	.109	.082
o Aluminum Extrusion (7075-T731)	1.50	.387	.581
Subtotal		.805	$1.451
Material Scrap @ 10%			.145
Material Handling, Burden, etc @ 2%			.032
Total Direct Material			$1.628

DIRECT LABOR

Manufacturing Operations:	Man-Hours/Link	
o Bond Prep.	.002	
o Filament Winding	.023	
o Cure Cycle	.005	
o Drilling	.016	
o Cutting	.041	
Subtotal	.087	
Assumed Labor and Overhead Charge (@ $23.38/hr.)		2.035
Subtotal		3.663
Part Scrap @ 3%		.110
Subtotal (total cost)		3.773
Profit and Recovery of Non-Recurring Costs @ 15%		.566
Total Estimated Link Cost		$4.34

*Based on weights from Vought fabricated links

FIGURE 24. COST ESTIMATE FOR END CONNECTOR LINK LARGE QUANTITY PRODUCTION S-2 GLASS/EPOXY/7075-T731 EXTRUSION, OPTION 2

DIRECT MATERIALS	COST/LB.	LB./LINK	COST/LINK
o E-Glass Roving	$ .55	.315	.173
o Epoxy Resin & Film Adhesive	.75	.109	.082
o Aluminum Extrusion (6061-T6)	1.00	.375	.375
Subtotal			.630
Material Scrap @ 10%			.063
Material Handling, Burden, etc @ 2%			.013
Total Direct Material			.706

DIRECT LABOR

Manufacturing Operations:	Man-Hour/Link
o Bond Prep.	.002
o Filament Winding	.023
o Cure Cycle	.005
o Drilling	.016
o Cutting	.041
Subtotal	.087

Assumed Labor and Overhead Charge (@ $23.38/hr.)	2.035
Subtotal	2.741
Part Scrap @ 3%	.082
Subtotal (total Cost)	2.823
Profit and Recovery of Non-Recurring Costs @ 15%	.423
Total estimated link cost	3.246

*Based on weights from Vought fabricated links.

FIGURE 25. COST ESTIMATE FOR END CONNECTOR LINK LARGE QUANTITY PRODUCTION E-GLASS/EPOXY/6061-T6 EXTRUSION, OPTION 1

4.0 MANUFACTURING DEMONSTRATION AND LINK EVALUATION

The tank end connector link was used as a baseline component in a Vought internally funded IRAD program for demonstrating low cost manufacturing concepts. Links were fabricated for preliminary manufacturing development and structural analysis verification. The following sections detail the fabrication and testing of these demonstration articles.

4.1 Manufacturing Demonstration

The links were fabricated using the procedures outlined in section 3.4.1. After cure, voids in certain of the wrap plies were discovered. These voids were due to the lack of tension on the tape as it was wrapped around the mandrel. This problem was solved by using a single tape tensioning device. Drilling of the holes and trimming of the part to net size posed no problem, and care was taken so as to not delaminate or burn the material. Figures 26 and 27 show photographs of a completed link.

The links fabricated consisted of a 6061-T6 machined aluminum mandrel with S-glass/S-1009 epoxy tape overwrap. The total link weight was 0.805 lbs. The weight distribution was 48 percent aluminum and 52 percent composite. This link weight can be projected to a weight savings of 2154 lbs. per tank (1.795 lbs. per link) or a savings of 69 percent.

4.2 End Connector Link Tests

Two links were tested. Figure 28 shows the structural arrangement and material systems used in the link fabrication. One link was used for static test and one link used for fatigue test. Both links were tested to simulate the net tension design condition.

One end connector link was statically tested to failure. Four axial strain gages were installed on the link to measure critical strains and strain distributions. Figure 29 shows the strain gage locations.

