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Technical Report

No. ________

THE DESIGN, DEVELOPMENT AND FABRICATION
OF M1A1 COMPOSITE ROADWHEELS
FINAL REPORT
CONTRACT DAAE07-89-C-R085

JUNE 1991

By Gregory J. Hintz, James L. Pytleski
and David K. Rock
General Dynamics Land Systems Division
P.O. Box 2094
Warren, Michigan 48090-2094

(GDLS #VJ-89-04057-002)

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RESEARCH, DEVELOPMENT & ENGINEERING CENTER
Warren, Michigan 48397-5000

20020813375

NOTICES

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION Unclassified	1b. RESTRICTIVE MARKINGS None
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved by Public Release: Distribution is Unlimited
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) VJ-89-04057-002	5. MONITORING ORGANIZATION REPORT NUMBER(S) 13525
6a. NAME OF PERFORMING ORGANIZATION General Dynamics Land Systems Division 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION U.S. Army Tank-Automotive Command
6c. ADDRESS (City, State, and ZIP Code) P.O. Box 2094 Warren, Michigan 48090-2094	7b. ADDRESS (City, State, and ZIP Code) Warren, Michigan 48397-5000
8a. NAME OF FUNDING/SPONSORING ORGANIZATION TACOM 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER DAAE07-89-C-R085
8c. ADDRESS (City, State, and ZIP Code) TACOM Warren, Michigan 48397-5000 Bldg. 200A	10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO. / PROJECT NO. / TASK NO. / WORK UNIT ACCESSION NO

11. TITLE (Include Security Classification)
The Design, Development and Fabrication of M1A1 Composite Roadwheels.

12. PERSONAL AUTHOR(S) G. J. Hintz, J. L. Pytleski, D. K. Rock
General Dynamics Land Systems Division

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
FINAL	FROM 9/89 TO 4/91,	1991, 04, 30	55

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	Carbon Fiber, Compression, Fiberglass, Suspension, Glass Fiber, Composite, Filament Winding, Epoxy Resin, Roadwheel, Compression Molding

19. ABSTRACT (Continue on reverse if necessary and identify by block number)
This report documents a program to design, develop and fabricate a composite roadwheel for the M1A1 tank. The roadwheel incorporates composite materials to reduce net weight when compared to the aluminum counterpart.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☐ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION Unclassified
22a. NAME OF RESPONSIBLE INDIVIDUAL Luis A. Hinojosa	22b. TELEPHONE (Include Area Code) 313-574-5814 22c. OFFICE SYMBOL AMSTA-TMF

DD FORM 1473, 84 MAR — 83 APR edition may be used until exhausted. All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE

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1.0 INTRODUCTION

The original design weight for the M1 tank was 58 tons. Additional capabilities, such as improvements introduced in the Block I program, have led to significant weight growth of the vehicle. The current M1A1 vehicle being manufactured by GDLS weighs 65 tons. Planned improvements in survivability, track and Block II will lead to a 70 ton vehicle if weight growth is not offset by weight reduction in the base vehicle platform. A 70-ton tank will lead to severe transportability problems and may impact some key automotive performance parameters.

The composite material roadwheel offers an excellent opportunity to reduce the fundamental structural weight of the M1 vehicle chassis. GDLS has utilized its knowledge of the M1 Main Battle Tank system and composite structures to design and fabricate 40 composite material roadwheels which weigh significantly less than and are interchangeable with the current aluminum design.

2.0 OBJECTIVE

The major objective for the M1A1 Composite Material Roadwheel Program was to develop a cost effective composite material roadwheel that is significantly lighter and interchangeable with the current aluminum design.

GDLS has formulated a detailed design of a composite material M1A1 roadwheel based on the methodology that has been developed and proven. The GDLS design is completely interchangeable with the current aluminum roadwheel. The structural weight of the design is 19 percent less than the current aluminum roadwheel and will result in weight savings of 400 pounds on the M1A1 tank.

3.0 APPROACH

This report, prepared by General Dynamics Land Systems Division (GDLS), for the U.S. Army Tank-Automotive Command under Contract DAAE07-89-C-R085 describes the process used for developing and fabricating forty M1A1 composite roadwheels, lighter than the current M1A1 aluminum roadwheels. The weight savings was achieved by using organic composite materials to replace the current forged aluminum. The composite wheel design allowed the rubberization and wear plate assembly processes to take place in the same basic manner as on the aluminum wheel.

4.0 CONCLUSION

Weight reduction in the M1A1 Abrams tank (and the future M1A2) continues to be a highly desirable goal. The composite roadwheel provides a significant reduction in weight when compared to the current aluminum design. In addition, the wheel is completely interchangeable with the current design and utilizes a cost efficient fabrication process which is adaptable to producing composite roadwheels at production volumes. The materials used in the fabrication of the composite roadwheels are available at a reasonable cost in quantities sufficient to support production.

5.0 RECOMMENDATIONS

The wheel design, materials and fabrication processes, chosen under this contract represent an economical cost versus performance compromise to produce the required forty composite roadwheels. Subsequent testing of these wheels has yielded very positive results. Given this fact and that the processing method used to produce these wheels is readily adaptable to mass production, a strong effort should be made to continue funding a development program for composite roadwheels. Ideally, a formalized full scale engineering development (FSED) program would take the composite roadwheel from its present state through to production. Such a program would address key issues to assure a successful transition from the development phase to a production phase.

In its present state of development, the composite roadwheel has achieved essentially all of its technical goals. There are, however, technical issues which could be addressed under a follow-on program. Some of these key issues are listed below:

- Residual stresses created during processing
- Elastomer optimization to reduce heat buildup
- Design optimization to improve strength and reduce weight
- Improved material properties to minimize delamination under load

Although the Economic Analysis section of this report estimates the cost of producing composite roadwheels will be somewhat higher than that of the current aluminum wheel, under a FSED program additional cost reductions are possible. A redesigned wheel using less carbon fiber material could provide a significant reduction in cost. Further cost decreases are possible through improved processing techniques reducing the time, labor and material required to produce the composite wheels.

It is recommended that implementation of the composite roadwheel into production should begin in April 1994 of the M1A2 tank production. Production of composite roadwheels would need to be initiated in January of 1993. A production volume of 24,000 wheels annually would be sufficient to cover M1A2 production and the retrofit of existing vehicles.

6.0 REQUIREMENTS

The following are the mechanical/physical requirements and the process requirements outlined by the contract for the composite roadwheels:

Mechanical/Physical Requirements:

- o Interchangeable with current aluminum wheel
- o Capable of aluminum wheel duty life cycle
- o Overall wheel diameter remains unchanged
- o Tire width remains unchanged
- o Bolt hole diameter remains unchanged
- o Bolt circle remains unchanged
- o Hub opening remains unchanged
- o Wear plate position remains unchanged
- o Support dynamic load of 79,000 pounds
- o Self-extinguishing materials
- o Compatible with epoxy primer and CARC paint in accordance with MIL-STD-193
- o Operating temperature range of -40°F to 350°F
- o Bolts maintained applied torque of 300 to 350 ft-lbs
- o 90 pound maximum wheel assembly weight
- o Wear ring quality remains unchanged
- o Use of rubber tire
- o Tire durometer of 73 $\pm$ 3 for 5.59 inch tire width
- o Adequate wheel/tire bond methods

Process Requirements:

- o Develop cost-effective production process for M1A1 roadwheel development
- o Fabrication process is cost efficient
- o Fabrication process capable of producing 16,000 to 32,000 wheels annually with consistent properties
- o Resin operating temperature range of -40°F to 350°F
- o Resin available in quantity for production
- o Resin available at reasonable cost for production

7.0. ENGINEERING DESIGN

All engineering functions relating to the composite roadwheel design such as structural concept, analysis, materials, fabrication processes, testing and economic analysis are discussed in this section of the report. The design philosophy employed by GDLS was to balance risk and cost. While a more sophisticated approach may have yielded a stronger or lighter roadwheel, the cost impact of a more complex design would have eliminated the possibility of future production. GDLS feels its design is simple enough to satisfy the cost requirements of production. Vehicle testing performed at Yuma Proving Ground, AZ and Fort Greeley, AK in January through March 1991 indicate the need to make minor design changes to enhance wheel/tire durability.

7.1. Structural Design Criteria

The structural design criteria for the M1A1 composite roadwheel are essentially the same as for the aluminum wheel. They are:

1. The composite wheel must withstand a static radial load of 79000 lbs. for five minutes.

2. The composite wheel must be interchangeable with the current M1A1 aluminum wheels.

3. The composite wheel must meet the duty life cycle of the aluminum wheel. This duty cycle is shown in Table 7.1-1.

4. The following aluminum design requirements must be maintained.

    - Overall wheel diameter
    - Tire width
    - Tire thickness
    - Bolt hole diameter
    - Bolt circle
    - Hub opening
    - Wear plate position
    - Function of the wear plate

5. A target weight of 90 lbs. or less for the completed roadwheel assembly must be maintained.

    The GDLS design meets these requirements except for the 79000 lb. static load. This will be discussed in Section 7.6 (Testing).

Table 7.1. M1 Roadwheel Duty Cycle

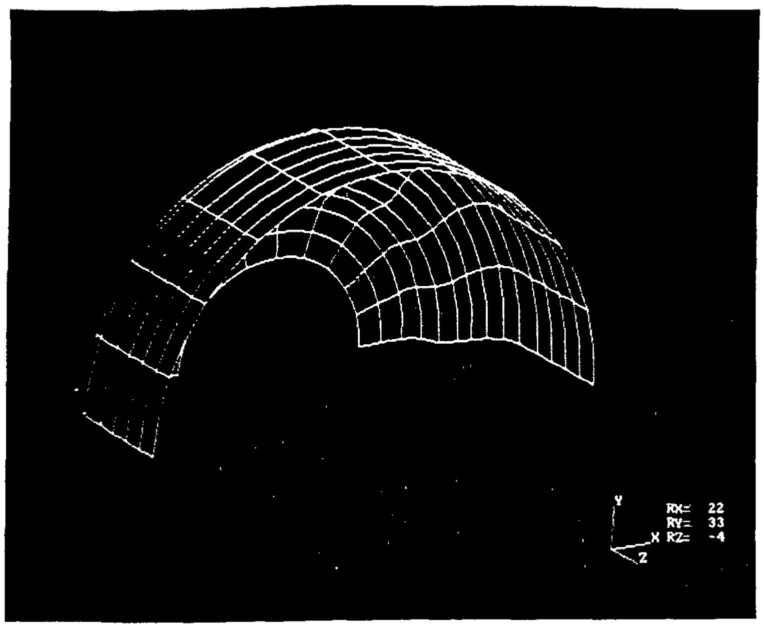
Radial Loading Ratio			
Radial Load (lbs)	Minimum Maximum	No. Cycles	Lateral Load (lbs)
18,000	0	40,600	4,500
18,000	0.2	209,000	4,500
18,000	0.4	250,000	4,500
18,000	0.7	132,000	4,500
20,000	0.4	31,500	5,000
22,000	0.7	20,000	5,500
24,000	0.2	211,000	6,000
26,000	0	76,000	6,500
36,000	0	44,500	9,000
36,000	0.2	62,000	9,000
45,000	0	43,000	0
55,000	0	44,500	0
62,000	0	12,700	0
80,000	0	15,000	0
158,000	0	13,000	0

7.2. Structural Analysis Model Development

GDLS developed an analytical model to accurately predict the structural performance of metallic and/or composite material roadwheels. This model was initially correlated with test data available for the production M1 aluminum roadwheel.

