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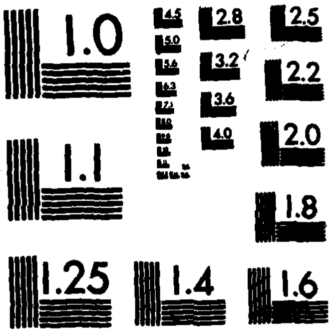

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AMMRC TR 79-42

FEASIBILITY OF COMPOSITE MATERIAL APPLIED TO TRACKED AND WHEELED VEHICLES

June 1979

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Final Report

Contract No. DAAG-78-C-0068

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Prepared for

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Commercial fiber/resin systems were evaluated to determine the feasibility of redesigning M60 Army tank torsion bars to utilize fiber-reinforced composite materials to achieve weight reduction while maintaining service life and reliability. An AS graphite composite torsion bar was designed which met design requirements and weighed 35.3 lb compared to the existing 105-lb steel torsion bar.

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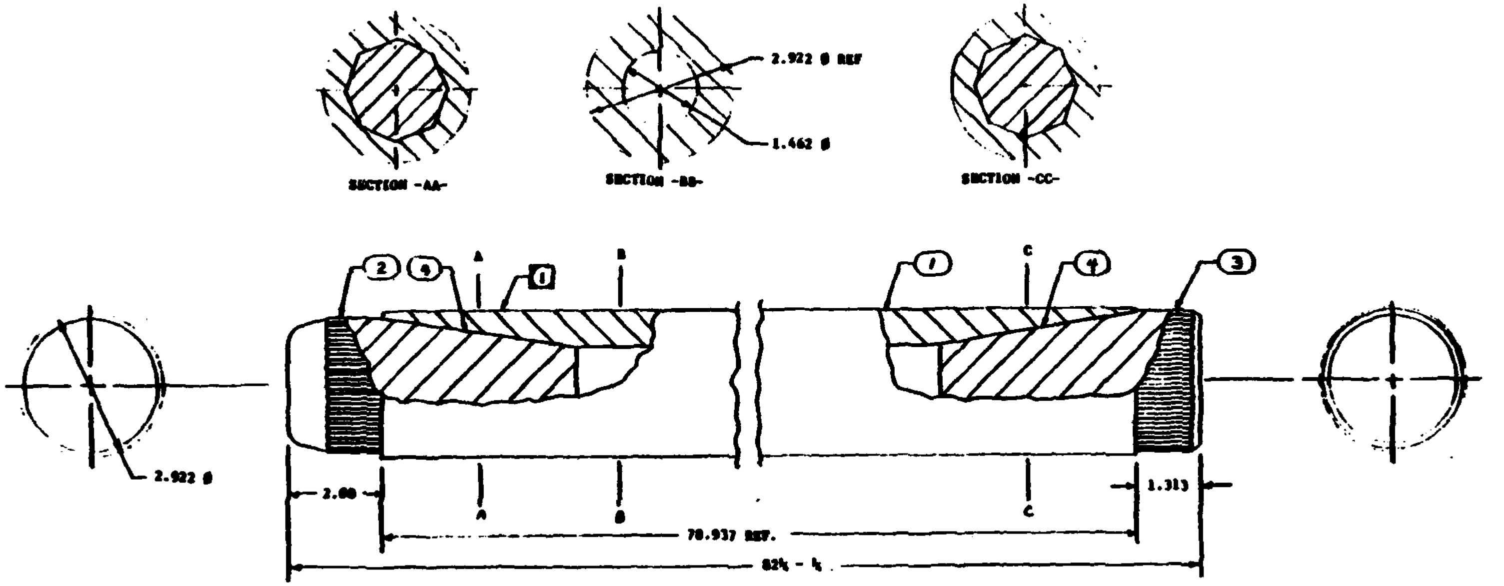
SUMMARY

The technical objectives of this program were to analyze load and envelope requirements for the M-60 Army tank torsion bars (part numbers 7359890 and 7359891) and to evaluate the feasibility of redesigning these torsion bars to utilize fiber reinforced composite materials to achieve weight reduction while maintaining service life and reliability.

Design studies indicated that the only fiber composite of those commercially available in 1978, which could be used in redesigning the torsion bar and be capable of achieving the design requirements, was AS graphite fiber (or its commercial equivalent) in an epoxy resin matrix. This grade of graphite fiber exhibits a fiber strength of 440,000 psi and a modulus of 34.0×10^6 psi. For optimum composite shear properties, the fiber orientation was ± 45 degrees and high fiber volume content was achieved by filament winding the body. Steel end fittings with tapered, octagonal cross section stubs were bonded to the mating inner surface of the composite body to form the composite torsion bar. The proposed design configuration is illustrated in Figure 1. A comparison of the cost, weight, and performance of the composite torsion bar with the existing steel torsion bar is summarized in Table I.



NOTES:

1 FILAMENT WOUND WITH A HELICAL ANGLE OF 45 ± 1 DEGREES RELATIVE TO MERIDIONAL LINE. WINDING TENSION TO BE VARIED UNIFORMLY FROM 10 ± 1 LB/TOW INITIALLY TO 2 $^{+0}_{-1}$ LB/TOW FINALLY.

2 HERCULES 3501-6/AS PREPREG OR EQUIVALENT

3 COMPUTED COMPONENT WEIGHTS ARE:

GRAPHITE FIBER	16.05 LB
RESIN	5.77 LB
SMALL END FITTING	7.24 LB
LARGE END FITTING	6.24 LB

4	AR		ADHESIVE	HYSOL 934
3	1		LARGE END FITTING	
2	1		SMALL END FITTING	
1	1		COMPOSITE TUBE	1
FIND NO.	QTY REQD	PART NO.	NOMENCLATURE	MATERIAL

PARTS LIST

SPRING, TORSION BAR SUSPENSION

Figure 1. Engineering Sketch of Composite Torsion Bar Suspension Spring

TABLE I

COMPARISON OF COMPOSITE TORSION BAR WITH EXISTING STEEL TORSION BAR

Parameter	Design Requirement (Existing Steel Bar)	AS Graphite Composite
Total Weight (lb.)	105.0	35.3
Unit Cost (Dollars)		
10 items	-	2079
100 items	-	1329
10,000 items	98.85	654
Spring Rate (in-lb/deg)	7330	7336[1] 7116[2]
Maximum Angle of Twist (deg)	50.5	50.5[1] 52.0[2]
Torsional Load (in-lb)	370,165	451,260[1] 370,100[2]
Total Length (in)	82¼	82¼
End Fittings	Compatible	Compatible

---

[1] on 1st cycle loading

[2] after 45,000 load cycles

PREFACE

The work described in this report was performed by Hercules Incorporated at the Allegany Ballistics Laboratory (ABL) in compliance with Army Materials and Mechanics Research Center Contract DAAG46-78-C-0068, ABL Authorization Order 2003. This final program report covers a work period from September 29, 1978 to March 29, 1979. Technical director of this project was Mr. John Plummer, Army Materials and Mechanics Research Center. At ABL, the program was controlled by Mr. C. M. Minke with Mr. T. C. White performing design and analysis studies.

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INTRODUCTION

The purpose of this contract effort was to evaluate the feasibility of using fiber reinforced composites for selected components in track and wheel Army Vehicles; specifically torsion bars for the M-60 Army tank. The goal was to optimize weight reduction while maintaining (or increasing through material properties) service life and reliability.

Composite designs were to be developed utilizing fibers and resin systems commercially available for calendar year 1978 and attendant properties. Major state-of-the-art methods of fabrication for the torsion bars were to be reviewed for applicability based upon technology and cost with recommendations made for fabrication techniques to produce 10, 100, and 10,000 items.

The basic tasks to be performed in the program were:

(1) Tabulate load and envelope requirements.

(2) Evaluate feasibility of redesigning torsion bars utilizing fiber reinforced composite materials.

(3) Perform design studies using state-of-the art composite material properties.

(4) Review methods of fabrication for applicability (technology and cost).

(5) Make recommendations for fabrication techniques to produce 10, 100, and 10,000 items.

PROGRAM DETAILS

DESIGN AND ANALYSIS

A. Load and Envelope Requirements

The specifications and requirements for the torsion bars (part numbers 7359890 and 7359891 on Dept. of the Army Ordnance Corps. Drawing 8668989) are defined based upon the following AMMRC supplied information.

Design loads are:

Maximum Angle of Twist - 50.5 deg.

Spring Rate - 7,330 in. lb/deg.

Fatigue Requirements - MIL-S-45387

The envelope specification was that the end fittings must be compatible. The configurations of the end fittings were described in drawing 8668989. The fatigue requirement specified in MIL-S-45387 was that the springs have an endurance life of not less than 45,000 cycles. Each cycle shall be such that it imposes a deflection range from 5% to 100% of the maximum wind up angle.

The design torsion load, T, was computed based upon spring rate, k, and maximum angle of twist, θ, at design conditions:

$$T = k\theta$$

$$= 7330 \times 50.5$$

$$T = 370{,}165 \text{ in lb.}$$

The effective length, ℓ, of the torsion bar was computed based upon the existing steel torsion bar.

$$\ell = \frac{KG}{k}$$

where: K = torsional stiffness factor

$$= \frac{\pi D^4}{32} = \frac{\pi (2.350)^4}{32}$$

$$K = 2.9941 \text{ in}^4$$

G = Shear Modulus of Steel

$$G = 11.0 \times 10^6 \text{ psi}$$

$$\ell = \frac{2.9941\ (11.0 \times 10^6)}{7330} \times \frac{\pi}{180}$$

$$\ell = 78.422 \text{ in.}$$

Based upon these specifications, load data, and envelope requirements the baseline established to be evaluated in a composite configuration is summarized in Table II.

B. Rationale for Materials Selection

The composite designs were to be developed utilizing fibers and resin systems commercially available for calendar year 1978 and attendant properties.