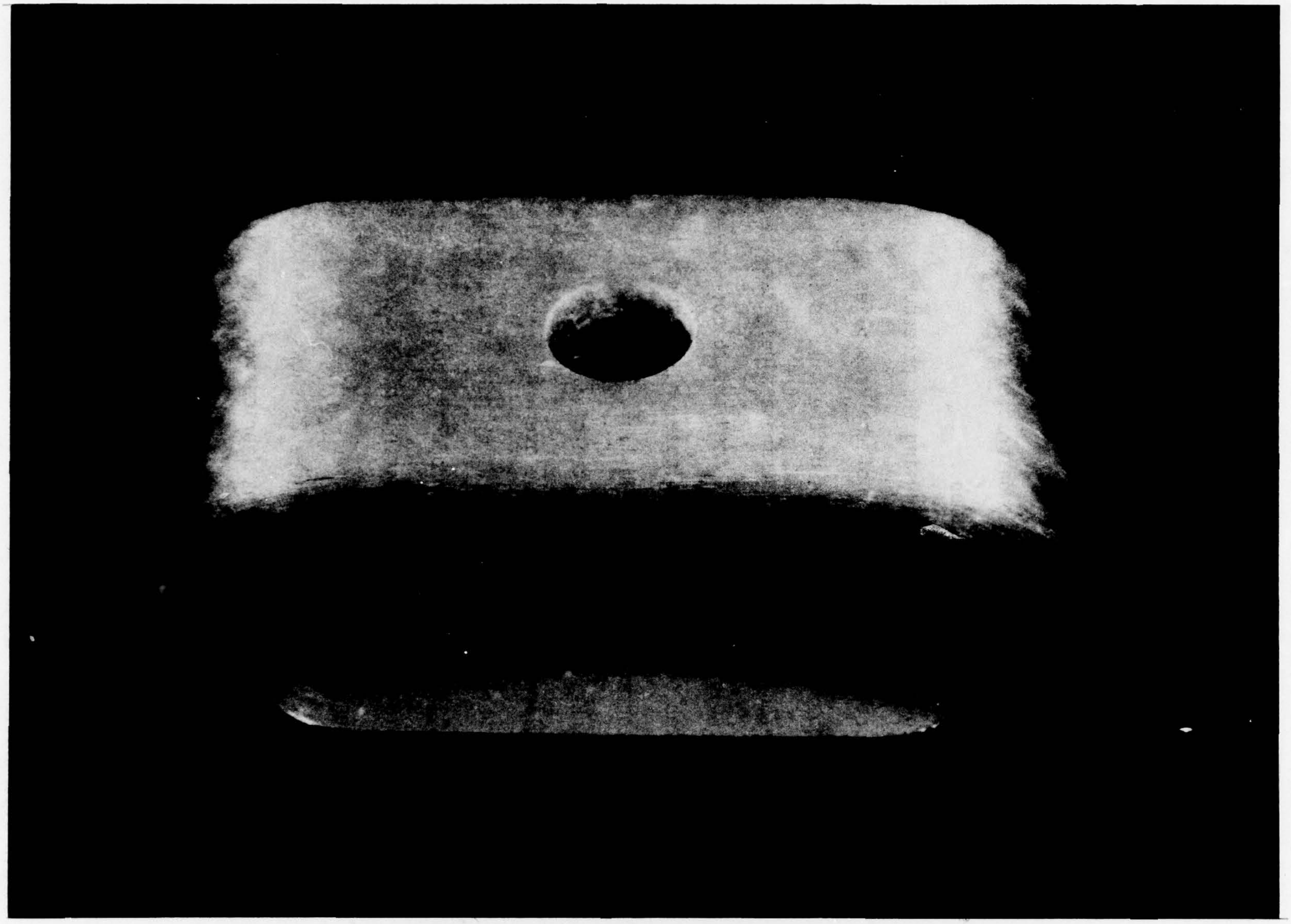


FIGURE 26 PHOTOGRAPH OF END CONNECTOR LINK

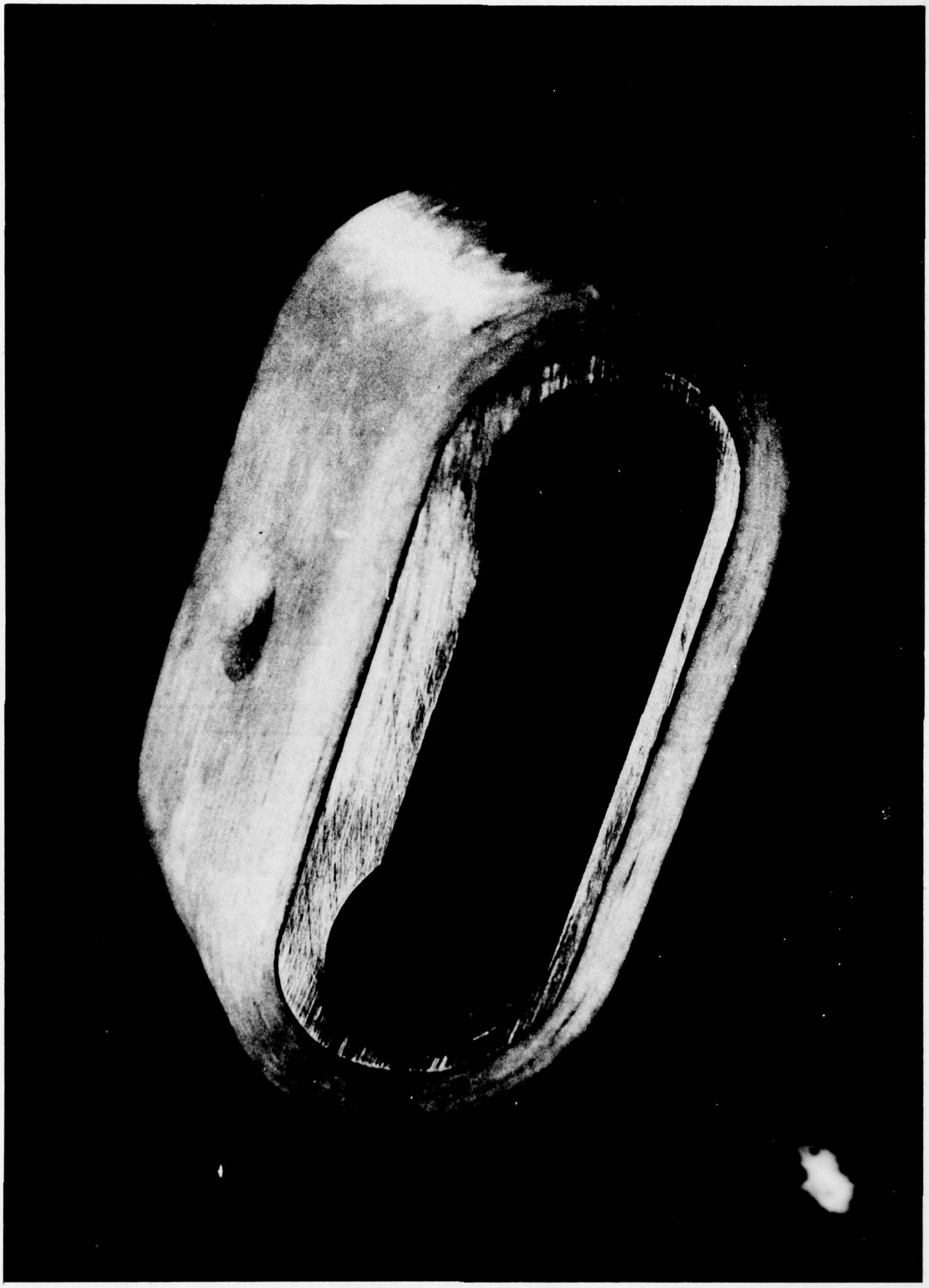
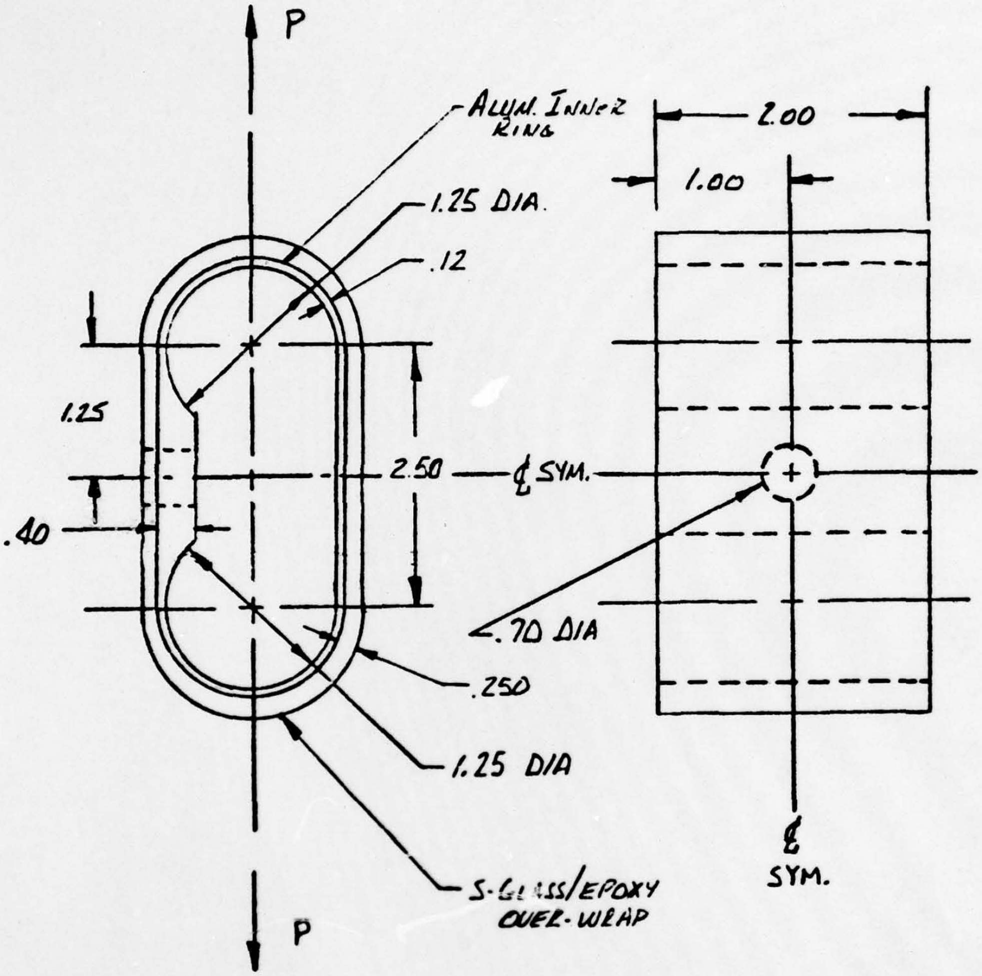
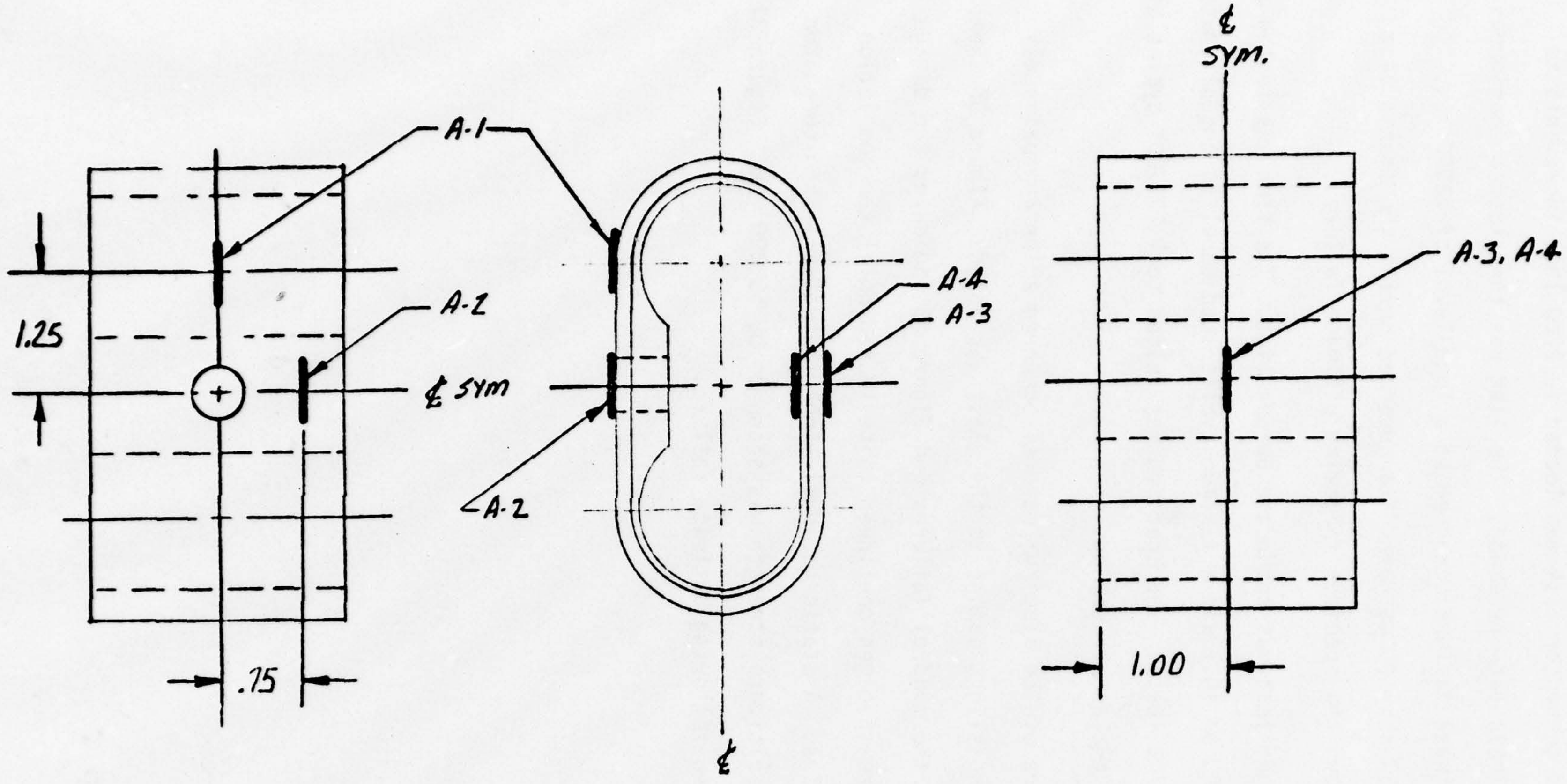


FIGURE 27 PHOTOGRAPH OF END CONNECTOR LINK



END CONNECTOR LINK STRUCTURAL ARRANGEMENT

FIGURE 28



STRAIN GAGE LOCATIONS ON END CONNECTOR LINK

FIGURE 29

The end connector link was loaded in 2000 lbs. increments to 60000 lbs. and strain data recorded. The link was then loaded continuously to failure. Ultimate failure occurred at a load level of 72800 lbs. Figures 30 thru 33 show the strain data recorded during the static test and Figure 34 shows the specimen following ultimate failure.