The analytical model was developed using the NISA finite element analysis code. The NISA II program is available from Engineering Mechanics Research Corporation (EMRC) of Troy, Michigan. The strength of this program is its ability to handle a wide range of material properties with particular emphasis on composite materials.

A representative finite element model is shown in Figure 7.2.-1. It is composed of 3-D shell isoparametric plate elements that are linear and elastic. The thickness to diameter ratio of the wheel analyzed is sufficiently large so that 3-D solid elements are not required. This isoparametric nature of the elements allows the thickness contour to change across an element. The model was constrained by fixing nodes that were located at the ten mounting bolt positions.



7.2.-1. Roadwheel Finite Element Model

The rubber tire was not included in the finite element model. Elastomeric materials are difficult to model using finite element analysis because they are incompressible (Poisson's ratio = 0.499). This causes mathematical problems in the formation of the stiffness matrix used in the finite element program. It has been the experience of GDLS that better analytical results are obtained by assuming a load distribution resulting from the presence of the elastomeric material. In the case of a roadwheel all of the applied load will be transferred through the rubber tire into the structural wheel. A cosine distribution of load is usually assumed to apply in such cases and proved to be accurate in this application due to good correlation of predicted strain values with actual test data.

The current M1 aluminum roadwheel is made of 2014-T6 alloy. The cross-sectional profile of this wheel is shown in Figure 7.2.-2. The properties assumed in the finite element analysis of this component are given in Table 7.2.-1.

Structural load testing of an aluminum roadwheel had previously been performed and documented, by another contractor, in TACOM report number 12985. This report is entitled, "Radial Load Test of Aluminum Roadwheel for the M1 Abrams Main Battle Tank." The roadwheel was statically loaded in 1000-pound increments up to 60,000 pounds. Strains at selected points on the roadwheel were measured using strain gages. The locations of these strain gages are shown in Figure 7.2-2.

Table 7.2.-1. Properties of 2014-T6 Aluminum

Property	Value
Young's Modulus, E	10.5 x 106 psi
Shear Modulus, G	4.0 x 106 psi
Poisson's Ratio	0.3
Yield Strength	60 ksi
Shear Strength	42 ksi

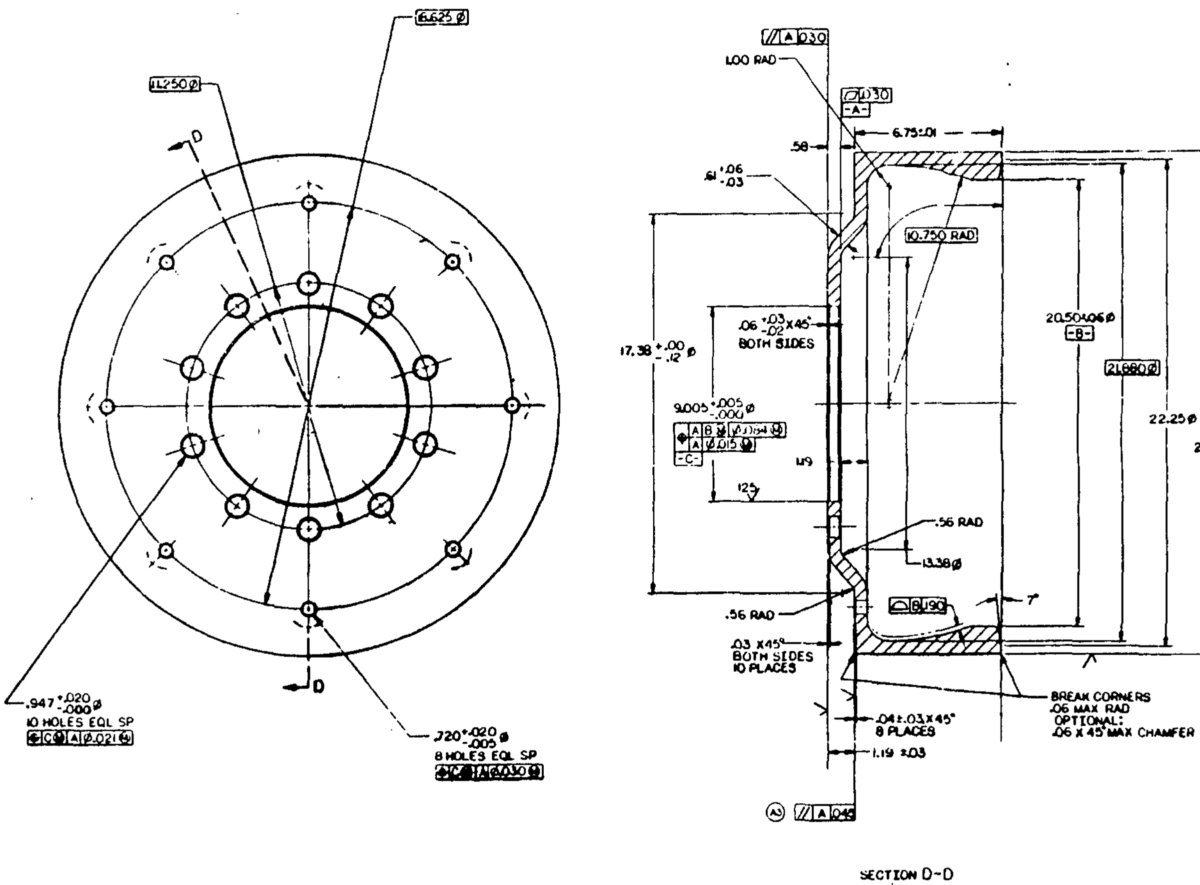


Figure 7.2.-2. Cross-Sectional Profile of M1 Aluminum Roadwheel

The comparison of GDLS analytical results at a 60,000-pound load is given in Table 7.2.-2. In geneal, there is good agreement between analysis and test. The only major disagreement is with the hoop gage mounted near the hoop stiffening ring of the rim. The measured value is almost zero while the prediction from he GDLS model is a large tensile strain. Intuitively, which is validated by the finite element results, hoop strains in the rim should be large. No hoop reinforcement ring would be required if hoop strains were low. Strains on the bottom of the rim should be tensile, and on the top, compressive. From the limited data that is availabe in the referenced report, is is assumed that the hoop gage or its data acquisition was faulty.

The referenced report (TACOM No. 12958) incorrectly reports stresses from the unidirectional strains measured and compares them with stresses from a 3-D solid finite element model. In order to calculate stresses at any point in an isotropic material, three strains must be measured at that point.. This is usually accomplished using a triaxial gage. When strain is measured in only one direction at a point, as was the case with the aluminum wheel test, strains from the analytical model must be compared along with the same orientation. Stresses cannot be direclty compared in this case.

Table 7.2.-2. Analytical Model Correlates with Aluminum Wheel Test Data

Gage No.	Load (lbs)	Direction of Strain	Predicted Strain μin	Test Measured Strain $\frac{\mu in}{\mu in}$
0	60,000	Radial	813	341
1	60,000	Radial	-1521	-1602
2	60,000	Radial	-267	-14
3	60,000	Radial (90° away from load)	-1098	-968
4	60,000	Radial (180° away from load)	1347	1747
5	60,000	Axial	2763	2772
6	60,000	Hoop	7255	-110

The same methodology used to successfully model the M1 aluminum roadwheel was applied to the analysis of the M1A1 Composite Roadwheel.

7.3. M1A1 Composite Roadwheel Design

The composite roadwheel design is an E-glass/graphite/epoxy hybrid. With the exception of the steel wear plate and fasteners, there are no metal parts. Initial concerns over short edge margins in the hub region were shown to be overly cautious through lab testing. The cross sectional profiles of both the current aluminum and composite roadwheel are shown in Figure 7.3-1.

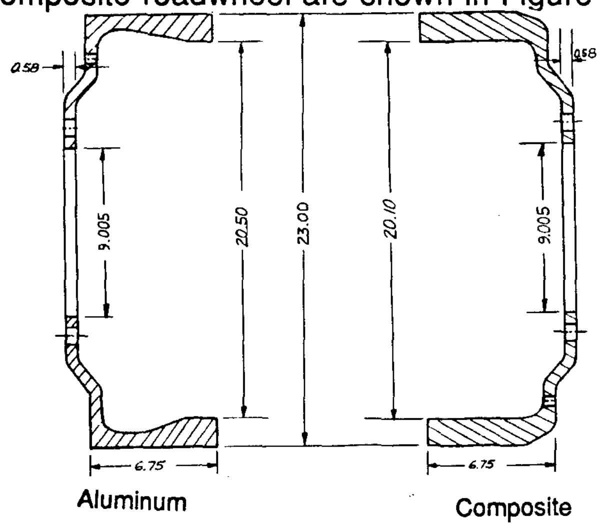


Figure 7.3.-1. Cross Sections-Aluminum and Composite Roadwheels

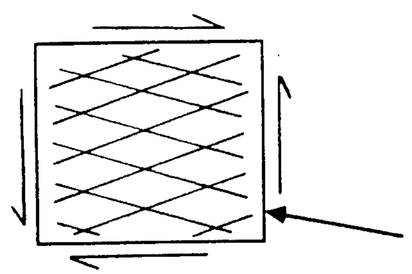
Of critical importance to the interchangeability requirement was maintaining the hub thickness at .58 inches. Initially, a slightly greater thickness in this region would have been preferred because of low calculated margins of safety. However, subsequent lab testing has shown this region to be of adequate strength to meet the load requirements discussed in Section 7.1 (Structures Design Criteria).

The overall approach to design and analysis of the M1A1 composite roadwheel was to utilize both finite element and conventional analysis methods, but before analysis could begin, a set of design allowables for the composite materials was required. Since the roadwheel is subject to a complex stress state, it was necessary to obtain design allowables for possible through-thickness failure modes, as well as the more typical in-plane modes. The composite design allowables used represent "B" basis values as defined in MIL-HDBK-5. This valve is defined as having 90 percent reliability under 95 percent confidence and usually is about 15 percent less than typical material properties. The reason for this reduction is to account for data scatter, and environmental degradation. Allowables were obtained through a combination of in-house testing and outside literary searches. Table 7.3-1 lists the critical details and corresponding allowables used in the analysis. The bearing open hole compression, and bolt pull through allowables were determined through proprietary GDLS test procedures. Figures 7.3-2 through 7.3.-4 provide a source of the other allowables.