The commercially available fibers suitable for fiber reinforced composite applications were grouped into four basic materials:

(1) Boron
(2) Fiberglass
(3) Graphite
(4) Kevlar

The primary fiber forms were continuous filament, chopped filament, and woven cloth. Basic resin systems considered were polyester, thermosetting epoxy, and polysulfone thermoplastic.

The basic forms of the combined fiber and resin considered in component fabrication included filament winding - automated, hand layup or a combination of the two, and pultrusion.

Initial calculations indicated that to achieve the necessary torsional stiffness and strength in the composite torsion bar, high efficiency in composite strength and fiber volume content were required. This lead to the conclusion that the fiber form should be continuous filament with the fabrication technique being filament winding to achieve high fiber volume content, high composite shear strength, and variable winding tension control.

The resin matrix selection criteria were:

(1) adequate fiber impregnation during fabrication.

(2) commercial availability at a reasonable cost.

(3) maintenance of high mechanical properties in the composite (in particular, high shear property values) in a temperature range of $-40^{\circ}F$ to $+150^{\circ}F$.

A summary of guidelines in the selection of suitable resins is given in Table III. Based upon the goal of maintaining high composite properties at operating temperatures up to $150^{\circ}F$, the use of polyesters was eliminated. Epoxy thermosetting resins have the most widespread use in the composites fabrication industry, with several systems having been well characterized. Commercially available and well characterized epoxy resin systems suitable for filament winding which meet the guidelines specified in Table III are identified in Table IV along with physical properties. The first resin system listed in Table IV consisted of Hysol 826, Ciba-Geigy Araldite RD-2 diluent,

TABLE II

BASELINE FOR COMPOSITE CONFIGURATION

Dimensions

Total Length (L)	82.25 in.
Effective Length (ℓ)	78.422 in.
End Fittings	per Drawing 8668989
small end	spline major dia. - 2.750 in.
large end	spline major dia. - 2.845 in.
material	steel, Rockwell C47-51
Body Cross Section (D)	2.350 in. diameter

Performance Parameters

Maximum Angle of Twist (θ)	50.5 deg.
Spring Rate (k)	7330 in lb/deg.
Torsion Load (T)	370,165 in/lb.
Endurance Life	45,000 cycles
Deflection Range (δ)	5% to 100% max. θ
Torsional Stiffness (KG)	32.9351×10^6 lb. in.^{2}
Weight	minimum

TABLE III

RESIN SELECTION GUIDELINES

Property	Goal
Initial Viscosity	700 to 1500 cps
Time to 5000 cps @ 25°C	18 hrs.
Density	1.23 gm/cc max.
Water Absorption	3% max.
Shrinkage	low
Low temperature cure	~200°F
Non toxic and low vapor pressure	
Reliable ingredient supply	

TABLE IV

SUMMARY OF RESIN PROPERTIES

RESIN SYSTEM	INITIAL VISCOSITY @ 25°C (CPS)	TIME TO 5000 CPS @ 25°C (HRS)	HEAT DISTORTION TEMPERATURE °C	DENSITY (gm/cc)	WATER ABSORPTION 28 DAYS @ 130°F (%)	MODULUS (10^6psi)	STRENGTH (psi)	ELONG. (%)	CURE CONDITIONS (TYPICAL)
Hysol 826/ RD2/Tonox	1050	14.5	119	1.209	3.4	0.45	12,800	8.0	6 hr @ 50°C 3 hr @ 90°C 4 hr @ 120°C
Hysol 953/ RD2/Tonox	910	16.0	37	1.079	2.2	0.15	3,400	54.0	6 hr @ 50°C 2 hr @ 90°C 4 hr @ 120°C
Hysol 826/ MTHPA/ BDMA	900	29.0	153			0.49	13,200	5.7	6 hr @ 65°C 5 hr @ 177°C
Epon 826/ D230	500		46 84	1.162 1.162		0.45 0.43	6,040 10,600	1.3 7.7	7 days @ 25°C 16 hr @ 80°C
Epon 828/ T403	1000	3.5	84	1.162		0.35	8,750	13.0	6 hr @ 90°C
DER 332/ T403	1000	16.0	62.5	1.162	0.80	0.50	8,600	2.3	3 wk @ 25°C

and Uniroyal Tonox 6040 curing agent. This system is currently one of the most extensively characterized resins and exhibits high mechanical properties in structural applications where the component is cured at 120°C (250°F). For these reasons, the Hysol 826/RD2/Tonox 6040 resin system was selected for the composite torsion bar.

A novel approach to achieve a rapidly (almost instantaneous) curing composite; and at the same time lock in radial prestress in the filament wound composite with a programmed winding tension, was to use a thermoplastic matrix such as polysulfone. Both the polysulfone and fiber prepregged with polysulfone are commercially available; however, its application in structural components has been limited to development programs. Because of its limited use, the polysulfone was not recommended for the composite torsion bar application at this time.

To more precisely delineate the selection of fiber for use in the composite, the following specific fiber products were determined to be representative of all fiber materials commercially available.

Basic Fiber Material	Commercial Fiber
Boron	Avco Boron
Fiberglass	
Industrial reinforcement	Owens/Corning E Glass
High strength	Owens/Corning S Glass
Graphite	
Intermediate Strength/modulus	Hercules AS Graphite
High modulus	Hercules HMS Graphite
Ultra high modulus	Celion GY 70 Graphite
Kevlar	Dupont Kevlar 49

These fibers and their attendant properties were selected for the design trade studies.

C. Design Approach

The criteria considered in sizing the torsion bar dimensions for incorporating composites into the previously metallic product are summarized by three strength of material equations.

(1) Spring Rate, $k = \frac{KG}{\ell}$

(2) Torsion Load, $T = \frac{JK}{\rho}$

(3) Maximum Angle of Twist, $\theta = \frac{T}{k}$

where: k = spring rate - in lb/deg.
K = torsional stiffness factor
ℓ = torsion bar effective length - in.
T = torsion load - in/lb.
τ = shear stress - psi.
ρ = distance from centroid to extreme fiber - in.
θ = angle of twist - rad or deg.

It was assumed that the cross section was uniform over the effective length, ℓ.

Specified values for these coefficients were:

k = 7330 in lb/deg.
ℓ = 78.422 in.
T = 370,165 in/lb.
θ = 50.5 deg. = .8814 rad.

The coefficients K and ρ were dependent upon the cross section and τ was a function of the composite configuration.

The approach was to configure the composite to meet the spring rate and maximum angle of twist values without exceeding the composite material shear strength.

D. Computation of Composite Properties

Lamina properties of the selected fibers in an epoxy matrix with a 60% fiber volume content are tabulated in Table V. These data are first cycle, nominal values at room temperature.

The torsion springs were required to satisfy the fatigue requirements specified in MIL-S-45387. The criteria established by this specification was that the springs shall have an endurance life of not less than 45,000 cycles. Each cycle shall be such that it imposes a deflection range from 5% to 100% of the maximum wind up angle. Based upon experimentally measured values reported in Reference (1), the following torsional shear strength and modulus degradation factors were tabulated for the fiber reinforced composites being considered as materials for the torsion springs:

Composite	Strength Factor*	Modulus Factor**
Boron	.82	.97
E-Glass	.47	.95
S-Glass	.47	.95
AS Graphite	.82	.97
HMS Graphite	.82	.97
GY-70 Graphite	.82	.97
Kevlar	.56	.95

$$\text{*Strength Factor} = \frac{\text{Strength after 45,000 cycles}}{\text{Initial strength}}$$

$$\text{**Modulus Factor} = \frac{\text{Modulus after 45,000 cycles}}{\text{Initial modulus}}$$

TABLE V

TABULATION OF NOMINAL FIBER/EPOXY LAMINA PROPERTIES AT ROOM TEMPERATURE

PROPERTY		FIBER						
		Boron	Fiberglass		Graphite			Kevlar
			"E"	"S"	AS	HMS	GY 70	
E_{11}	(msi)	30.0	6.7	8.8	19.0	29.6	42.0	11.8
E_{22}	(msi)	3.0	1.8	1.9	1.33	1.4	.9	.76
G_{12}	(msi)	.6	.8	.88	.60	.60	.65	.27
ν_{12}		.3	.25	.30	.30	.30	.25	.34
α_{11}	(10^{-6} in/in/^{o}F)	2.5	3.5	3.5	-.20	-.30	-.30	-.30
α_{22}	(10^{-6} in/in/^{o}F)	8.0	12.0	12.0	15.0	13.0	13.0	19.0
ϵ_{11_T}	(in/in)	.0077	.0224	.0280	.0018	.0055	.0021	.0161
ϵ_{11_C}	(in/in)	-.0133	-.0224	-.0170	-.0100	-.0058	-.0021	-.0036
ϵ_{22_T}	(in/in)	.0030	.0033	.0052	.0142	.0043	.0040	.0038
ϵ_{22_C}	(in/in)	-.0133	-.0111	-.0240	-.0100	-.0100	-.0100	-.0178
γ_{12}	(in/in)	.0133	.0075	.0100	.0170	.0123	.0092	.0201
F_{11_T}	(ksi)	230.0	150.0	246.4	224.2	145.0	90.0	190.0
F_{11_C}	(ksi)	-400.0	-150.0	-149.6	-160.0	-145.0	-90.0	-42.6
F_{22_T}	(ksi)	9.0	6.0	9.9	9.6	6.0	3.6	2.9
F_{22_C}	(ksi)	-40.0	-20.0	-21.1	-30.0	-25.0	-20.0	-13.5
τ_{12}	(ksi)	8.0	6.0	8.8	10.2	8.0	6.0	5.4

The properties of the composite laminate for helical layer orientations between 0 degrees and 45 degrees were computed with respect to the meridional axis of the torsion bar using a laminate properties program developed in-house on a Hewlett-Packard 9810 calculator. The properties important in this study are shear strength and shear modulus and are tabulated, based upon lamina properties given in Table IV, in 5 degree helical angle increments for the fiber composites in Table VI. As noted in this Table VI, both shear strength and shear modulus are maximum at the helical angle of 45 degrees. Also, the shear properties as a function of helical angle are symmetrical about the 45 degree helical angle value, thus, the shear properties are the same for a given helical angle and its complement angle (such as $0^\circ = 90^\circ$, $10^\circ = 80^\circ$, $30^\circ = 60^\circ$, etc.).