A fatigue test was conducted on one link. The link was tested at a stress ratio, R. of +0.1 and a maximum cyclic load equal to the ultimate design load (11,700 lbs.). The specimen was tested to 1,177,201 cycles at a frequency of 5 cycles per second.

Fracture of the aluminum mandrel occurred after approximately 309,000 cycles and slight damage to the glass was noted. Figure 35 shows the locations of the mandrel failures and Figure 36 indicates the damage to the glass. The specimen continued to be tested until the completion of 1,177,201 cycles. A static residual strength test was then conducted on the link, and ultimate strength was shown to be 50,200 lbs. Figure 34 shows the specimen following ultimate failure.

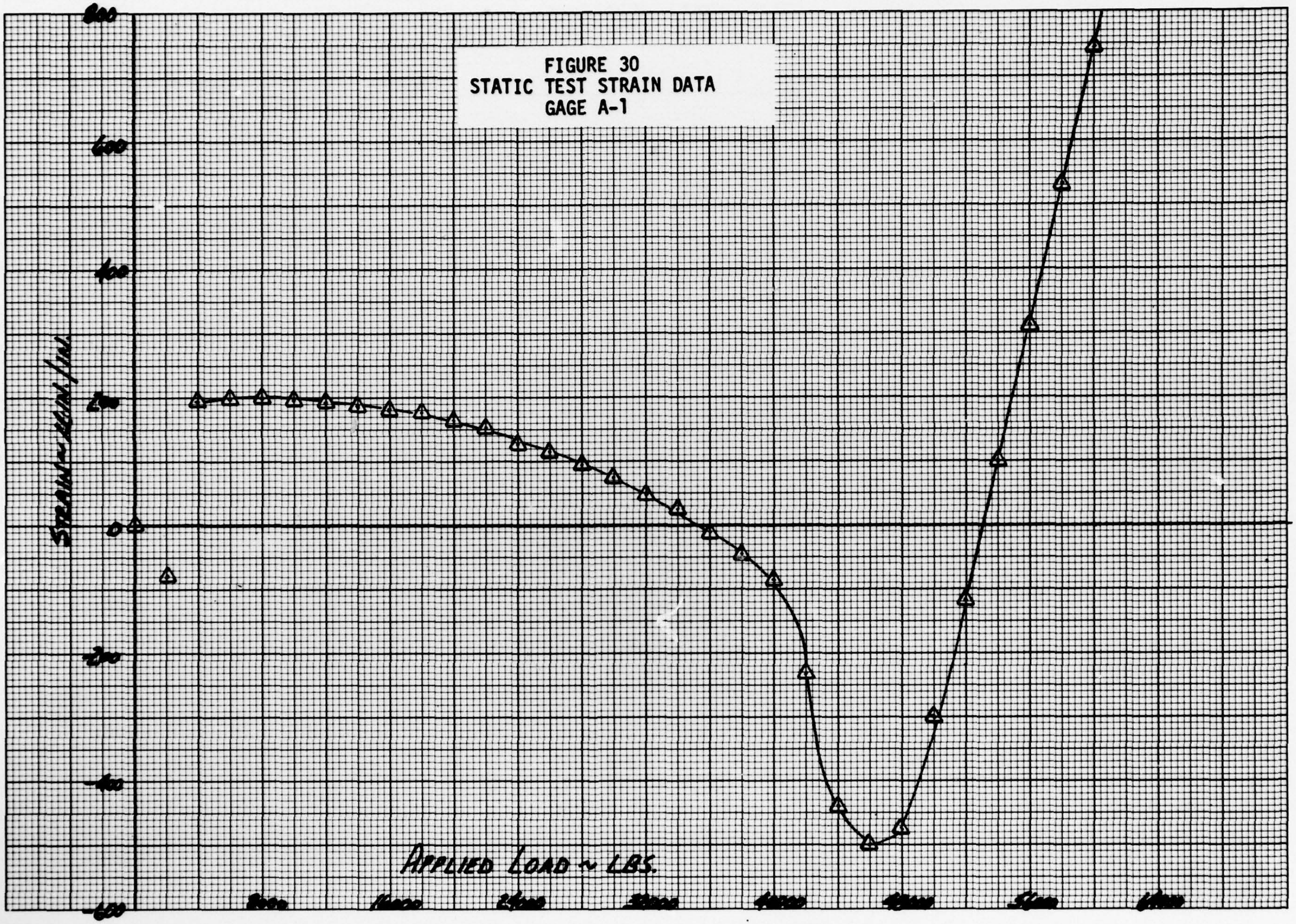


FIGURE 30
STATIC TEST STRAIN DATA
GAGE A-1

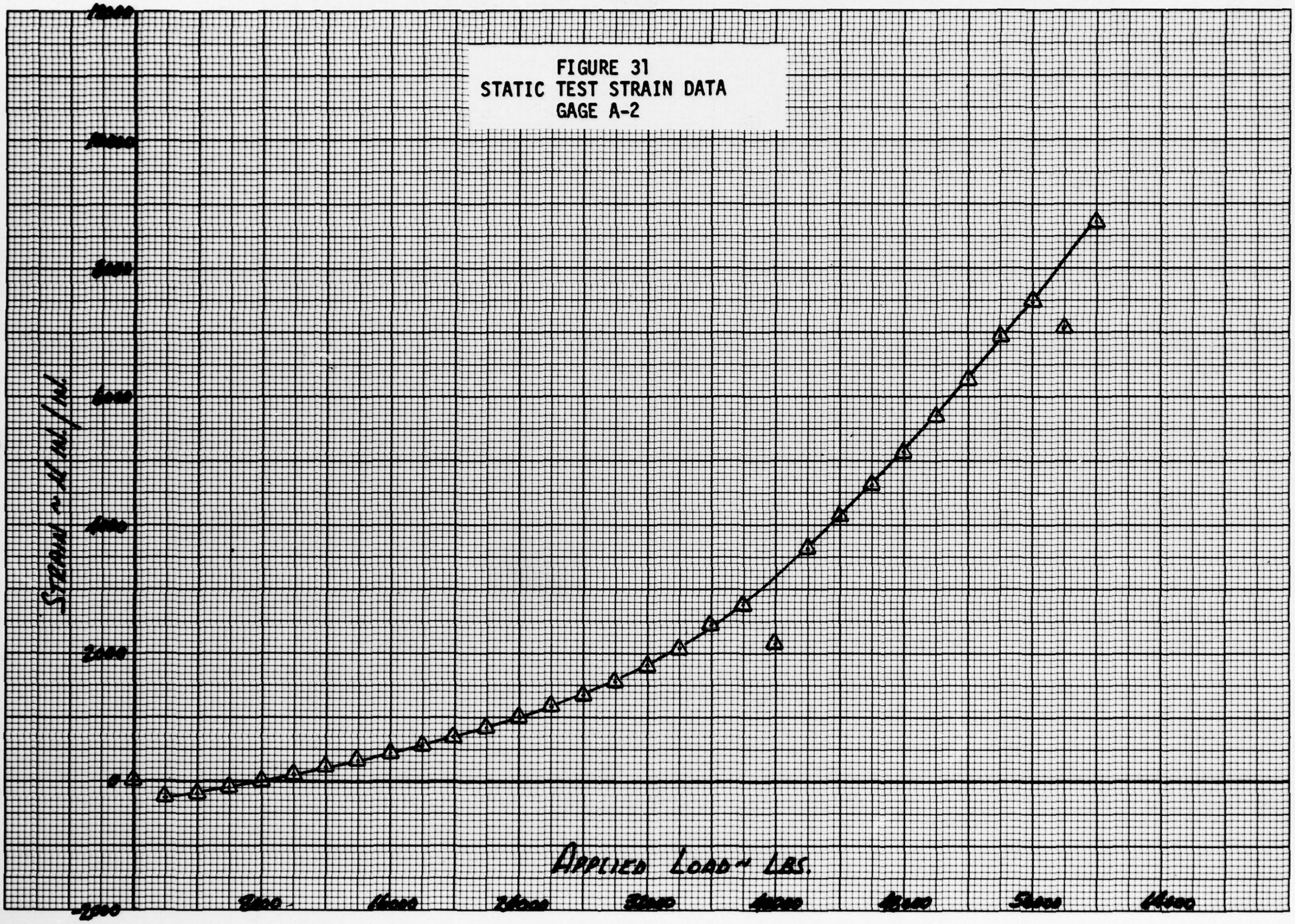


FIGURE 31
STATIC TEST STRAIN DATA
GAGE A-2

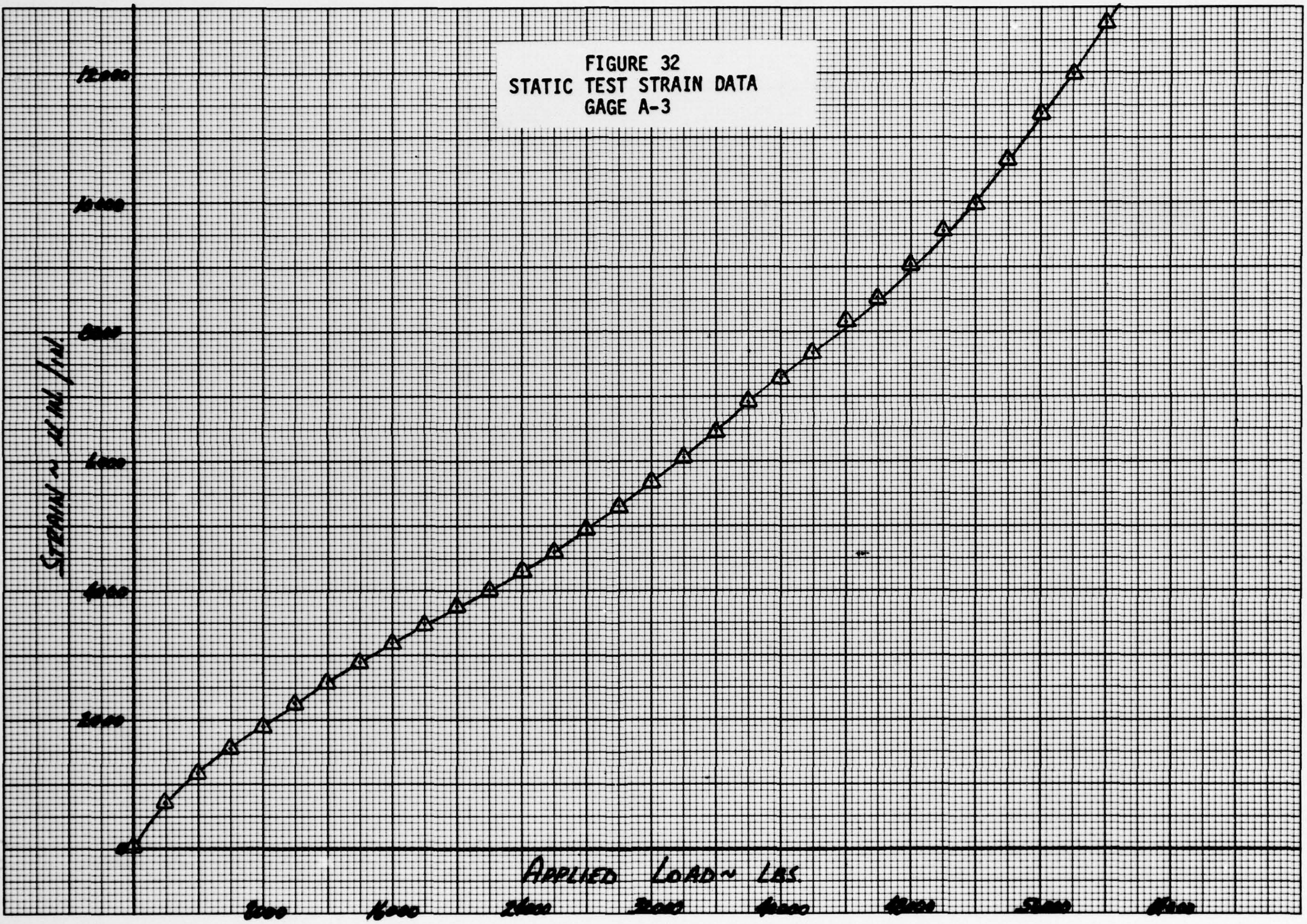


FIGURE 32
STATIC TEST STRAIN DATA
GAGE A-3

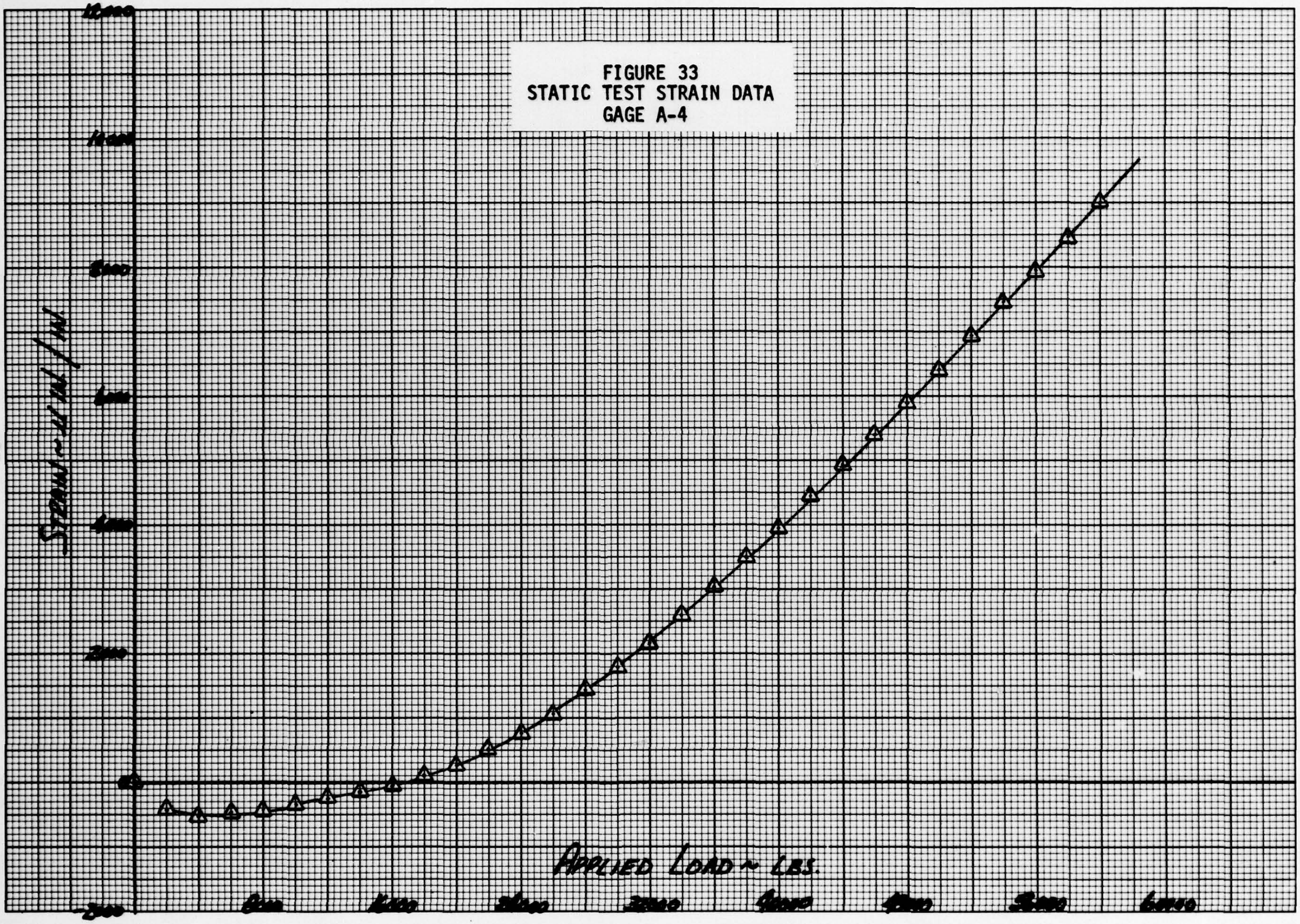