Table 7.3.-1. Design Allowable Summary

MATERIAL	MODE	"B" BASIS * ALLOWABLE STRESS (ksi)
GRAPHITE / EPOXY	TENSION	+ 143
"	COMPRESSION	- 143
E-GLASS / EPOXY	TENSION	+127
"	COMPRESSION	- 76
"	TRANSVERSE TENSION	+ 6
"	TRANSVERSE SHEAR	13
"	BEARING	58.2
"	PULL THROUGH	4.6
"	HOLE DETAIL	6400μ in/in

* 90% RELIABILITY / 95% CONFIDENCE



LAMINATE SHEAR ALLOWABLE = 26ksi @ 1% ϵ_{FIBER}

(50% RANDOM MAT
50% ± 21° POLAR)

TRANSVERSE SHEAR ALLOWABLE $\approx$ 50% LAMINATE SHEAR ALLOWABLE *

TRANSVERSE SHEAR ALLOWABLE = 13 ksi

* UNIV. OF DELAWARE HANDBOOK SEC. 1.7

Figure 7.3.-2. Transverse Shear Allowables

F_{tu} L = 150 x 0.85 = 127 ksi

F_{cu} L = 90 x 0.85 = 76 ksi

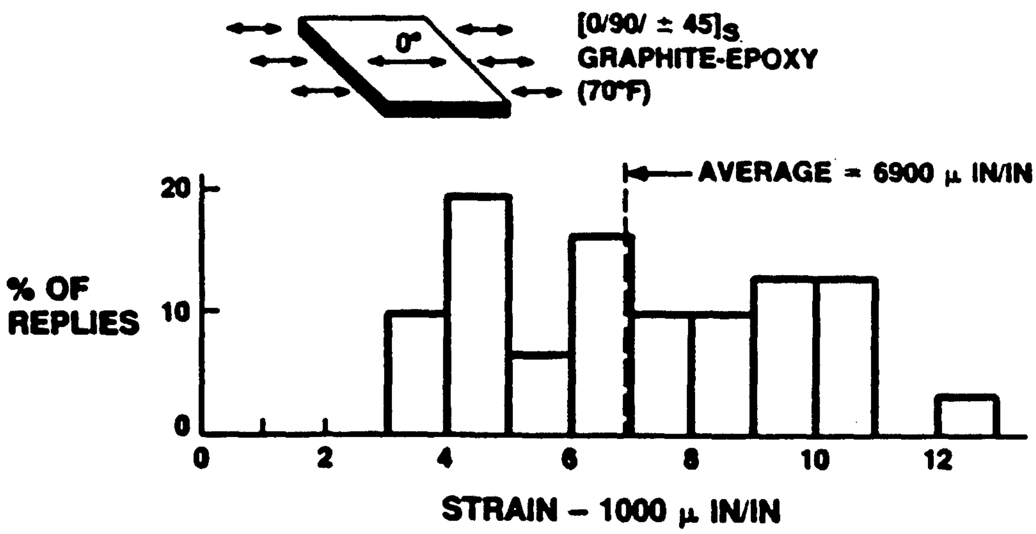
F_{tu} T = 7 x 0.85 = 6 ksi

F_{SU} = 10 x 0.85 = 8.5 ksi (IN- PLANE)

- "B" BASIS ALLOWABLE 0.85 x AVERAGE VALUE

- AVERAGE VALUES PER UNIVERSITY OF DELAWARE COMPOSITE ENCYCLOPEDIA TABLE 1.7 - 5

Figure 7.3.-3. Transverse Tension & Shear Allowables



ALLOWABLE $= E \times \epsilon = 20.8 \times 10^{6} \times 0.006900 = +$ 143 ksi

REF: ROBERT M. JONES INDUSTRY SURVEY 1989, VPI

Figure 7.3.-4. Strain at Design Ultimate Load (No Holes)

Figure 7.3.-4. Strain at Design Ultimate Load (No Holes)
Finite element modeling in combination with conventional analysis methods were used in the roadwheel stress analysis. Design and stress contour plots from NISA for critical regions of the initial design roadwheel (1.25 inch thick rim) are provided in 7.3.5. through 7.3.8.

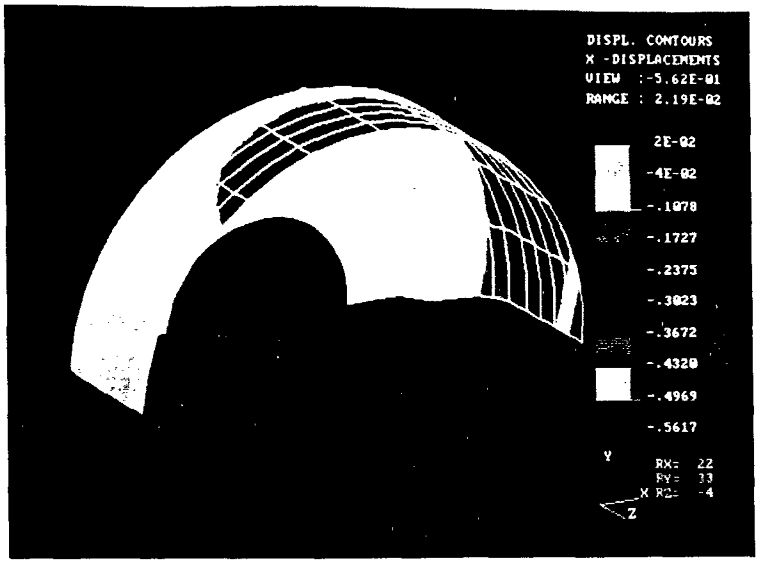


Figure 7.3.-5 Composite Roadwheel Displacements

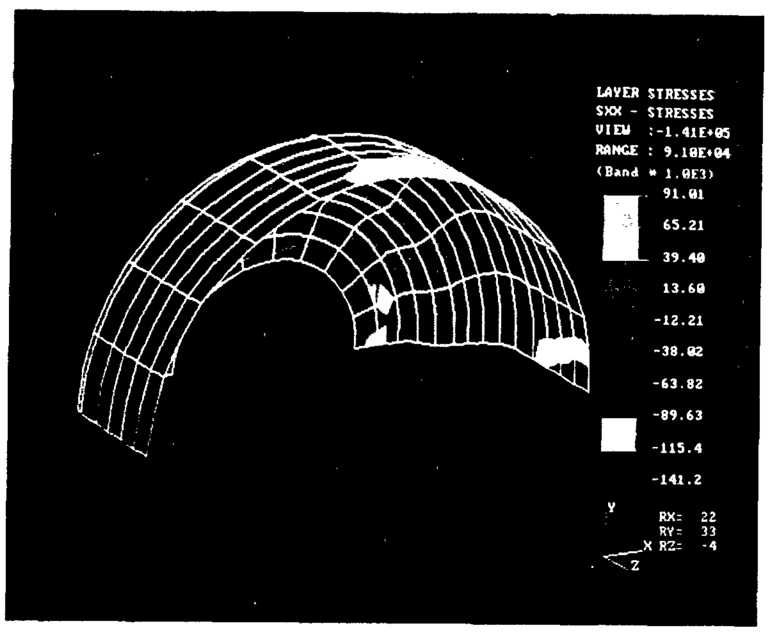


Figure 7.3.-6 Maximum Compression in Rim

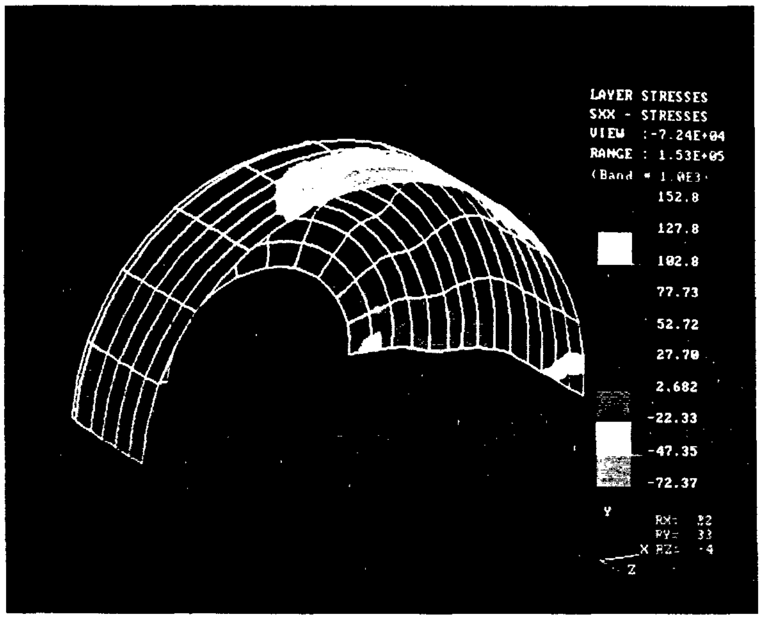


Figure 7.3.-7 Maximum Tension in Rim

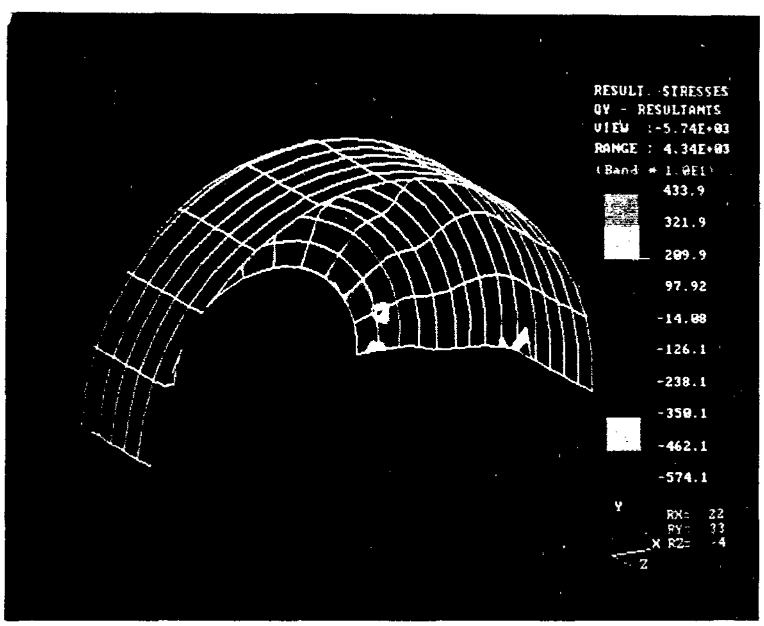


Figure 7.3.-8 Maximum Transverse Shear at Rim/Disk Interface

7.3.1. Disk Region Design. The design of the composite roadwheel must be sufficient to meet the ultimate load and duty cycle requirements. It must also provide for attachments of the steel wear plate to the roadwheel and of the roadwheel to the roadarm hub. The disk design was somewhat constrained due to the interchangeability requirement. The final design is shown in Figure 7.3.1.-1.