E. Composite Design Studies

(1) Designs Using Existing Diameter and Length

Based upon the 2.350 inch diameter and 82¼ inch length of the existing steel bar as the limiting diameter and length, the composite configuration which most nearly satisfied the design goals was a round, solid cross section bar fabricated by filament winding the composite at a helical angle of ± 45 degrees. The round, solid cross section provided the maximum torsional stiffness parameter, K, with the lowest maximum shear stress and the ± 45 degree fiber orientation resulted in the maximum value of both shear modulus and torsional shear strength.

The values of spring rate, maximum angle of twist, and allowable torsion load for the candidate composite materials are tabulated in Table VII. Plotting the parameters of allowable torsional load versus spring rate of the composite materials in Figure 2, their relative performance compared to the design goal located in the upper right area of the Figure was noted. The material most nearly satisfying the torsion load and angle of twist requirements was AS graphite/epoxy. The first cycle torsional load capability was 68% of the design goal and allowable angle of twist exceeded the design requirement. Initial spring rate was 45% of the value desired. After 45,000 cycles, the torsional load capability of AS graphite was 55% of design goal. GY-70 graphite epoxy exhibited the highest first cycle spring rate of 7082 in.lb/deg; 97% of design value decreasing to 94% of design spring rate after 45,000 cycles. However, the maximum angle of twist and allowable torsion load of the GY-70 graphite composite were very low, being only 32% and 31%, respectively, of design requirements during the first load cycle. After 45,000 cycles, the torsional load capability of the GY-70 was 25% of design goal.

Based upon this evaluation, the composite material most nearly meeting design goals of the existing torsion bar configuration was AS graphite/epoxy.

(2) Designs Using Existing Length But With Increased Diameter

Based upon the existing torsion spring length of 82¼ inches and the nominal 1st cycle strengths of the composite materials, the maximum cross sectional diameters which could be achieved without exceeding the torsional

TABLE VI

NOMINAL INITIAL LAMINATE SHEAR PROPERTIES OF VARIOUS FIBER COMPOSITES AT ROOM TEMPERATURE

ORIENTATION (deg)	BORON		E GLASS		S GLASS		AS GRAPHITE		HMS GRAPHITE		GY70 GRAPHITE		KEVLAR	
	τ*	G**	τ	G	τ	G	τ	G	τ	G	τ	G	τ	G
0	8.0	.60	6.0	.80	8.8	.88	10.2	.60	8.0	.65	6.0	.65	5.4	.27
5	11.1	.82	6.4	.83	9.4	.93	12.6	.73	10.7	.86	8.9	.95	7.2	.35
10	20.5	1.45	7.4	.93	11.3	1.06	20.0	1.11	19.1	1.46	17.8	1.82	12.5	.59
15	29.0	2.42	9.4	1.08	14.7	1.27	32.9	1.68	33.8	2.38	26.4	3.14	13.8	.96
20	33.6	3.60	12.4	1.27	19.9	1.52	52.9	2.38	47.0	3.51	31.2	4.77	15.8	1.41
25	38.1	4.87	12.6	1.47	24.4	1.79	81.8	3.13	52.9	4.71	35.7	6.50	17.8	1.89
30	41.9	6.05	12.7	1.65	24.6	2.05	88.6	3.84	58.0	5.84	39.4	8.13	19.5	2.34
35	44.8	7.02	12.8	1.80	25.0	2.26	93.8	4.41	61.9	6.76	42.3	9.46	20.8	2.71
40	46.6	7.65	12.9	1.90	25.2	2.39	97.2	4.78	64.3	7.36	44.0	10.33	21.6	2.95
45	47.2	7.87	12.9	1.93	25.3	2.44	98.3	4.91	65.1	7.57	44.6	10.63	21.8	3.03

*τ is torsional shear strength (ksi)

**G is shear modulus (msi)

TABLE VII

PROPERTIES OF COMPOSITE TORSION BAR BASED UPON 2.350 INCH DIAMETER AND 82¼ INCH LENGTH

COMPOSITE	CYCLE	SPRING RATE (In.lb/deg)	MAX. ANGLE OF TWIST (Deg.)	ALLOWABLE TORSION LOAD (In.lb.)
Design Goal	1	7330	50.5	370,165
	45,000	7330	50.5	370,165
Boron	1	5249	22.9	120,250
	45,000	5092	19.3	98,244
E Glass	1	1285	16.3	20,902
	45,000	1220	8.0	9,719
S Glass	1	1624	25.2	40,993
	45,000	1543	12.4	19,062
AS Graphite	1	3275	76.5	250,435
	45,000	3177	64.4	204,605
HMS Graphite	1	5046	32.9	165,941
	45,000	4895	27.7	135,574
GY70 Graphite	1	7082	16.1	113,731
	45,000	6870	13.5	92,918
Kevlar	1	2021	27.5	55,653
	45,000	1920	16.2	31,166

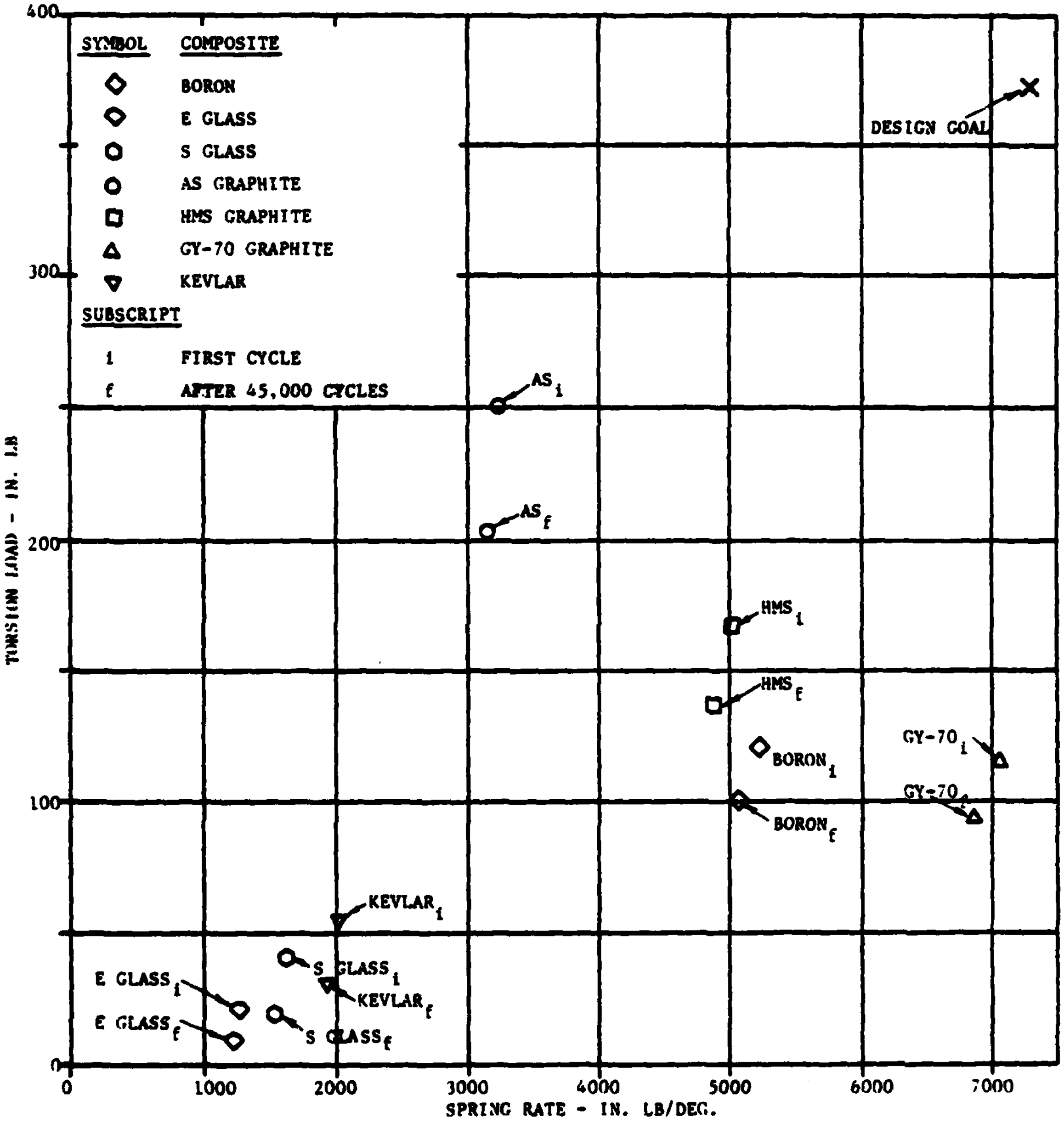


Figure 2. Relative Comparison of Composite Materials in Meeting Torsion Load and Spring Rate Requirements of Existing Torsion Bar Configuration

shear stength were computed, along with resultant spring rate and maximum angle of twist and are tabulated in Table VIII. A solid, round uniform cross section was again assumed since this section resulted in the maximum stiffness-to-stress ratio and the design torsion load which had to be met was 370,165 in lb. The data in Table VIII indicated that only the AS graphite bar was capable of meeting the maximum angle of twist requirement of 50.5 degrees.