FIGURE 33
STATIC TEST STRAIN DATA
GAGE A-4

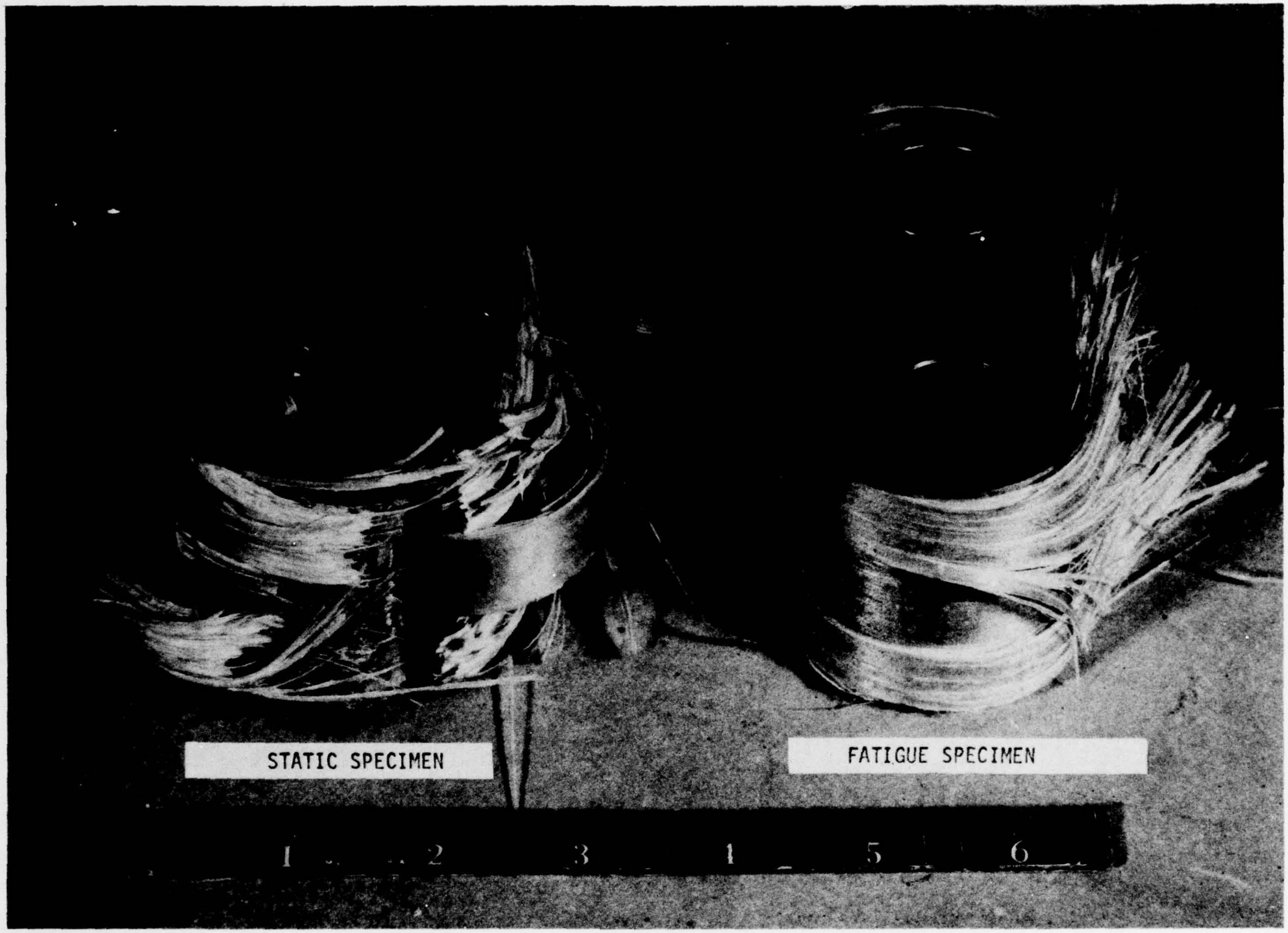


FIGURE 34
SPECIMENS AFTER FAILURE IN STATIC TENSION

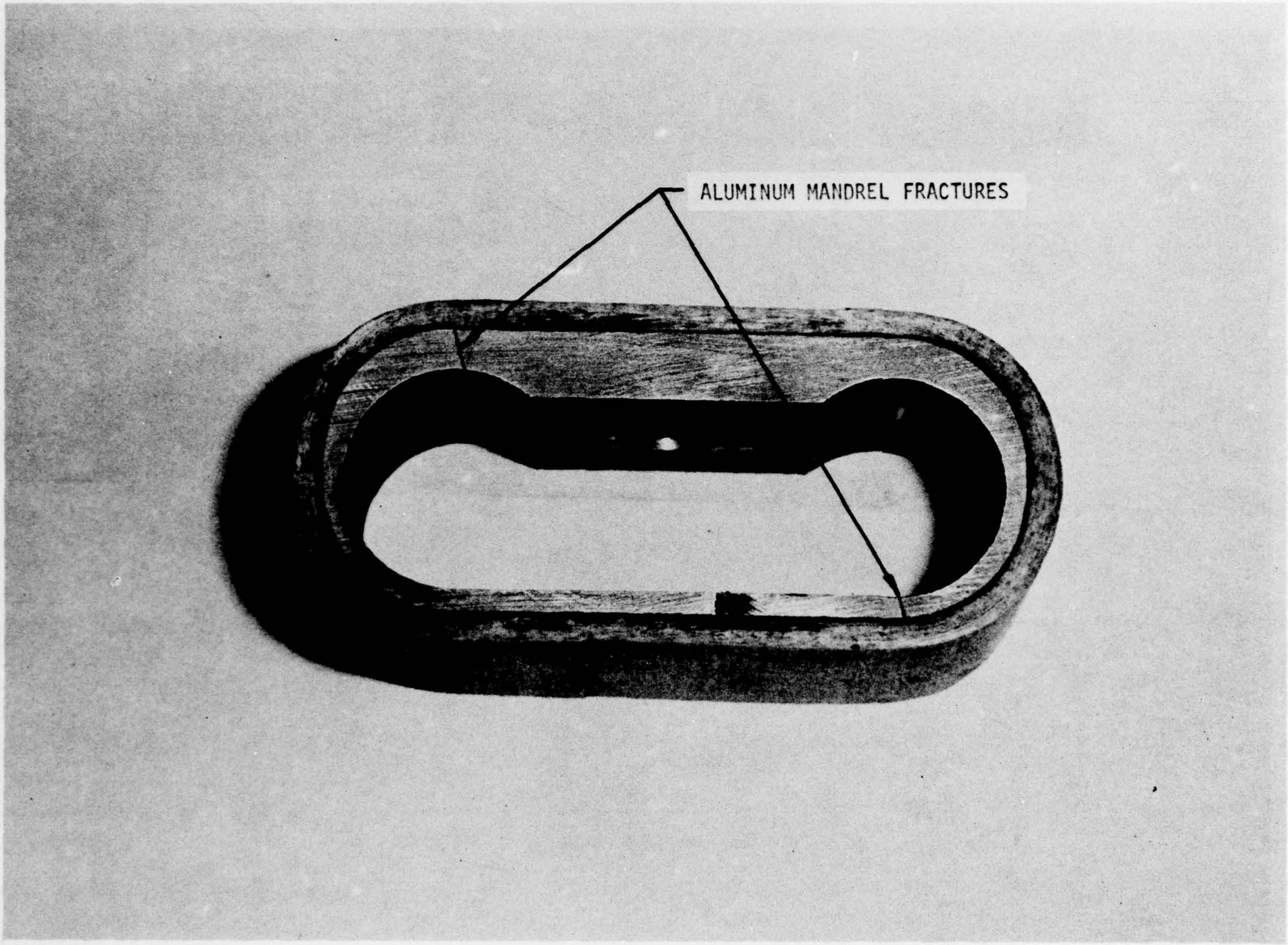


FIGURE 35
FATIGUE SPECIMEN AFTER 309,000 CYCLES

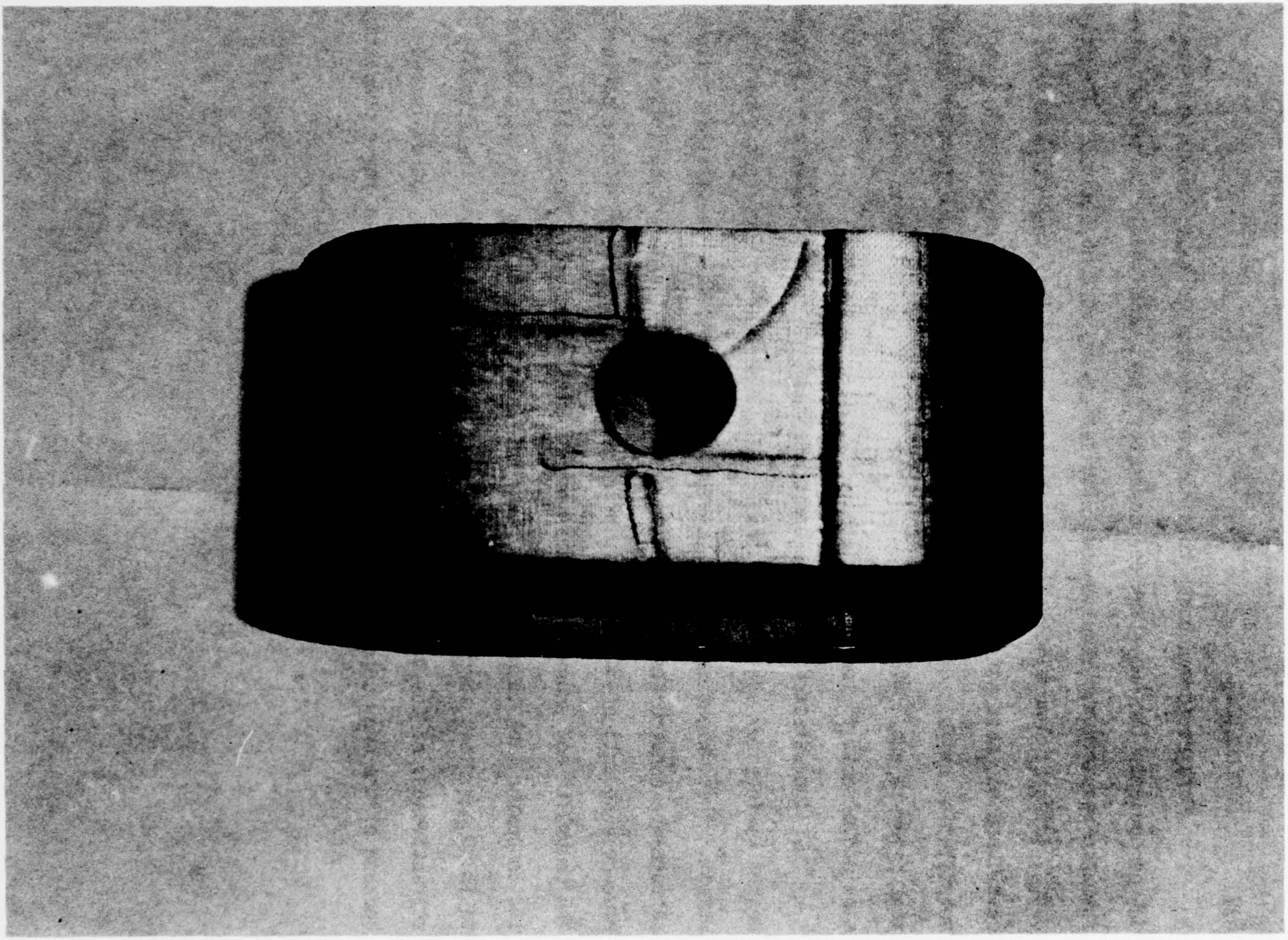


FIGURE 36
FATIGUE SPECIMEN AFTER 309,000 CYCLES

5.0 CONCLUSIONS

Work performed under this contract indicates that composite material design concepts for Army tank end connector links were unable to satisfy performance requirements simultaneous with satisfying cost objectives. The filament wound, integral mandrel glass/epoxy-aluminum hybrid link, representative of low cost concepts, does not satisfy existing structural requirements on a direct substitution basis. Other technical issues that would require further development prior to qualifying a composite link include resistance to wear and abrasion and effects of low energy impact.