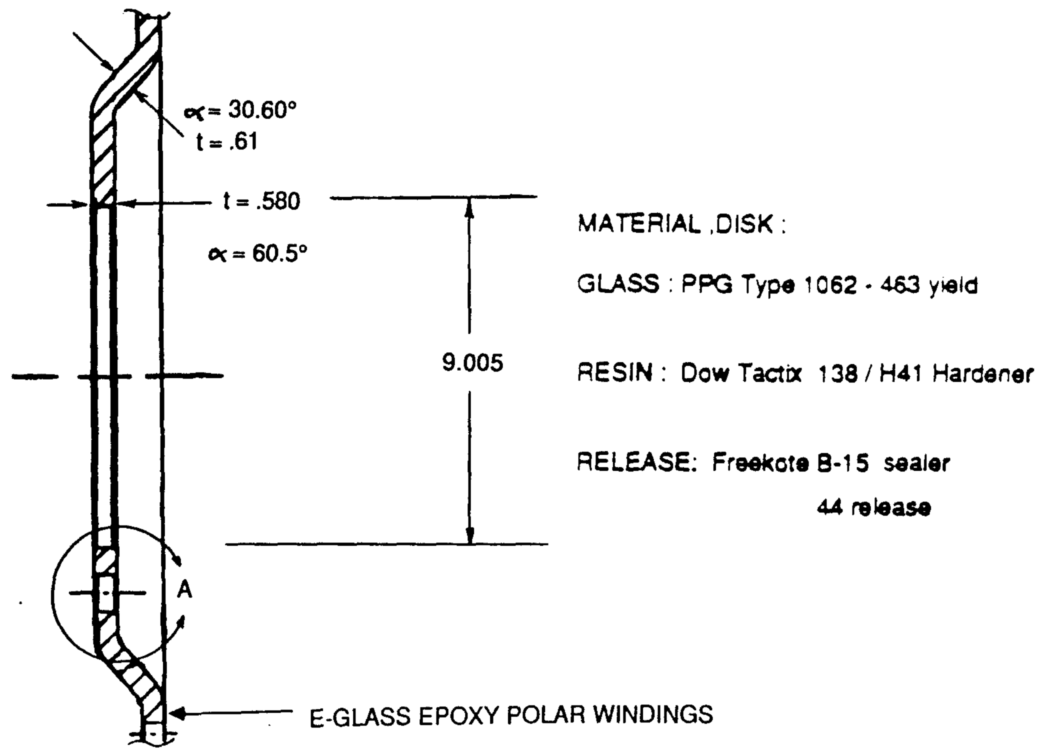
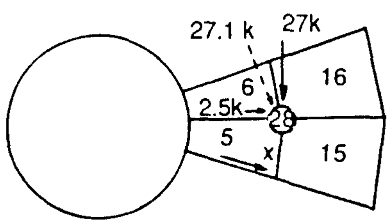


Figure 7.3.1.-1 M1A1 Composite Roadwheel Disk

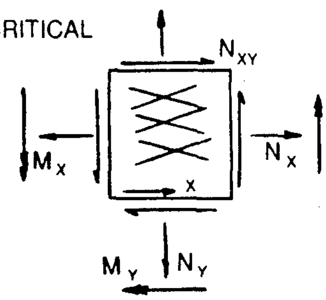
The thickness and orientation of the composite plies in the disk are fabricated by polar filament winding around an aluminum mandrel. This process is explained in detail in Section 7.5. When this manufacturing process is used, the size of the polar winding opening determines the winding angle and relative thickness at every radial point in the disk. This is true because filament winding is essentially a constant volume process, i.e., a constant volume of material is laid at every radial location of the mandrel. Therefore, as the radial position increase the thickness of the plies decrease.

In the design of a composite roadwheel, it is desirable to wind around as large a polar opening as possible. This will provide for fiber orientation which is higher (less radially oriented) than winding around a smaller opening. The resulting laminate will have less transverse tension and shear affects during wheel loading because fibers will be slightly more biased away from the radial direction. The fiber orientations vary from approximately ± 80 degrees at the hub to ± 23 degrees at the rim.

Given an opportunity for a completely new design, a suitable mounting hub which takes into account the joint design requirements unique to composites, specifically, extra edge margin, and increased part thickness would have been desired. Given the constraints of the program, increasing the hub thickness resulted in two unacceptable effects. The existing stud length would be too short, and the track centerline would be moved outboard. Interleaving metal plies in this region was explored but rejected due to added complexity and cost with very little strength improvement. Stress analysis for the disk region is presented in figures 7.3.1.-2 through 7.3.1.-5. The lowest calculated margin of safety was -.38 with the failure mode being bearing stress at fastener number 28. This would suggest a premature wheel failure during static testing.



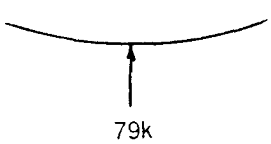
ELEMENT 15 CRITICAL



THICKNESS = .580
$\alpha = \pm 39.6°$
E-GLASS / EPOXY

N_x = 5810 lb / in
N_y = -7980 lb / in
N_{xy} = -746 lb / in
M_x = 910 in-lb / in
M_y = -240 in-lb / in

MAX FIBER STRAIN = +2470μ

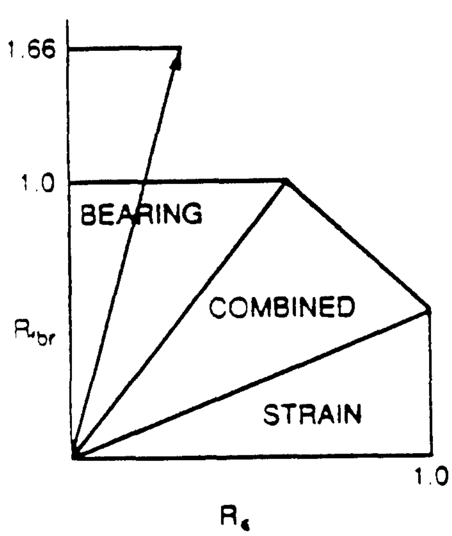


$$R\ (\text{USE FACTOR}) = \frac{2470}{6400} = .39$$

LOADS REFERENCE : NISA RUN WHIO, 1 NOV. 1989

$$R_{br} = \frac{P}{D\ T} = \frac{27.1}{.94 \times .58} = 49.7\ \text{ksi}$$

$$R_{fbr} = \frac{49.7}{30} = 1.66$$

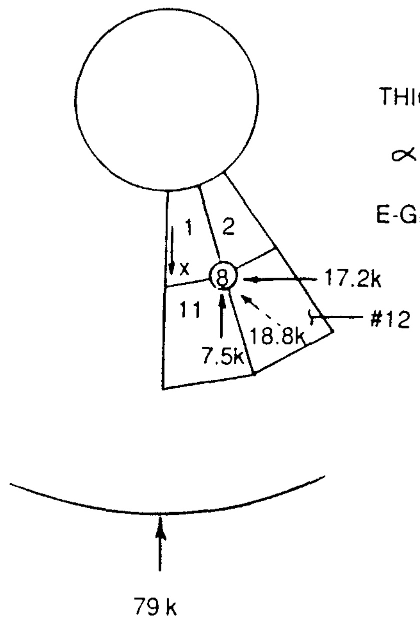


MARGIN OF SAFETY = -.38

BEARING CRITICAL

MAXIMUM LOADED FASTENER # 28

Figure 7.3.1-2 Disk Stress Analysis

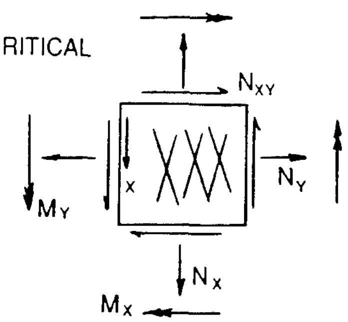


ELEMENT # 11 CRITICAL

THICKNESS = .580

$\alpha = \pm 39.6°$

E-GLASS / EPOXY



N_x = 5630 lb / in
N_y = 2880 lb / in
N_{xy} = 3047 lb / in
M_x = - 267 lb / in
M_y = - 732 lb / in

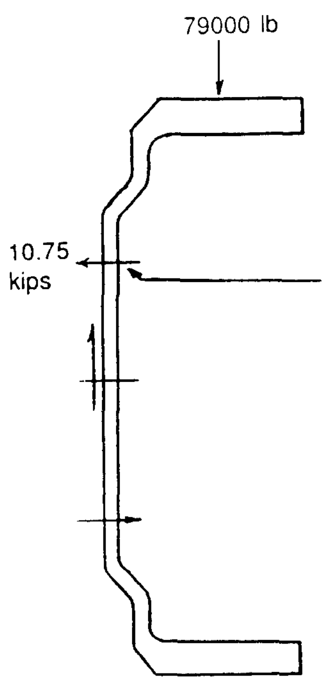
MAX TRANSVERSE TENSION = 8340 psi

MARGIN OF SAFETY = $\frac{6000}{8340} - 1 = -.28$ (TRANS. TENSION)

NEGLECTS BOLT CLAMP UP

LOADS REFERENCE : NISA RUN WHIO, 1 NOV.1989

Figure 7.3.1.-3 Maximum Disk Strain Field



MAX PULL THROUGH AT BOLT #8

PULL THROUGH STRESS = $\frac{\text{BOLT TENSILE FORCE}}{\text{HEAD CIRCUMFERENCE X THICKNESS}}$

$= \frac{10700}{1.8 \times 0.580} = 3.3$ ksi

MARGIN OF SAFETY = $\frac{4.6}{3.3} - 1 = +0.39$ (PULL THROUGH)

LOADS REFERENCE : NISA RUN WHIO, 1 NOV. 1989

Figure 7.3.1.-4 Bolt Pull-Through Stress

ASSUME : 40 ksi PRELOAD ON A $\frac{15}{16}$ BOLT

AREA = .69 in^2

P = .69 x 40 = 27.6 kips

= .35 LAMINATED PLASTIC / STEEL (DYNAMIC) per MARK'S HDBK.

RESISTING FORCE AT EACH BOLT = 27.6 x .35 = 9.7 kips

TOTAL RESISTING FORCE = 10 x 9.7 = 97 kips POTENTIAL

BOLT CLAMP UP WILL BE ACCOUNTED FOR THROUGH
TESTING OF COMPLETED ASSEMBLIES

Figure 7.3.1.-5 Effect of Bolt Clamp-Up

Actually, most of the load transfer between disk and hub is accomplished through clamp-up friction. The effect of bolt clamp-up is shown in Figure 7.31-6 where 97 kips is calculated as the potential capability of the disk/hub interface in friction. This exceeds the 79 kip static load requirement. Subsequent lab testing revealed no problems in this area.

7.3.2. Rim Area Design. The rim section of the structural roadwheel must support loads transferred through the tire, minimize roadwheel deflection and provide a bonding surface for the elastomeric tire. It must be able to withstand the maximum dynamic load of 79,000 pounds and the duty cycle requirements. Design of the rim area had fewer constraints than did the disk because thickness was not critical to interchangeability. The biggest challenge was achieving the necessary stiffness at the free edge without resorting to a flange type or edge stiffener. The rim design is shown in figure 7.3.2-1.