The next criteria considered was to determine the solid bar diameter necessary to satisfy the spring rate of 7330 in.lb/deg., again assuming the existing effective torsion spring length of 78.422 inches. A general plot of required shear modulus and resultant shear stress as a function of bar diameter is shown in Figure 3. The specific composite configurations, which were tabulated in Table IX, showed that the torsional load requirement of 370,165 in. lb. could be met only by the AS graphite composite.

The conclusion, drawn from this trade study in which only the diameter was allowed to increase, was that AS graphite was the only fiber composite that could be used and satisfy initial spring rate, angle of twist, and torsional load requirements. The properties of the round, solid cross section, AS graphite torsion bar which satisfy design requirements with the exception of cross sectional diameter are tabulated in Table X.

(3) Designs Allowing Variation in Both Length and Diameter

The next trade study was performed assuming that both the diameter and length of the solid, round cross section bar could vary. The required design properties were:

$$T = 370{,}165 \text{ in-lb}$$

$$\theta = 50.5 \text{ deg.}$$

$$k = 7330 \text{ in-lb/deg.}$$

$$\tau = \text{Composite } \tau_{allow}$$

with all composites wound at a ± 45 degree helical angle. The length and diameter were varied according to the angle of twist equation,

$$\theta = \frac{T\ell}{KG}$$

which may be expressed in the form,

$$\frac{\ell}{R^4} = \frac{\pi\theta G}{2T}$$

solving this equation and the equation for shear stress, τ,

$$\tau = \frac{Te}{K}$$

TABLE VIII

COMPOSITE BAR CROSS SECTIONAL DIAMETERS WHICH SATISFY TORSION LOAD USING EXISTING TORSION BAR LENGTH OF 82½ INCHES

Fiber Composite[1]	Dia. (in.)	Spring Rate (in.lb/deg)	Max. Angle of Twist (deg)	Max. Shear Stress[2] (psi)
Boron	3.418	23,469	15.77	47,200
E Glass	5.267	32,453	11.406	12,900
S Glass	4.205	16,651	22.23	25,355
AS Graphite	2.677	5,513	67.14	98,281
HMS Graphite	3.071	14,706	25.17	65,122
GY-70 Graphite	3.483	34,156	10.84	44,632
Kevlar	4.419	25,284	14.64	21,840

[1] Fiber orientation was ± 45 degrees.

[2] Maximum shear stress at torsion load of 370,165 in.lb. equal to material 1st cycle nominal shear strength.

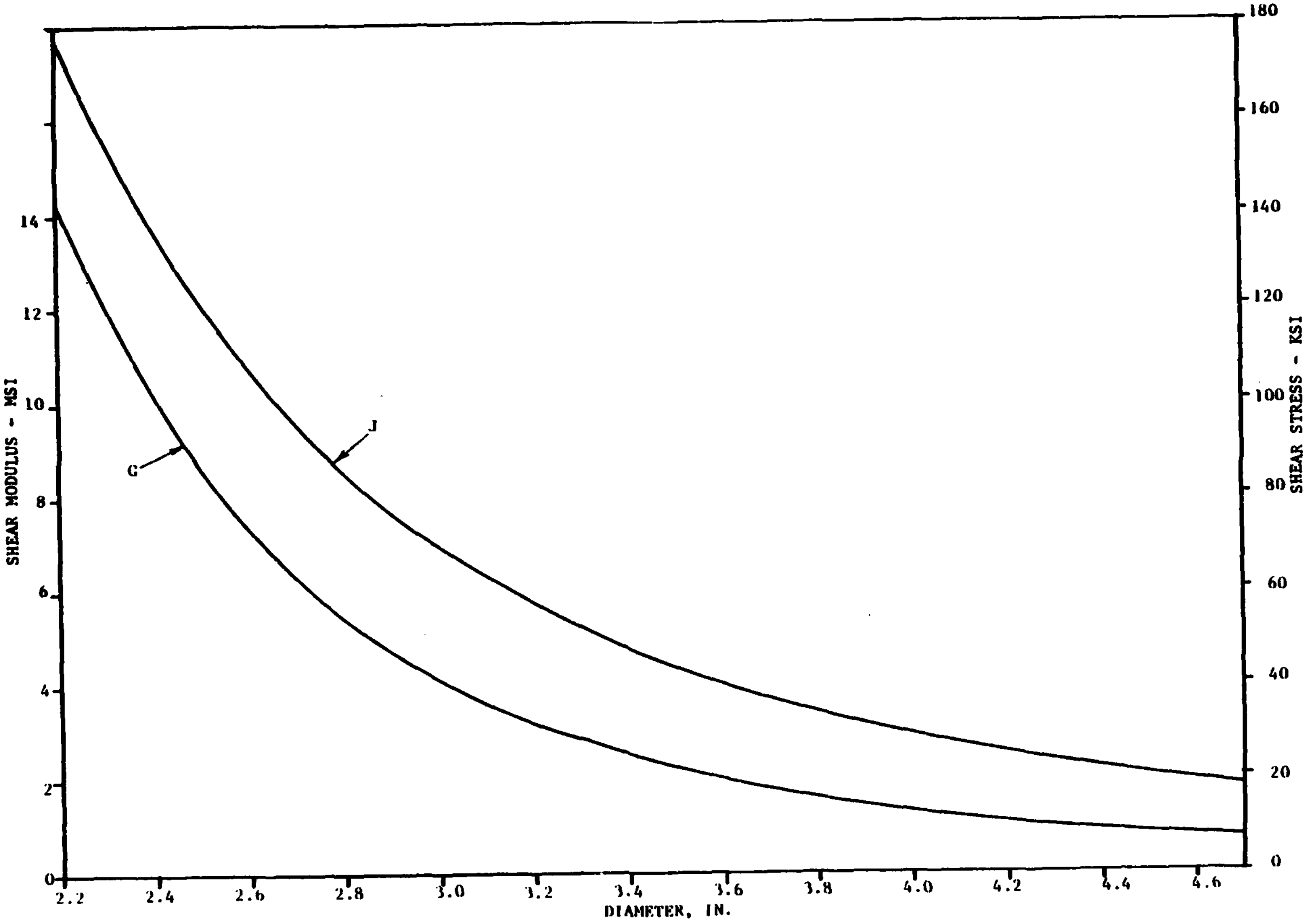


Figure 3. Torsion Bar Modulus and Stress as a Function of Solid Bar Diameter

TABLE IX

COMPOSITE BAR DIAMETERS WHICH SATISFY SPRING RATE USING TORSION BAR LENGTH AT 82½ INCHES

Fiber Composite[1]	Dia. (in)	Allow Torsion Load (in-lb)	Max. Angle of Twist (deg)	$\frac{T_{allow}}{T_{design}}$
Boron	2.555	154,612	21.09	0.42
E Glass	3.631	121,255	16.54	0.33
S Glass	3.425	200,008	27.29	0.54
AS Graphite	2.874	458,284	62.52	1.24
HMS Graphite	2.580	219,589	29.96	0.59
GY-70 Graphite	2.370	116,720	15.92	0.32
Kevlar	3.243	146,258	19.95	0.40

[1] Fiber orientation was ± 45 degrees

TABLE X

PROPERTIES OF SOLID, ROUND CROSS SECTION, AS GRAPHITE TORSION BAR COMPARED TO DESIGN REQUIREMENTS

Parameter	AS Graphite* Configuration	Design Requirement
Torsion Load (in lb)	458,284	370,165
Spring Rate (in lb/deg)	7,330	7,330
Max. Angle of Twist (deg)	50.5	50.5
Diameter (in)	2.874	2.350
Total Length (in)	82¼	82¼

*1st cycle properties

such that the shear stress equals the composite allowable shear stress, a plot of effective length as a function of maximum shear stress for the various composite materials is shown in Figure 4. For the specific allowable shear strength of each fiber composite, the effective length and corresponding bar diameter was tabulated in Table XI.

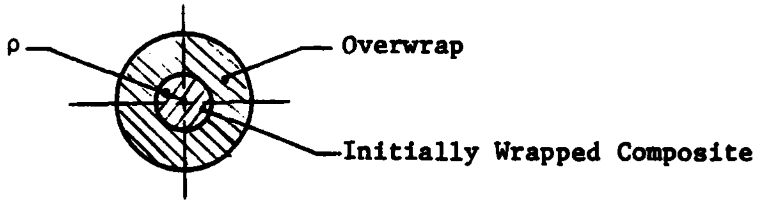
Since the required lengths exceeded the baseline value for all materials except AS graphite, torsional column buckling was checked using the following equation,

$$T_{cr} = \frac{2\pi\ EI}{\ell}$$

As shown in Table XII, all materials except GY-70 exhibited positive margins of safety against torsional column buckling. It was found that the GY-70 composite bar length would have to be reduced to 310 inches with a consequential increase in spring rate of 8909 in-lb/deg. and maximum angle of twist decreased to 41.55 deg. Based upon this calculation, the GY-70 graphite composite configuration cannot meet the design goals without experiencing torsional column buckling unless laterally constrained.

(4) Hybrid Configuration

Another consideration in configuring the torsion bar was the use of a hybrid configuration, in which a high modulus but low strength composite was used initially in the filament winding operation followed by overwrapping with a higher strength composite as depicted in the following cross section.