The selected composite end connector link design showed a 69 percent weight savings per vehicle or approximately 2 percent of the gross vehicle weight. This weight savings is attainable, however, only if existing design/performance constraints can be relaxed or revised. The weight savings will produce a reduction in fuel consumption and its associated fuel cost savings. The composite end connector link is economically feasible. The initial cost of the composite link is within the range of \$3.25 to \$4.34 per link as compared to \$3.50 per steel forged link. Fuel cost savings will add to the economic attractiveness of the composite link. Life cycle costs were not evaluated because of the many unknowns that would influence accuracy of these predictions.

6.0 AREAS OF FURTHER STUDY

The results of this effort have identified several critical areas which require further study in order to accurately evaluate the suitability of fabricating tank track connector links with composite materials.

The abrasion resistance design criteria must be defined. A systematic program of material qualification should be undertaken; in particular, the wear resistance of urethane and the applicability of particle deposition should be investigated.

In the present study, the most severe load environment is due to bending through the section of the link which contains the bolt hole. This bending is a direct result of pad pin torsion. Composite materials would provide a much more viable approach to link applications if a means to reduce the amount of torsion that the link must react were found. The most obvious approach to this problem would be to select a rubber with a decreased shear stiffness to transfer pad moment into the link. This would result in a smaller torsion load in the link but would necessitate a belt-tensioning mechanism for the track in order to maintain integrity in service. This and other methods of reducing the torsion load environment in the link must be pursued if composites are to be used.

Currently, composite/metal hybrid bolted joint technology is in its infancy. The response of these hybrid joints, after the metal has yielded, is even less understood. The aluminum is needed as an inner lining in the link to provide a suitable bearing surface for the pins. The preferred approach to the design of such a joint is to have failure in the glass/epoxy simultaneous with or preceding yield in the metal. Certainly more emphasis must be placed on the design and evaluation of this portion of the link.

To summarize, additional research should be directed toward the study of the (1) abrasion resistance of composite materials and their protection, (2) methods of reducing the track pad pin torsional load requirements, and (3) the non-linear elastic-plastic response of bolted composite/metal hybrid joints.

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3. Whitney, J. M., and R. J. Nuismer, "Stress Fracture Criteria for Laminated Composites Containing Stress Concentrations," Journal of Composite Materials, Vol. 8, 1974, p. 253.

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