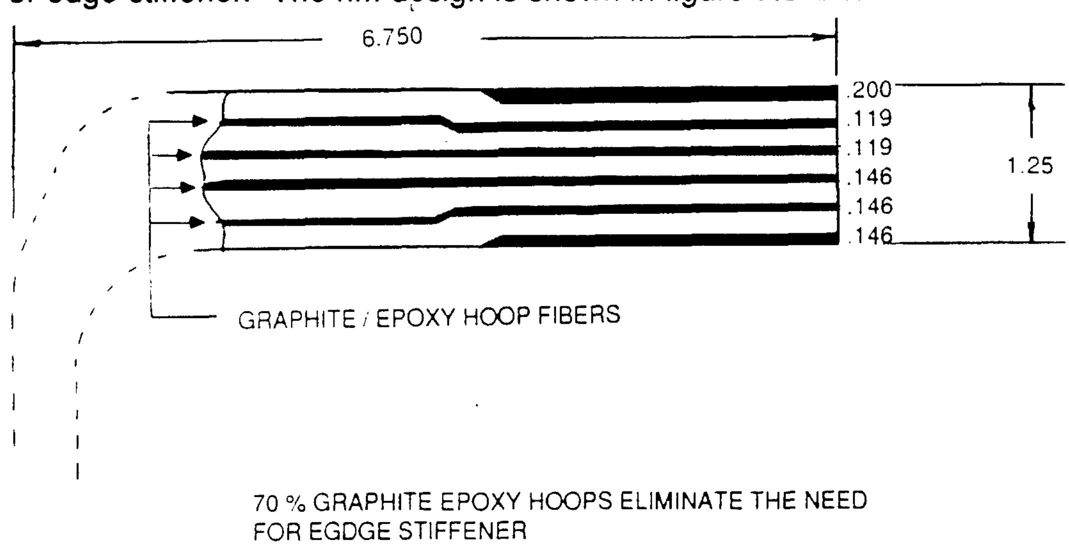


Figure 7.3.2.-1. M1A1 Composite Roadwheel Rim

Figure 7.3.2.-1. M1A1 Composite Roadwheel Rim

Due to tooling complexities, a free edge stiffener was ruled out in favor of utilizing graphite interplies to raise stiffness. This resulted in a constant thickness rim which was necessary to keep tooling cost and fabrication time within acceptable limits. This concept also eliminates the high risk of a bonded in edge stiffener.

The cross-section of the rim has been optimized for structural performance by varying the thickness, stacking sequence and percentage of hoop layers on the compression side of the neutral axis. The rim varies in thickness from 0.750 inches on the inside to 1.250 inches on the outside. The varying thickness was accomplished by winding different numbers of hoop layers along the axis of the rim. This is easily accomplished by using a numerically controlled filament winding machine. The stacking sequence of layers through the thickness of the rim also varies since bending is the critical loading at the inside of the rim and hoop loading is critical at the outside of the rim. By putting polar layers on the outside surfaces near the inside of the rim, bending loads are handled efficiently. Hoop layers are on the outside surface of the rim to handle hoop loads on the outside of the rim. Compression stress allowables for carbon/epoxy materials are usually lower than tension allowables. Therefore, the thickness of hoop layers have been biased somewhat toward the compression side of the rim neutral axis (outside surface of roadwheel) to reduce hoop compressive stresses.

Carbon/epoxy materials are used in the hoop layers of the rim to minimize the size and weight of the rim. An all E-glass construction was considered, but it was considerably thicker than the proposed design. This causes problems in accessing the wear plate attachment bolts and erodes most of the weight advantage of the composite roadwheel.

Another area of concern was the rim/disk interface or radius region. The potential problem was risk of a transverse (through-thickness) shear failure unless someway could be found to "bulk up" the thickness. The polar winding process will result in a thickness of only .175 inch because of the large diameter involved. GDLS achieved the desired thickness of .70 inch by interspersing plies of continuous strand mat or woven fabric in the radius. A detail of the disk/rim interface is illustrated in figure 7.3.2.-2.

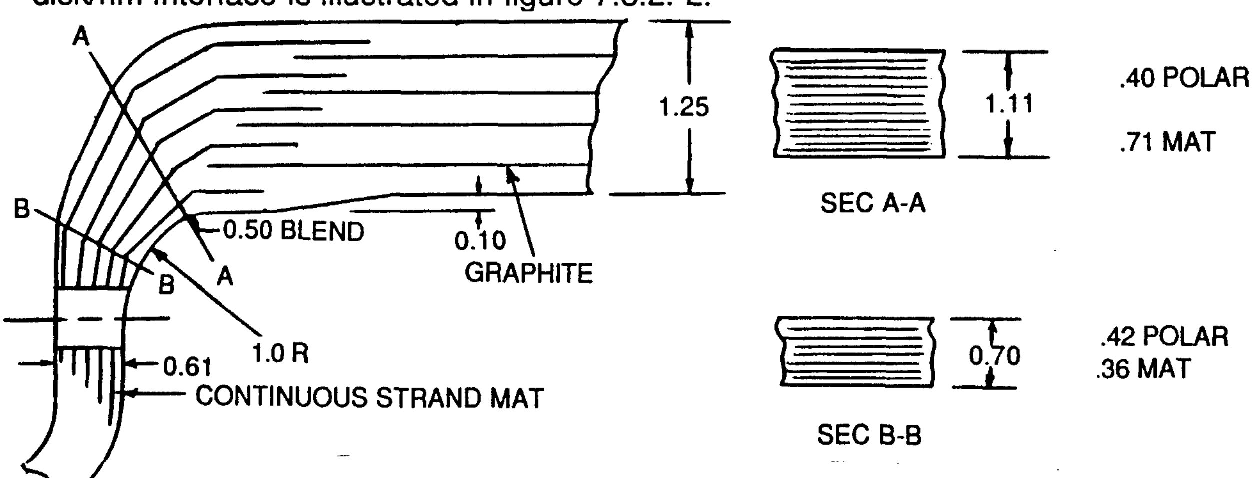
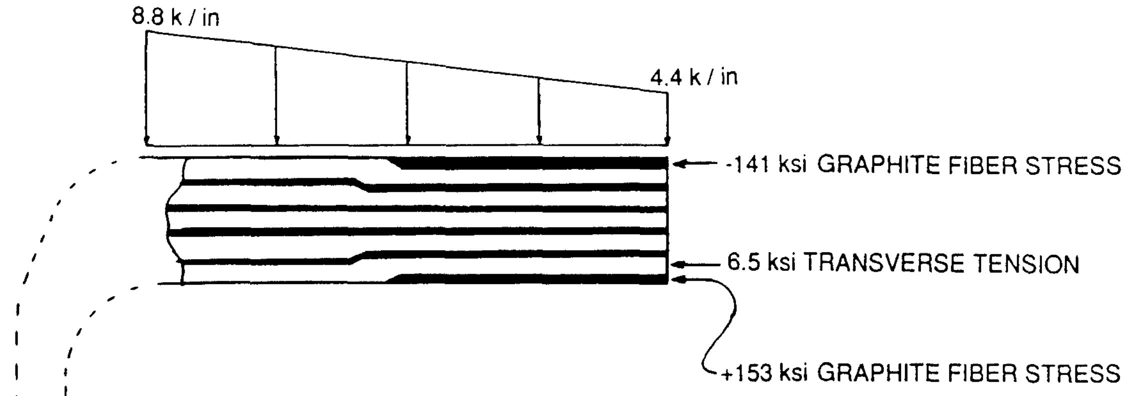


Figure 7.3.2.-2. M1A1 Composite Roadwheel Disk/Rim Interface

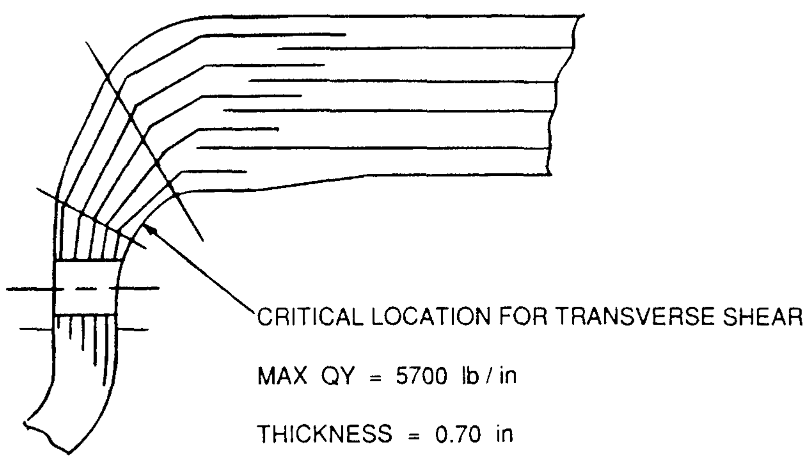


GRAPHITE / EPOXY MARGIN OF SAFETY = $\frac{143}{153} - 1 = -0.06$ (FIBER STRESS)

E-GLASS / EPOXY MARGIN OF SAFETY = $\frac{6}{6.5} - 1 = -0.08$ (TRANSVERSE TENSION)

LOADS REFERENCE : NISA RUN WHIO, 1 NOV. 1989

Figure 7.3.2.-3. Roadwheel Rim Stress Analysis



MAX QY = 5700 lb / in

THICKNESS = 0.70 in

TRANSVERSE = $\frac{5700}{0.70} = 8100$ psi

MARGIN OF SAFETY = $\frac{13}{8.1} - 1 = +0.60$

LOADS REFERENCE : NISA RUN WHIO, 1 NOV. 1989

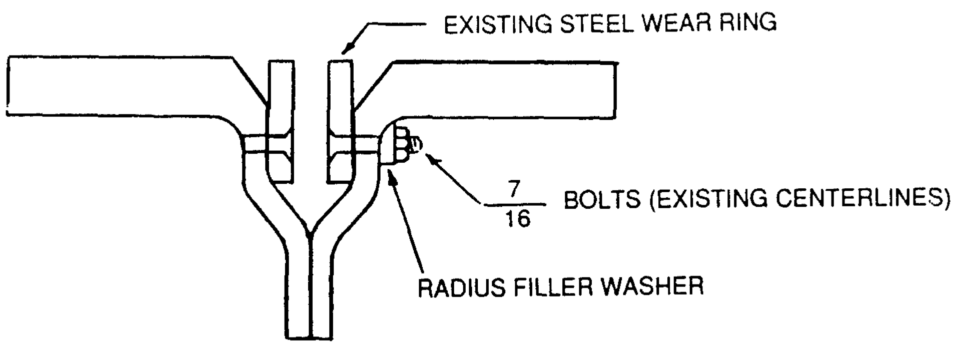
Figure 7.3.2.-4. Disk/Rim Interface Analysis

All calculated margins of safety for the rim area are positive. Stress analysis of critical areas are provided in figures 7.3.2.-3 and 7.3.2.-4.

7.3.3 Composite/Elastomer Interface. The selection of an SM8565 rubber for the tire molded by Goodyear Tire and Rubber Company is discussed in Section 7.4.4. Rubber/composite adhesion tests were used to assure adequate bonding between the wheel and the tire. No adhesion problems were experienced with the Chem-Loc series adhesive selected for use on the prototype roadwheels. Minimum adhesion values of 102 inch-pounds (sample 2) were achieved during testing at Goodyear. This is the same bonding system in use with the current aluminum M1A1 roadwheels.

Goodyear determined through adhesion testing that the highest values were obtained when the surface preparation consisted of a moderate sandblasting, solvent wipe and adhesive application. It was determined through testing at Goodyear, that the solvent wipe plus light sand blasting and adhesive did not supply sufficient rubber adhesion values.

7.3.4. Mounting and Attachment Interfaces. The critical interfaces of the composite roadwheel are the hub and wear plate regions. Since the aluminum wheel geometry was duplicated at the hub, fitup is assured. However, a consequence of the 1.25 inch constant thickness rim was that the existing stud/nut size of 11/16 inch interfered with the rim inner surface. To solve this problem, GDLS used existing wear plates but re-drilled them for 7/16 inch bolts. This in combination with custom made radius washers which fit tightly into the corner prevented any interference or gouging of the composite due to nut or flatwasher contact. This concept is illustrated in Figure 7.3.4.-1.