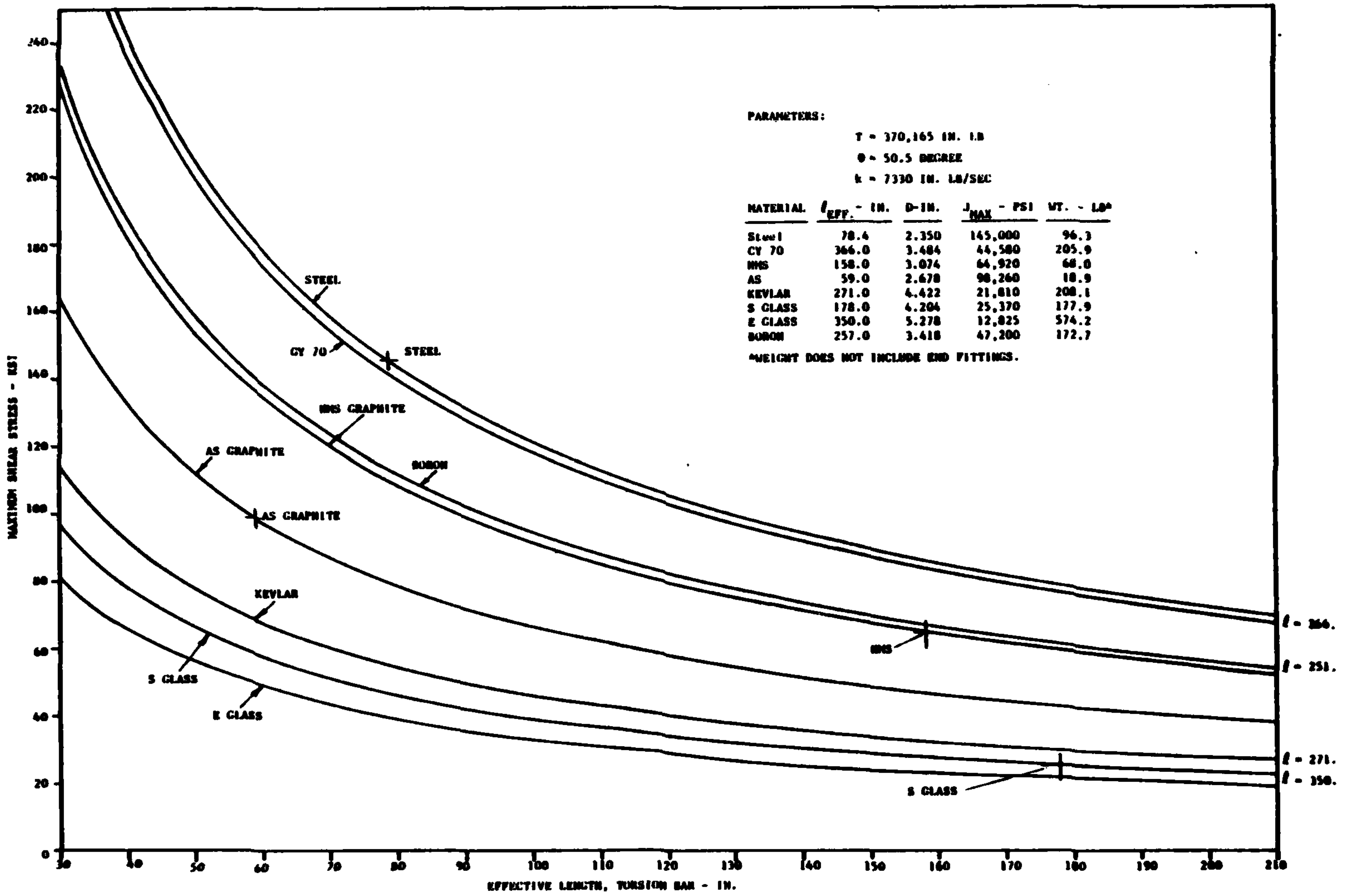


The best combination for this case was ± 45° HMS graphite overwrapped with ± 45° AS graphite composite. For a maximum angle of twist of 50.5°, the maximum radius of the HMS graphite composite without exceeding its allowable shear strength was computed.

$$\rho = \frac{\ell}{\theta} = \frac{\tau\ell}{G\theta}$$

for HMS: $\tau = 65{,}121$ psi
$\ell = 78.422$ in.
$G = 7.572 \times 10^6$ psi
$\theta = 0.8816$ rad.

$\therefore\ \rho = 0.765$ in.



PARAMETERS:

T = 370,165 IN. LB

θ = 50.5 DEGREE

k = 7330 IN. LB/SEC

MATERIAL	$\ell_{EFF.}$ - IN.	D-IN.	J_{MAX} - PSI	WT. - LB*
Steel	78.4	2.350	145,000	96.3
CY 70	366.0	3.484	44,580	205.9
HMS	158.0	3.074	64,920	68.0
AS	59.0	2.678	98,260	18.9
KEVLAR	271.0	4.422	21,810	208.1
S GLASS	178.0	4.204	25,370	177.9
E GLASS	350.0	5.278	12,825	574.2
BORON	257.0	3.418	47,200	172.7

*WEIGHT DOES NOT INCLUDE END FITTINGS.

Figure 4. Maximum Shear Stress as a Function of Torsion Bar Effective Length

TABLE XI

COMPOSITE DIAMETER AND LENGTH NECESSARY TO MEET LOAD REQUIREMENTS

Fiber Composite	Diameter (in)	ℓeff (in)	Composite Weight (lb)
Boron	3.418	251.0	172.7
E Glass	5.278	350.0	574.2
S Glass	4.204	178.0	177.9
AS Graphite	2.678	59.0	18.9
HMS Graphite	3.074	158.0	68.0
GY-70 Graphite	3.484	366.0	205.9
Kevlar	4.422	271.0	208.1

TABLE XII

TORSIONAL COLUMN BUCKLING MARGINS OF SAFETY FOR DIFFERENT FIBER COMPOSITES

Fiber Composite	Length (in)	Dia. (in)	Tcr (in - lb)	M.S.
Boron	251.0	3.418	$.403 \times 10^6$	+0.09
E Glass	350.0	5.278	1.419×10^6	+2.83
S Glass	178.0	4.204	1.475×10^6	+2.98
AS Graphite	59.0	2.678	0.579×10^6	+0.56
HMS Graphite	158.0	3.074	0.419×10^6	+0.13
GY-70 Graphite	366.0	3.484	0.305×10^6	-0.22
Kevlar	271.0	4.422	0.434×10^6	+0.17

The outer diameter of the AS composite overwrap necessary to satisfy the required torsional rigidity was:

$$OD = 2.844 \text{ in.}$$

This hybrid configuration meets the spring rate, torsion load, and maximum angle of twist criteria without exceeding the composite shear strengths; however, the resultant diameter of 2.844 inches is negligibly smaller than the all AS composite configuration which meets the design requirements with a diameter of 2.874 inches.

(5) Tubular Configuration

Since filament winding a solid cross section bar is not practical, the torsional stiffness decrease caused by a tubular cross section was computed as a function of internal radius. Based upon solid cross section designs developed in section (2) in which only the diameter of the bar was increased over the existing configuration, the torsion load capabilities of the fiber composites were calculated as a function of ratio of cross sectional inner to outer radius. Figure 5 compares the torsion load capability during the 1st load cycle and Figure 6 indicates load capability after 45,000 load cycles. As seen in Figure 6, only the AS graphite composite is capable of transmitting the design torsion load of 370,165 in. lb. after 45,000 cycles of loading. With an inner radius as great as 50% of the outer radius, the cross section demonstrated the capability of transmitting the design torsional load.

(6) Proposed Composite Configuration

The material trade study indicated that only one material, of the composites considered, was capable of meeting the design requirements of the torsion bar. This material was AS graphite/epoxy filament wound at a ± 45 degree helical angle orientation with respect to the torsion bar longitudinal axis. From a practical fabrication aspect, the cross section was tubular with an inner-to-outer radius ratio of 0.50. The tubular cross section also represented near maximum ratio of torsional stiffness to shear stress. The performance of this design was compared to the steel torsion bar configuration in Table XIII, illustrating that all performance requirements were met or exceeded.

(7) End Fitting Configuration

The end fittings, which must meet spline dimensions defined in drawing 8668989, must transmit the applied torsion load of 370,165 in-lb. into the torsion bar body. Because of the high stresses induced in the end fitting serrations, the mating details of the end fittings must be alloy steel. To satisfy the requirements of MIL-S-45387, the ends shall be formed by upsetting to provide a continuous, uniform grain flow with the serrations being either cold formed, hobbed or form ground. The end fittings shall be quenched and tempered to a hardness of Rockwell C47-51 from the half radius to the outside of the finished fitting. The fittings should be shot peened in accordance with MIL-S-13165 to a minimum peening intensity of 0.010C for the body and 0.007C for the serrations.

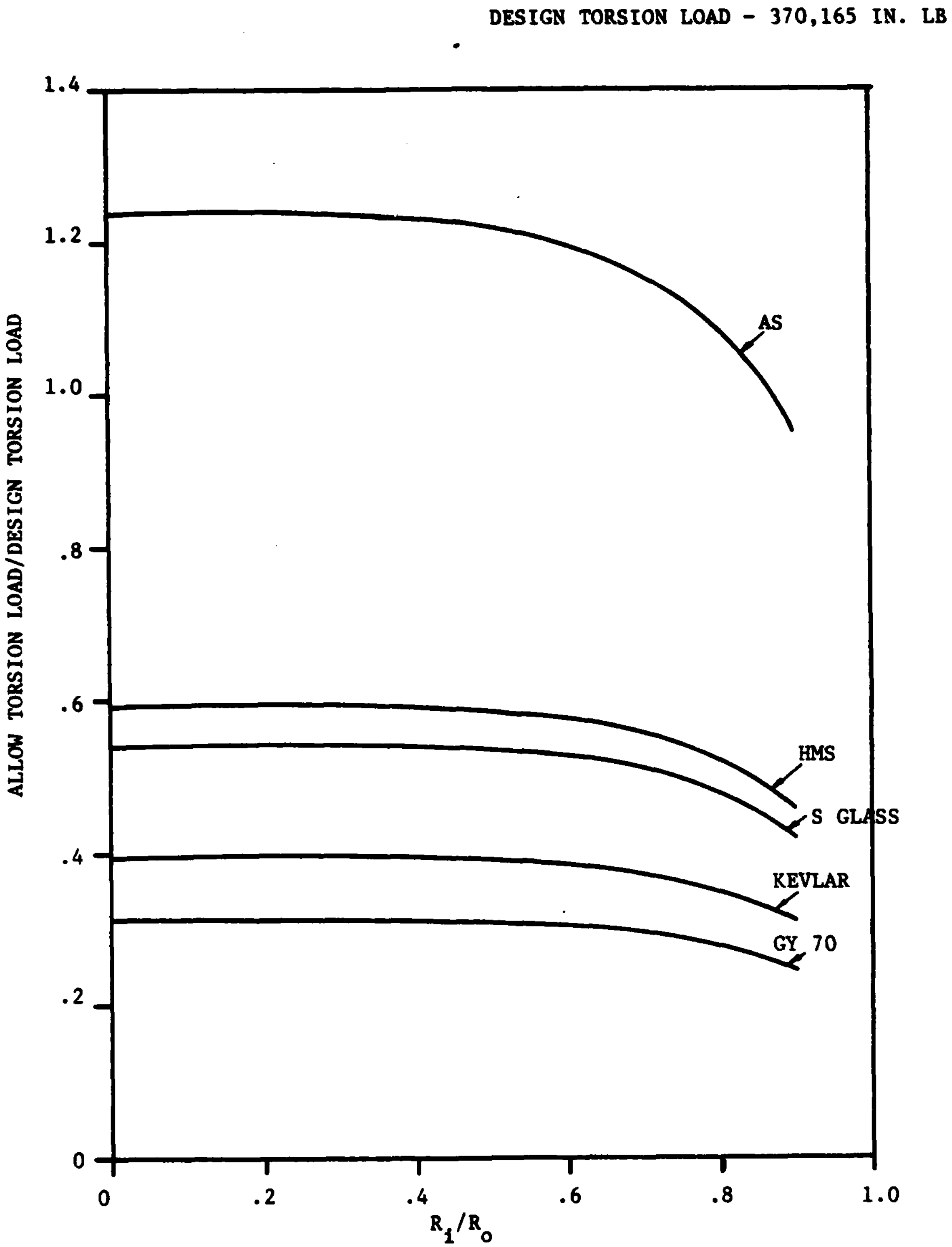


Figure 5. First Cycle Torsion Load Capability as a Function of Radius Ratio, R_i/R_o for Various Composites

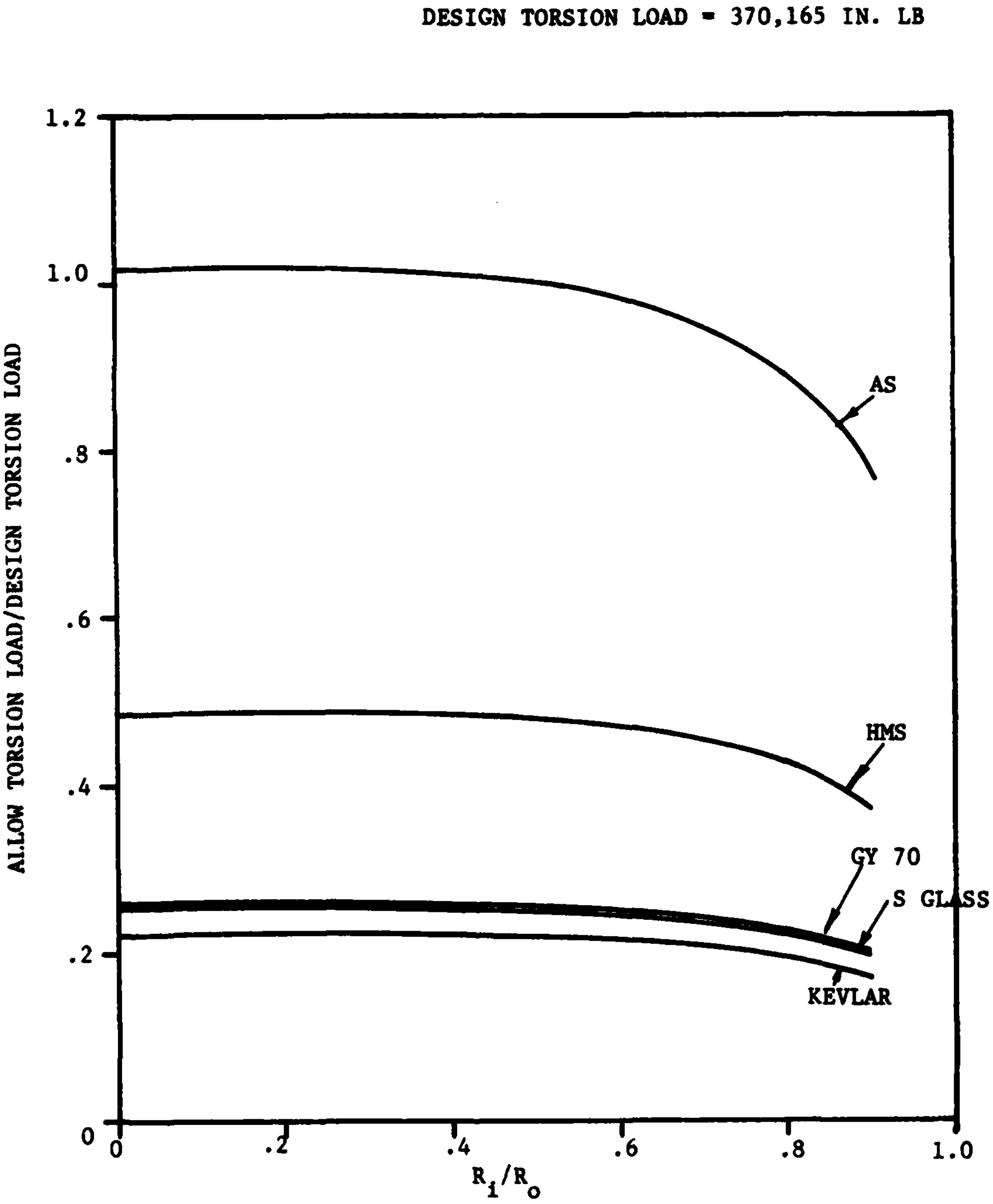


Figure 6. Torsion Load Capability After 45,000 Cycles as a Function of Radius Ratio, R_i/R_o for Various Composites

TABLE XIII

PROPERTIES OF TUBULAR AS GRAPHITE COMPOSITE CROSS SECTION COMPARED TO STEEL BAR DESIGN

Parameter	Design Requirement	AS Graphite Configuration	
		1st Cycle	450,000th Cycle
Total Length (in)	82¼	82¼	82¼
Diameter			
Outer (in)	2.350	2.922	2.922
Inner (in)	-	1.461	1.461
Torsion Load (in-lb)	370,165	451,260	370,100
Spring Rate (in-lb/deg)	7,330	7,336	7,116
Max. Angle of Twist (deg)	50.5	50.5	52.0

Because of the high torsion load which must be transmitted from the end fitting into the torsion bar composite body, the load must be transferred mechanically in bearing and compression. By incorporating a tapered, octagonal cross section which was bonded into the mating composite inner surface as illustrated in Figure 7 for the small end fitting, the torsion load was transmitted into the composite over a 4.0 inch length. This joint cross section had a torsional stiffness value equal to or greater than the composite body. The average torsional shear stress in the composite was computed to be:

$$\tau_{ave} = \frac{T}{2\pi R^2 \ell}$$

where: T = torsional load = 370,165 in-lb
R = average joint radius = 1.012 in.
ℓ = joint length = 4.0 in.

$$\tau_{ave} = 14{,}388 \text{ psi}$$

Estimating the peak stress at the edge of the joint to be 4.0 times the average stress,

$$\bar{\tau}_{peak} = 4.0 \times 14388$$

$$\underline{\bar{\tau}_{peak} = 57{,}552 \text{ psi}} \qquad \underline{\underline{\text{M.S.} = +0.40 \text{ after } 45{,}000 \text{ cycles}}}$$

Based upon this design concept, engineering sketches of the small end fitting and large end fitting were prepared and are shown in Figures 8 and 9, respectively.

(8) Finalized Composite Torsion Bar Design

The design trade study indicated that the redesign of the torsion bar using fiber reinforced composite materials was feasible. One design was evolved which optimized weight reduction while maintaining service life and reliability. The design, as shown in Figure 10, consisted of a filament wound, AS graphite composite tubular bar with steel end fittings bonding in place with Hysol 934 adhesive. The component weights were:

Component	Wt.(lb)
Graphite Fiber	16.05
Epoxy Resin	5.77
Small End Fitting	7.24
Large End Fitting	6.24
Total	35.30

The total assembly weight of 35.30 lb. for the composite bar was considerably less than the 105 lb. weight of the existing steel torsion bar.