- THICKER RIM INTERFERES WITH EXISTING 11/16 BOLTS
- SIDE LOADS APPLIED TO WHEEL ARE REACTED THROUGH SURFACE CONTACT BETWEEN RING AND WHEEL
- BOLTS HOLD WEAR PLATE IN PLACE
- SCALLOPED WEAR RING WILL SAVE AN ADDITIONAL 60 lb PER VEHICLE

Figure 7.3.4.-1. M1A1 Composite Roadwheel Wear Ring

7.3.5. Fatigue Life Cycle. The GDLS design has been chosen to maintain a theoretical fatigue life of at least 100,000 cycle in fiber fatigue. The duty cycle requirement is dominated by the 79,000-pound load at 13,000 cycles, and the fatigue life of the component is based on this load value alone.

Many investigators into the fatigue life of composites have attempted to describe the S-N curve for various fiber reinforced composites by the following logarithmic formula:

S	=	(m log N + b)
S	=	maximum fatigue stress
N	=	number of cycles to failure
	=	average static strength
m,b	=	material-related constants

GDLS conducted a literature search to obtain the most relevant fatigue data which could be applied to this model. The values researched and found for E-Glass/Epoxy and Carbon (T-300)/Epoxy are given below.

E-Glass/Epoxy	Carbon/Epoxy
m = -0.1573	m = -0.0542
b = 1.3743	b = 1.042

These constants result in S-N curves given in Figure 7.3.5.-1. The data represents tensile-tensile fatigue with a fatigue range, R = 0.1. Fatigue range is defined as minimum cycle stress divided by maximum cycle strength.

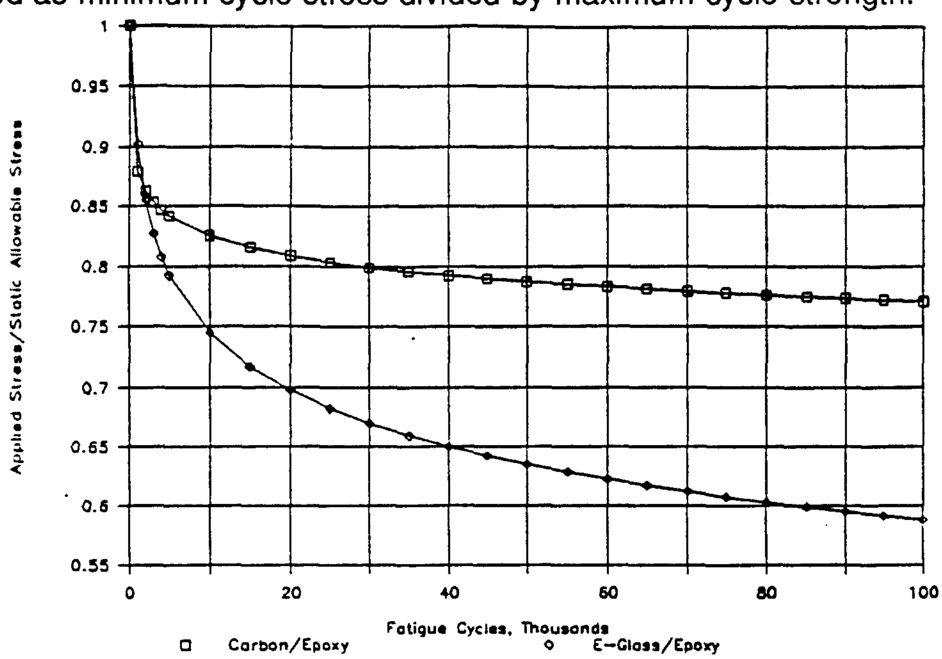


Figure 7.3.5.-1 Fatigue Life of Composite Materials

The predicted unidirectional fatigue life of the composite materials in the proposed design in both tension and compression are summarized in Table 7.3.5.-1. Compression-compression data is not generally available, and it has been assumed that the same fatigue life curve applies for these materials in both tension and compresison.

The fatigue life of the design is governed by the compression stress in the carbon/epoxy materials in the rim. This is true because the E-glass/epoxy material failure is governed by other modes of failure (i.e., transverse tensile and in-plane shear) rather than fiber fatigue. Therefore, the E-glass/epoxy material is not heavily loaded in the direction of the fiber. Since compressive stress allowable is usually lower than tensile stress in carbon/epoxy materials, the compressive stress becomes the critical parameter.

GDLS does believe that the duty cycle and ultimate load requirements are somewhat excessive and the ability of the current aluminum wheel to meet these requirements is open to question. In general, composite materials offer greatly increased fatigue resistance when compared to aluminum and a composite wheel should be capable of meeting a duty cycle equivalent to the current aluminum wheel.

MATERIAL	TYPE	MAXIMUM FATIGUE STRENGTH (KSI)	NO. CYCLES TO FAILURE	AVERAGE STATIC STRENGTH (KSI)
Carbon/Epoxy	Compression	-141	100,000	-200
Carbon Epoxy	Tension	153	>100,000	250
E-Glass/Epoxy	Compression	-64.3	>100,000	-160
E-Glass/Epoxy	Tension	91.1	>100,000	180

Table 7.3.5.-1 Predicted Fatigue Life of GDLS Design

1-Lorenzo and H.T. Hahn, Fatigue Failure Mechanisms in Unidirectional Composite Materials-Fatigue and Fracture, ASTM STP 907:210 (1986).

7.3.6. Weight Summary. GDLS had hoped to reduce M1A1 vehicle weight by 445 lbs. with the composite roadwheel. The redesign discussed in Section 7.3.7 resulted in an actual reduction of approximately 400 lbs. per vehicle. This is still nearly double the contractual requirement of 237 lb/vehicle. Table 7.3.6.-1 lists existing aluminum and composite roadwheel weights.

7.3.7. Design Revisions. Although all calculated margins of safety for the rim area of the composite roadwheel were positive, static lab testing resulted in failures at less than the required 79,000 pound radial load. Results of testing are summarized in Section 7.6. The cause of the early failure was interlaminar stress due to excessive deflection at the rim edge. This behavior is difficult to predict using linear elastic modeling techniques. Delaminations during the test

COMPONENT	CURRENT PROD. WT. (LB.)	PROPOSED WEIGHT (LB.)	WEIGHT REDUCTION (LB)	WEIGHT REDUCTION (%)
Structural Wheel	62.8	47.5	15.3	24
Rubber Tire	19.6	21.0	-1.4	-7
Wear Ring/ Attachments	15.0	15.0*	0	0
Total	97.4	83.5	13.9	14

*Scalloped wear ring weight = 13 lbs.

Figure 7.3.6.-1 Composite Roadwheel Weight Summary

further reduced stiffness and strength. While the rim edge itself did not actually fail, the resulting load shift toward the disk overloaded the rim/disk transition radius and caused a transverse shear failure. It was felt that added rim stiffness would solve the problem. This theory was verified by static testing a composite roadwheel with an aluminum stiffener ring temporarily clamped to the rim inner diameter near the free edge. This ring did not reduce loading on the composite but did demonstrate the benefit of increased stiffness. This demonstration wheel held 80,000 pounds for 5 minutes without any sign of damage.

Based on the test results, rim stiffness was maximized by increasing thickness from 1.25 inch to 1.45 inch. This was the upper limit for increase based on interference with the 7/16 inch wear plate fasteners. The additional thickness was made up entirely of extra graphite hoop windings and provided an additional 60 percent bending stiffness over the original composite design. It also required the inner winding mandrel to be remachined and replated. The redesigned rim area is illustrated in Figure 7.3.7.-1.

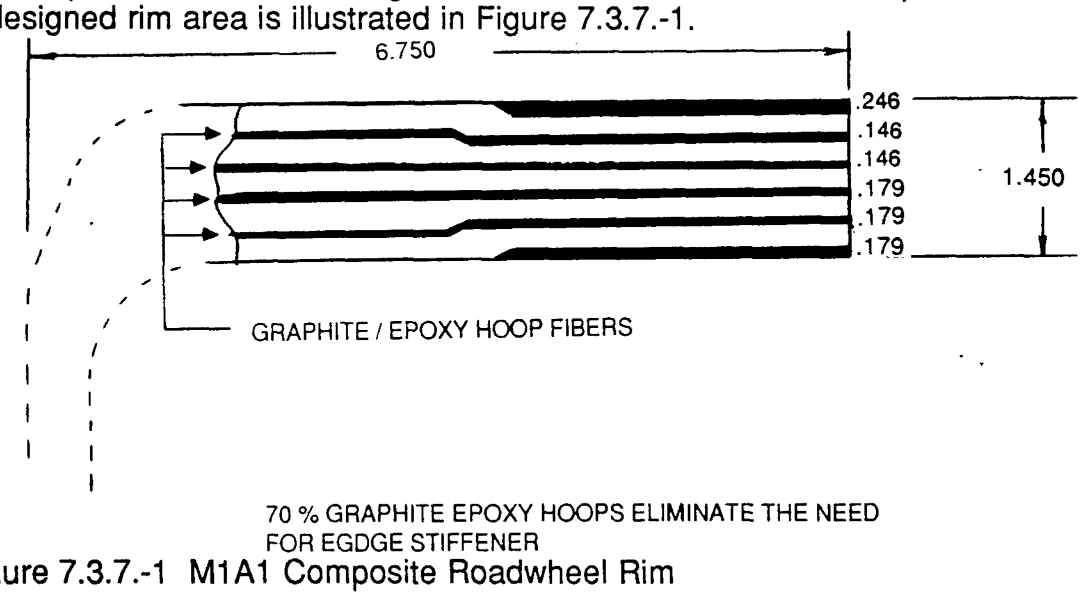


Figure 7.3.7.-1 M1A1 Composite Roadwheel Rim

7.4. <u>Materials</u>

7.4.1. Requirements. The M1 composite roadwheel materials requirements as outlined the contract are as follows:

- o Materials contained in the composite roadwheel must support a dynamic load of 79,000 pounds (Ref. C.2, p. 6).
- o The materials must be self extinguishing. Self-extinguishing properties of the material must be documented (Ref. C.2, C.2.1, p. 6).
- o The material used must be paintable with epoxy primers and Chemical Agent Resistant Coating (CARC) in accordance with MIL-STD-193 (Ref. C3, p. 6).
- o The operating temperature range for the roadwheels must be -40°F to +350°F (Ref C.4, p.6).
- o The resin used for the wheels must be capable of operating from -40°F to +350°F (Ref. C.7, p.6).
- o Wear ring may be of a different design than the current part, but possess the same qualities (Ref. C.6.1, p.6).
- o The resin must be readily available in sufficient quantity and cost to produce 16,000 to 32,000 wheels annually (Ref. C.7, p.6).
- o A rubber tire with durometer of 72 ± 3 for a nominal 5.59 inch tire width must be used (Ref. C.8, p.7, Attachment 3).
- o Methods to assure an adequate bond between the wheel and tire must be used (Ref. C.8, p.6).

The materials used in the composite roadwheel design were selected for strength, durability, high temperature tolerance and cost. All materials are readily available in commercial quantities at a reasonable cost. The details and justification for the materials used for this program are given in the following sections.