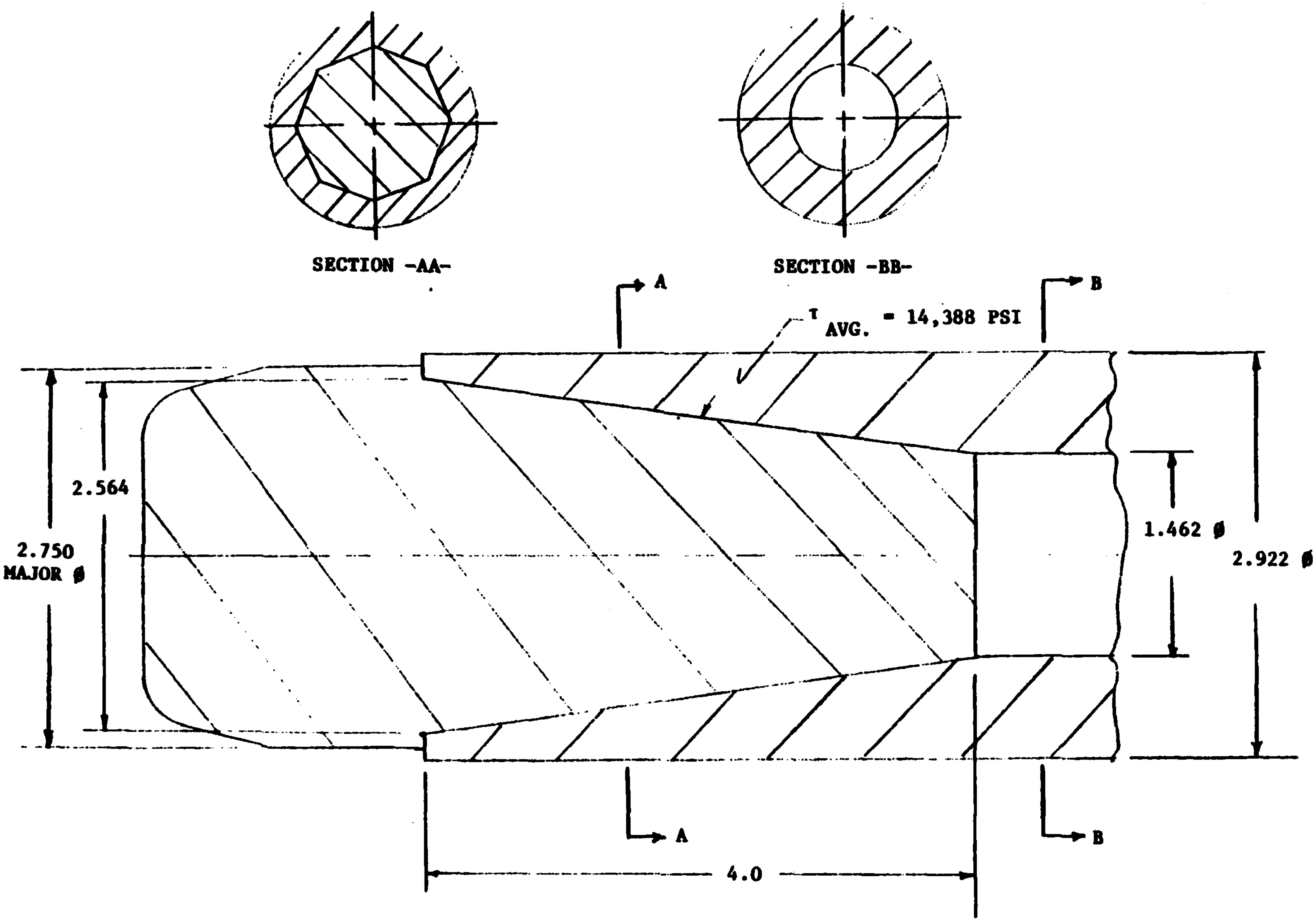


Figure 7. Torsion Bar End Fitting/Composite Body Joint

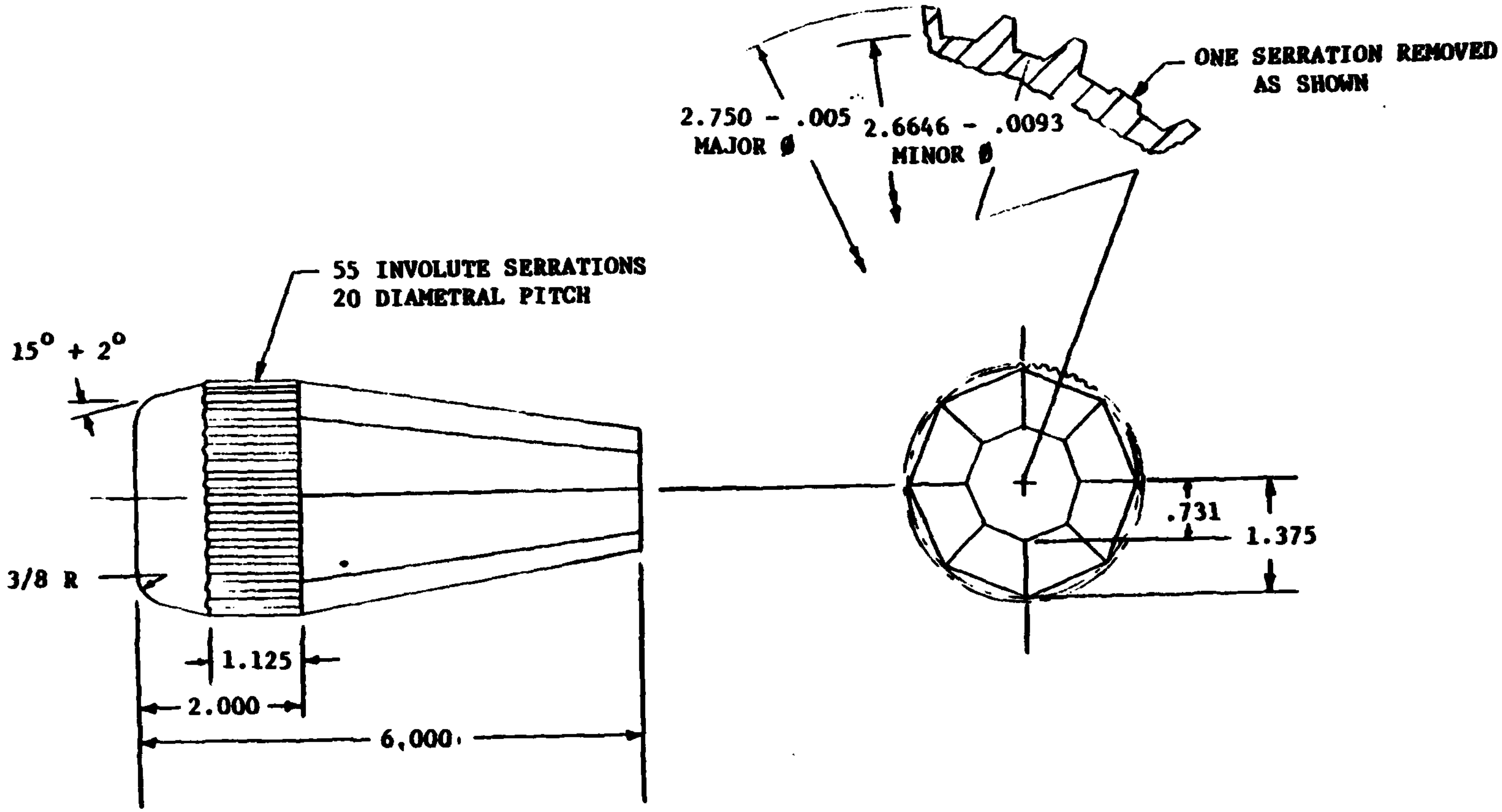


Figure 8. Engineering Sketch of Small End Fitting

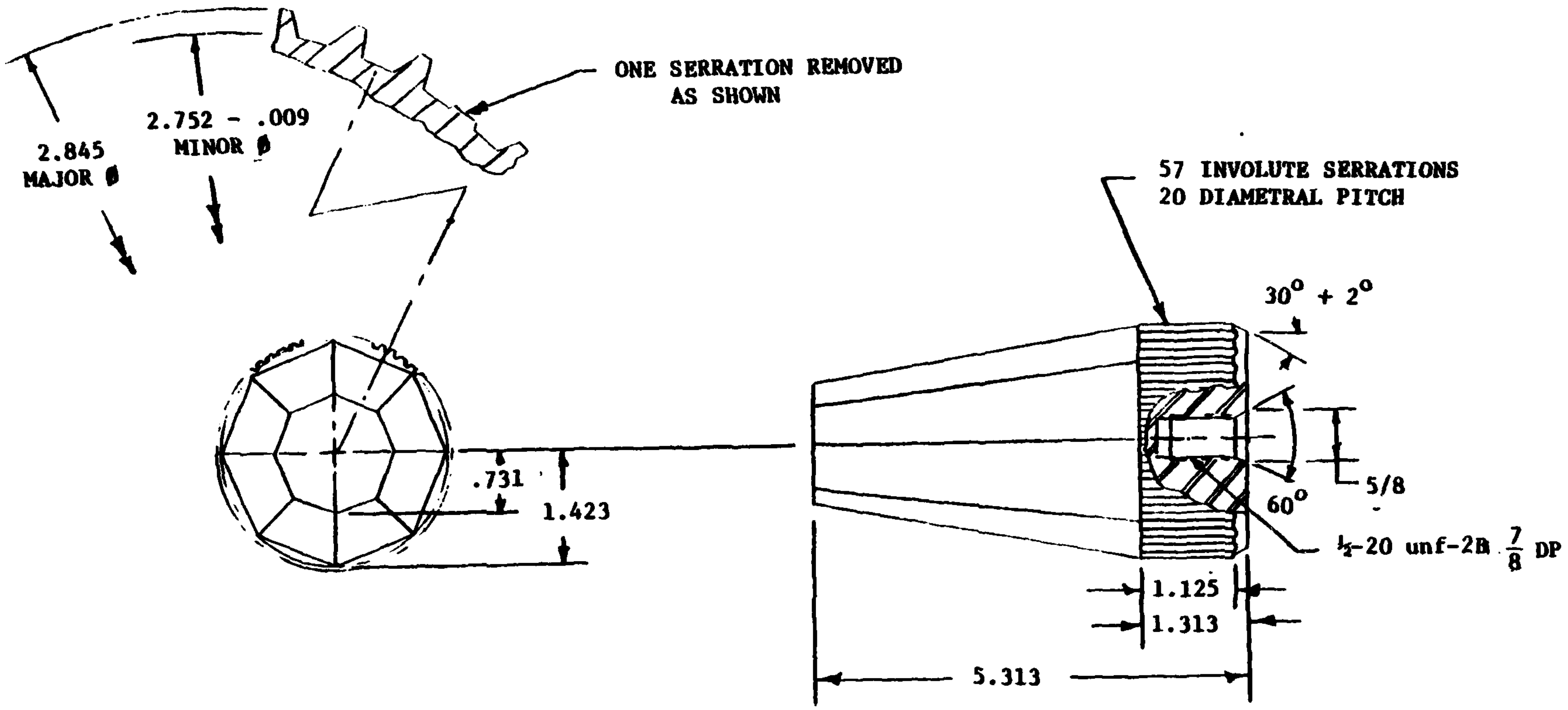
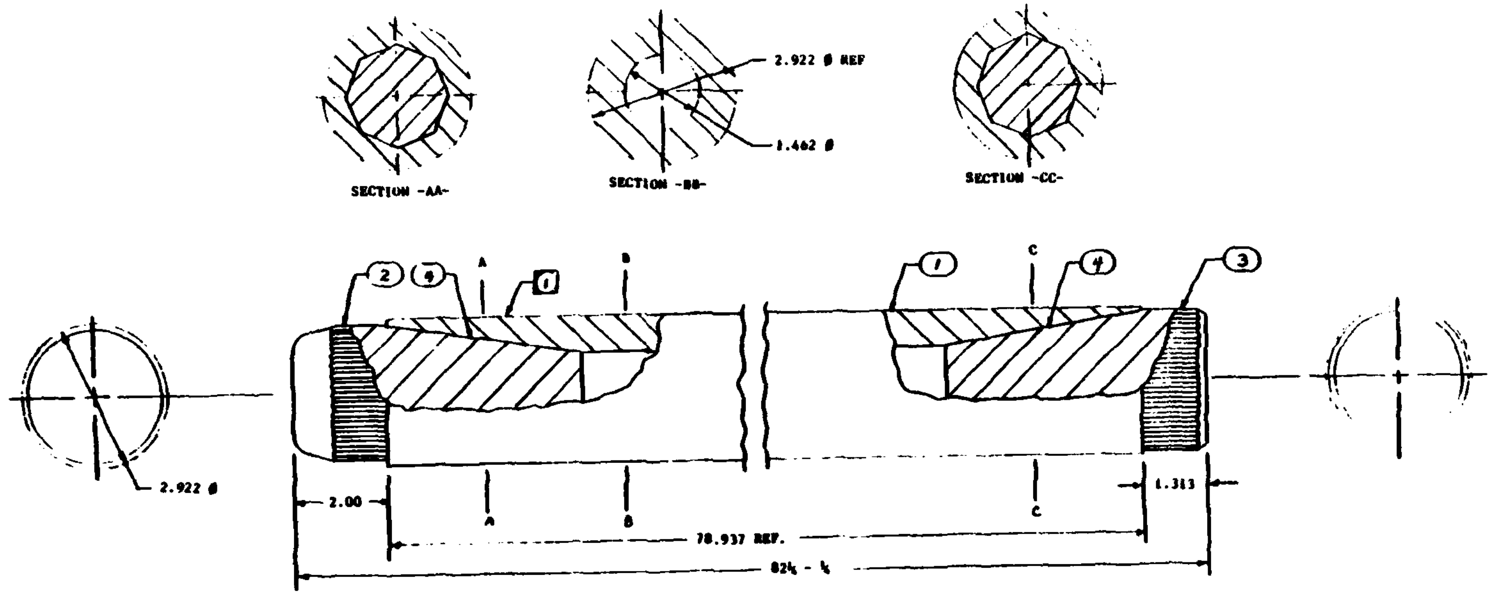


Figure 9. Engineering Sketch of Large End Fitting



NOTES:

1 FILAMENT WOUND WITH A HELICAL ANGLE OF 45 ± 1 DEGREES RELATIVE TO MERIODIONAL LINE. WINDING TENSION TO BE VARIED UNIFORMLY FROM 10 ± 1 LB/TOW INITIALLY TO 2 $^{+0}_{-1}$ LB/TOW FINALLY.

2 HERCULES 3501-6/AS PREPREG OR EQUIVALENT

3 COMPUTED COMPONENT WEIGHTS ARE:

GRAPHITE FIBER	16.05 LB
RESIN	5.77 LB
SMALL END FITTING	7.24 LB
LARGE END FITTING	6.24 LB

FIND NO.	QTY RQ'D	PART NO	NOMENCLATURE	MATERIAL
4	AR		ADHESIVE	HYSOL 934
3	1		LARGE END FITTING	
2	1		SMALL END FITTING	
1	1		COMPOSITE TUBE	2

PARTS LIST

SPRING, TORSION BAR SUSPENSION

Figure 10. Engineering Sketch of Composite Torsion Bar Suspension Spring

FABRICATION

A. Basic Approach

The fabrication approach is proposed as follows. Prototype units would be fabricated using state-of-the-art fabrication techniques and procedures that would produce torsion bar components with a minimum of process development and tooling. As the component configuration became firm, development of manufacturing methods at minimum cost for production quantities would be performed.

The design study conclusions indicated that the composite bar would have a tubular cross section and would be filament wound using epoxy resin and fiber oriented at a helical angle of ± 45 degrees. Tapered, octagonal cross sectional ends on the inner surface of the composite for attachment of end fittings would be formed by the winding mandrel. The end fittings, which were alloy steel, would be formed by upsetting to provide a continuous uniform grain flow with the serrations being either cold formed, hobbed or form ground.

B. Method of Fabrication

The composite body would be filament wound on a teflon coated steel mandrel. The mandrel, a three segment shaft, consists of a 70.95 inch length section with a diameter of 1.462 inches and tapered, octagonal cross section end segments, each 4.0 inches long with a maximum height of 2.750 inches for the small fitting end and 2.846 inches for the large fitting end. The mandrel end segments form an as-wound composite inner surface mating section for subsequent bonding of end fittings. Multiple AS graphite tows would be impregnated with epoxy resin and spread to form a bandwidth of approximately 1.0 inches for winding the ± 45 degree helical layers. For minimum cost fabrication, a prepreg graphite/epoxy band would be used. Since the wall thickness of the bar was fairly large, variation of winding tension in incremental steps would be incorporated in the filament winding schedule to assure uniform compaction of layers with minimum voids and resin rich areas. During filament winding, termination of layers in the area of the end fitting mating joints would be stepped to minimize buildup of the composite outer diameter in those areas. After completion of the filament winding, the composite would be cured at 325°F while rotating slowly. Machining would consist of parting the ends of the composite to length and machining the outer diameter in the end fitting joint area. The winding mandrel is then removed and steel end fittings are bonded in place using Hysol 934 adhesive. The fabrication of the composite torsion bar is complete.

The major difference in fabricating technique between prototype and production torsion bars would be a progression from a semi-automatic performance of operations to an automated sequence.

C. Projected Costs

1. Quantities of 10 and 100 Units

The fabrication of quantities of 10 and 100 composite torsion bars was based upon the use of existing facilities and machines. Filament winding would be performed on a photo-control programmed winding machine with one unit being wound at a time. The composite would be cured in a gas-fired, heated air oven, one unit at a time for the 10 unit quantity and five units at a time for the 100 unit quantity. After composite cure, each unit would be machined separately on a machining lathe, followed by bonding of steel end fittings. Required tooling consisted of one mandrel assembly for the 10 unit quantity and five mandrel assemblies for the 100 unit quantity. Estimated periods of performance for item delivery were 60 days for 10 unit quantity and 120 days for 100 unit quantity.

The estimated costs per unit, as tabulated in Table XIV, were:

Quantity	Cost/Unit (Dollars)
10	2,079
100	1,329

2. 10,000 Units

The fabrication of 10,000 torsion bars was estimated based upon that being a yearly rate. This quantity required modification of one winding machine and one machining lathe and fabrication of fifty mandrels and six transportation/cure carts. Eight units would be wound simultaneously on the semi-automated photo-control winding machine, followed by cure in groups of 48 in a gas-fired heated air oven. Composite machining would be performed in groups of eight on a machining lathe.

Based upon the use of large cross sectional area graphite tow, such as Hercules AS5 graphite tow, in the prepreg, with production performed in 1980, the estimated unit cost for 100,000 composite torsion bars as tabulated in Table IX was $654. As noted in the table, the major cost item was the graphite fiber prepreg which was projected to cost $25.00/lb.

TABLE XIV

ESTIMATED COSTS FOR VARIOUS QUANTITIES OF COMPOSITE TORSION BARS

Unit Cost Quantity	Unit Cost (Dollars) 10	 100	 10,000
Engineering	161	16	1
Tooling	23	12	10
Labor	983	467	29
Materials	912	834	614
Total Cost/Unit	2079	1329	654

CONCLUSIONS AND RECOMMENDATIONS

The evaluation of the feasibility of redesigning an M60 Army tank torsion bar to utilize fiber reinforced composite materials to achieve weight reduction while maintaining service life and reliability lead to the following conclusions:

- The only fiber composite, of those commercially available in 1978, which could be used in redesigning the torsion bar and be capable of achieving design requirements was AS graphite/epoxy (or its commercial equivalent).

- The weight of the composite torsion bar configuration was 35.3 lb. compared to the existing steel torsion bar weight of 105 lb.

- The recommended method of fabrication to achieve most optimum composite torsional shear properties was by filament winding the body using continuous filament tow at a winding angle of ± 45 degrees, and subsequent bonding of steel end fittings.

- The projected costs required to carry out development to prototype and production parts were:

Unit Cost ($)	No. Units
2079	10
1329	100
654	10,000

The cost of the existing steel torsion bar is $98.85.

REFERENCES

1. Pipes, R. Byron, "Interlaminar Shear Fatigue Characteristics of Fiber-Reinforced Composite Materials," ASTM STP 546, COMPOSITE MATERIALS: TESTING AND DESIGN (THIRD CONFERENCE), March, 1973.

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