7.4.2. Polymer Resin Selection. The main consideration in choosing the resin matrix for use in the fabrication of the composite roadwheel is -40°F to +350°F operating temperature requirement. Of the three types of resins commonly used (polyesters, vinylesters, epoxies), epoxies generally have the greatest resistance to heat. Polyesters and most vinylesters cannot meet the required temperature, and therefore, were not considered. It should be noted that other high temperature resins such as bismaleimides and polyimides are available and could have been used as the resin system in the composite roadwheel program. However, these resins were extremely high cost. Epoxy is significantly cheaper and easier to work with. In addition, both the epoxy resin and hardener were readily available in sufficient quantities at a low cost. Mechanical properties were not a major concern in selecting a resin as composite properties are dominated by the fiber reinforcements.

Matrix selection was a critical decision in the GDLS composite roadwheel design. Resins were evaluated on the following criteria: suitability for wet filament winding, minimum temperature range of -40°F to +350°F, damage tolerance, self-extinguishing capabilities, compatibility with epoxy primers and CARC, cost and availability.

An epoxy resin, DOW TACTIX 138 with a TACTIX H41 hardener, was the matrix system used for the roadwheel program. Properties for this resin system are summarized in Table 7.4.2. This resin met the temperature requirements, was self-extinguishing, and had good wet-out properties for wet filament winding. In addition, it was compatible with epoxy primers and CARC paint.

Table 7.4.2.-1 Tactix 138/H41 Resin Properties

Viscosity at RT (cps)	250.0
Glass Transition Temp (tg) °F	368.0
Flex Strength (Ksi)	16.0
Flex Modulus (Ksi)	412.0
Tensile Strength (Ksi)	11.0
Tensile Strength (Ksi)	410.0
Ultimate Tensile Elongation (%)	6.5

7.4.3. Composite Fiber Selection. Fiber reinforcement is a critical element to be considered when certain mechanical properties are required for composite parts. A variety of fiber types can be considered for reinforcement in the composite roadwheel. Fibers are selected on the basis of strength, modulus and cost. Operating temperature of the composite roadwheel will have a minimal effect on the fiber, and therefore, was not a consideration in the fiber selection. Table 7.4.3 summarizes different fibers and their properties.

Fibers for the composite roadwheels program were evaluated on the following criteria: cost, strength, stiffness, density and availability. Two fiber types were chosen as reinforcement in the composite roadwheel.

E-glass was used as the primary reinforcement fiber for the composite design. E-glass had the strength, mechanical properties and damage tolerance required for the roadwheel design. It was lower in cost than the other fibers and was readily available from many companies and distributors.

PPG 1062 E-glass fiber was selected for the composite roadwheel design. GDLS has had significant amount of filament winding and compression molding experience using this type of material. High strength (HS) carbon was used to provide additional hoop stiffness to the roadwheel in the rim area. The advantage of HS carbon is that it had the stiffness properties needed in the design, was low cost, and was readily available. The addition of carbon fiber also reduced the overall weight and volume of the roadwheel. Courtalds Grafil 33/500 HS carbon fiber was chosen because it provided the desired stiffness, was readily available and was significantly lower in price than any other high quality carbon fiber on the commercial market.

Table 7.4.3.-1 Typical Fiber Properties

Property	E-Glass	S-Glass	HS Carbon	IM Carbon	HM Carbon
Density (lb/in^3)	0.094	0.090	0.064	0.0635	0.067
Tensile Strength (psi)	500,000	665,000	650,000	800,000	456,000
Tensile Modulus (psi)	10.5×10^6	12.6×10^6	33×10^6	42×10^6	52×10^6
Elongation to Break (%)	4.8	5.4	1.95	2.00	0.75
Cost ($/LB)	0.87	3.5-5.0	12.0-25.0	40.0-60.0	30.0-50.0

7.4.4. Rubber Selection. Operating temperature was a critical factor in the selection of rubber for the M1A1 tire. Rubber selected in the roadwheel design must meet the specified -40°F to +350°F temperature range. In addition, a durometer of 72 ± 3 for a nominal 5.59-inch tire width is required.

The rubber selected was the current M1 roadwheel compound SM8565, a type of SBR rubber. Selection of SM8565 ensured that all current rubber material and temperature requirements will be met, and it reduced the number of variables in the evaluation of the composite roadwheel design. SM8565 had the advantage over other materials in that it has already proven reliable based on past performance in the M1A1 roadwheel application.

A Chem-Loc series adhesive was used to assure an adequate bond between the composite wheel and the rubber tire. The system used for the bond has been carefully considered. Reactivity between composite and rubber, quality of adhesive bond, temperature stability and surface preparation were all taken into consideration. The bonding agent selected had good temperature stability and bonded well to composite material. Surface preparation of the roadwheel prior to bonding consisted of a solvent wipe followed by a moderate sand blasting.

Goodyear Tire and Rubber Company was responsible for molding the rubber tire to the composite wheel. A conventional compression molding process was used. As a supplier of the current production M1A1 roadwheel rubber, Goodyear has had a significant amount of experience with rubbers and molding as well as previous experience with rubber-to-composite bonding applications. In addition, both the elastomer and the adhesive were readily available in sufficient quantities at low cost.

7.4.5. Wear Ring Material Selection. Operating environment and wear are critical elements that affect roadwheel performance. These were taken into consideration in the evaluation of the use of urethane for the roadwheel wear ring. Although a urethane wear ring has the advantages of lower noise level and less friction, it cannot meet the demanding high temperature (temperatures greater than 200°F) and point loading requirements. In addition, tearing problems would result due to misalignment of the center guide. Therefore, the current metal wear ring was used in the GDLS composite roadwheel design.

7.4.6. CARC Paint and Primers. Materials used for the composite roadwheel were compatible with epoxy primers and Chemical Agent Resistant Coating (CARC) in accordance with MIL-SD-171. This Military standard has replaced MIL-STD-193 and provides Government and contractor guidelines on the use and application of primers and CARC paint. CARC paint application was completed at the Composites Laboratory in the GDLS Sterling Technology Center (STC).

7.5. Fabrication Process

The fabrication approach employed by GDLS utilized two composite processes: filament winding and compression molding. A composite preform for two roadwheels consisting of polar and circumferentially wound rovings was fabricated using a wet filament winding process. Once completed, the preform was then compression molded and cured. After the cure was completed, the material is placed back in the filament winder and cut into two halves by means of a diamond wheel tile-saw fixed in a predetermined location, to produce two roadwheels. The wheels were then machined to their final dimensions in the rim (width) and the hub opening (dia.). The composite wheels were then sent to Goodyear Tire Rubber Company where the rubber tires were molded onto the wheels. Once back at GDLS, the final machining was completed, CARC paint applied, and the wear plate hardware assembled. Composite material fabrication processes, machining, hardware mounting and CARC paint application were all performed at the GDLS Composites Laboratory at GDLS Sterling Technology Center located in Sterling Heights, Michigan. Goodyear Tire and Rubber Company compression molded the rubber tire to the composite roadwheel at their facility in St. Marys, Ohio.,

7.5.1. Requirements. The M1A1 composite roadwheel fabrication and processing requirements outlined in the contract are as follows:

- o Contractor will provide the necessary personnel, facilities, materials and services to develop a cos effective, reliable production process for the design, development and fabrication of 40 composite M1A1 Abrams Roadwheels (RFP Ref. C.1.1, p.5).

- o The fabrication process must be cost efficient and capable of producing 16,000 to 32,000 wheels annually with consistent properties (RFP Ref. C.7, p.6).

- o Contractor will establish inspection procedures in accordance with MIL-I-45208A to assure compliance with the design requirements (RFP Ref. C.12, p.6).

- o Process required for fabrication and assembly of 40 prototype composite roadwheels must employ economical use of man-hours (RFP Ref. M.5.2.3.3, p.68).

The GDLS processing methods are virtually identical to those which could be used in the mass production of 16,000 to 32,000 roadwheels. Therefore, the process technology developed under this program would allow for easy transition to full-scale production.

7.5.2. Roadwheel Composite Fabrication Approach. The process utilized by GDLS to fabricate composite roadwheels required a minimal amount of processing and secondary operations. There are six main steps required for fabrication of complete roadwheel assemblies. They are:

- o Filament winding preform (polar and circumferential windings).
- o Compression molding and curing preform.
- o Cutting molded material into two wheels.
- o Bonding rubber tire to composite wheel.
- o Machining, drilling and boring holes for mounting and wear plates.
- o Applying CARC paint and primers.

Each of the major fabrication steps will be described in more detail in the following sections.

7.5.3. Filament Winding. The filament winding process for the composite roadwheel program utilized a mandrel made of chrome plated mild steel. The chrome plating enhances the mandrels durability, improves the wheels surface quality and aids in part removal from the mandrel. The mandrel consists of two identical sections which could be split vertically at the center allowing electrical band heaters to be installed in each half to provide a means of heating the mandrel. This mandrel configuration allows two roadwheels to be wound simultaneously.

In the filament winding process, the E-glass and carbon/fiber rovings used to create the preform are wet wound onto the mandrel using a numerically controlled filament winding machine. In this process, the dry fiber rovings wetted-out by being drawn through a series of rollers in an epoxy resin bath. An advantage of this process that the fiber and resin materials used are low cost as opposed to filament winding with pre-impregnated rovings. This results in lower cost processing.

Before the actual winding process begins, the winding mandrel is preheated to 180°F. By pre-heating, expansion, due to thermal expansion, in the mandrel will be present as the fibers are being wound. This, in essence, "pre-stresses" the fibers prior to the compression molding operation resulting in a part with reduced residual stresses. In addition to pre-heating, Freekote 44 mold release is applied to the mandrel before the filament winding process begins.

This filament winding process involves two basic fiber winding patterns: circumferential patterns and polar patterns. A circumferential layer (see Illustration 7.5.3.-1) is the first applied to the mandrel followed by a polar layer (see Illustration 7.5.3.-2). Additional circumferention and polar layers are alternately applied until eleven total layers of pattern have been wound. The fiber for each circumferential layer is carbon fiber, and for each polar layer, E-glass.

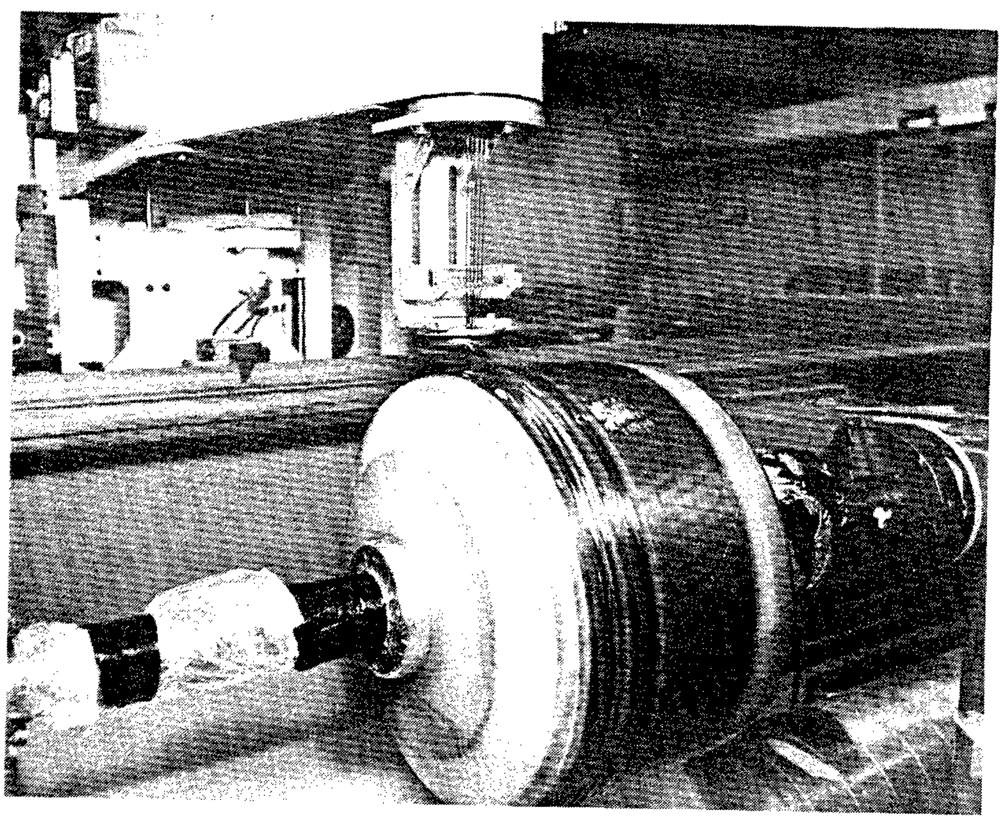


Figure 7.5.3.-1 Application of Circumferential Layer

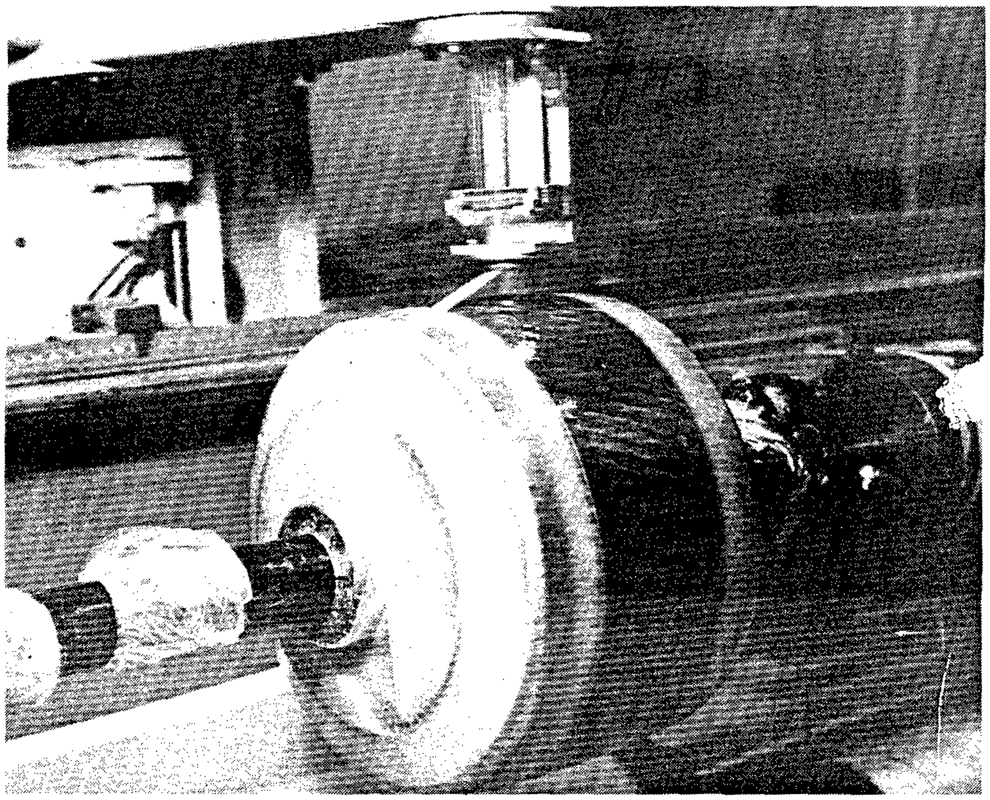


Figure 7.5.3.-2 Application of Polar Layer

During the polar winding process excess composite material is built up in the hub area of the preform, and is removed by cutting away the excess material. This is accomplished by placing a circular cutting template (see illustration 7.5.3.-3) in the hub region of the mandrel prior to winding the first polar layer. After the polar layer and the next circumferential layer are wound, the excess material was cut away by hand using a utility knife and a cutting guide. Cutting away the excess polar material after winding the next circumferential helps prevent movement of the polar fibers during the cutting operation. This cutting operation is repeated for each of the first four polar layers. The final polar layer is not cut. Though it is an extra process step, removal of the excess material creates a more weight efficient roadwheel design.

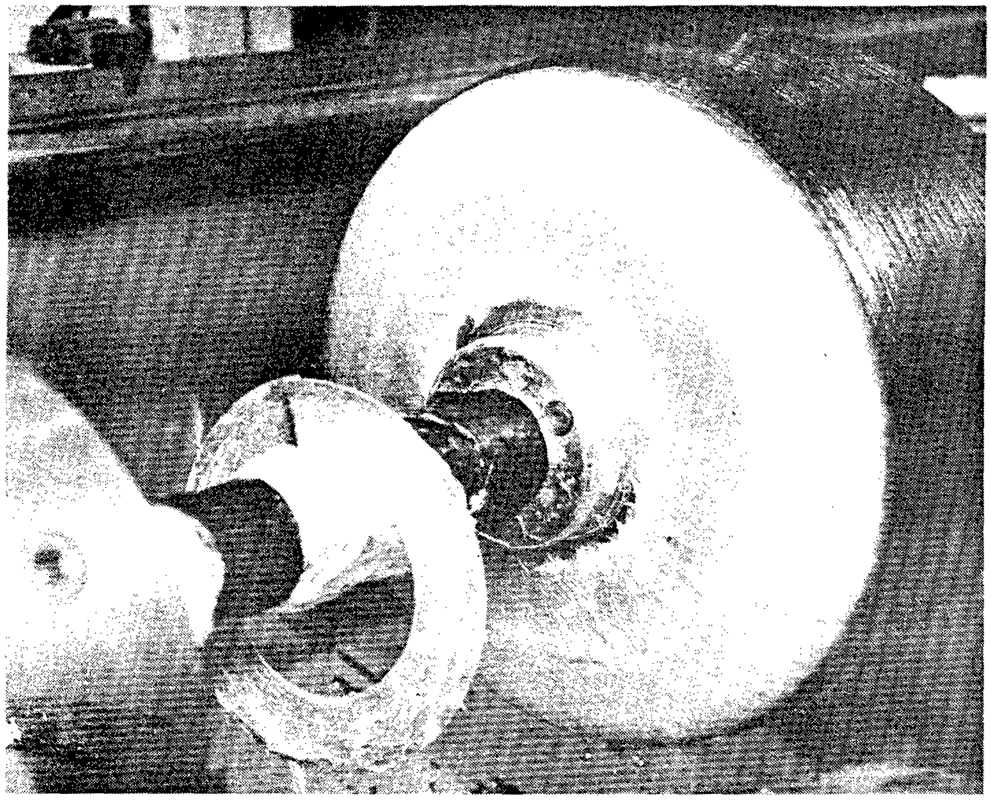


Figure 7.5.3.-3 Composite Roadwheel After Removal of Excess Material

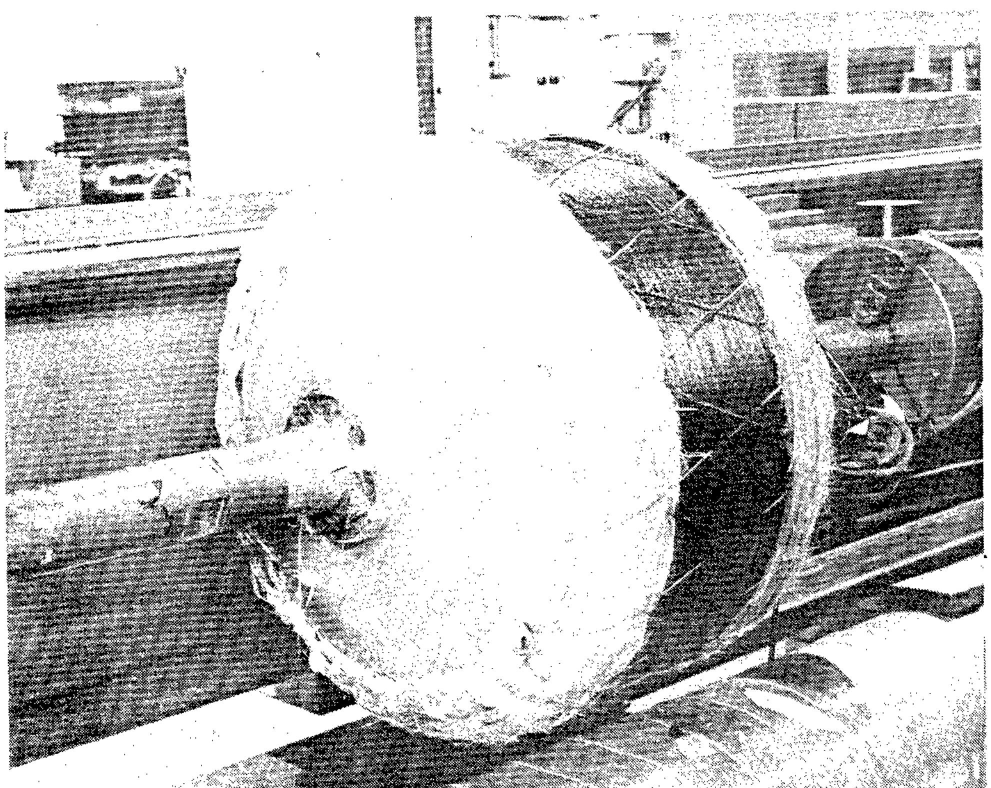


Figure 7.5.3.-4 Holding Build-Up Strips in Place

In the GDLS roadwheel design, it was necessary to place additional composite material in the transition region between the hub disc and the rim (see Section 7.3.2.). Due to limitations in the filament winding process, it was necessary to place this build-up material with a separate hand operation. The material used in this process was an E-glass/epoxy which was wound on a separate mandrel, cut into strips and stored for later use on the roadwheels. To place and hold these composite build-up strips on the roadwheel preform, it was necessary to develop a helical winding program which used a single fiberglass roving to hold the composite strips in place on the roadwheel (see Illustration 7.5.3.-4). These composite strips were placed on the roadwheel preform after the filament winding process and before the compression molding process.

7.5.4 Compression Molding. Once the preform is fully wound and the buildup material is in place, the mandrel is removed from the filament winding machine and placed in the compression mold/press. The compression mold used for the composite roadwheel program was made of mild steel and consisted of a top and bottom half with the bottom having four moveable slide sections (see Illustrations 7.5.4.1 and 7.5.4.2). The top and bottom mold sections were heated with oil but the four slides were each heated electrically. The majority of the slide movement is provided by hydraulic pressure, however, the final 1/2" of closing travel is cam activated by the top mold half as the mold is closed. A small amount of excess resin is typically squeezed out of the roadwheel preform as the mold is closed.

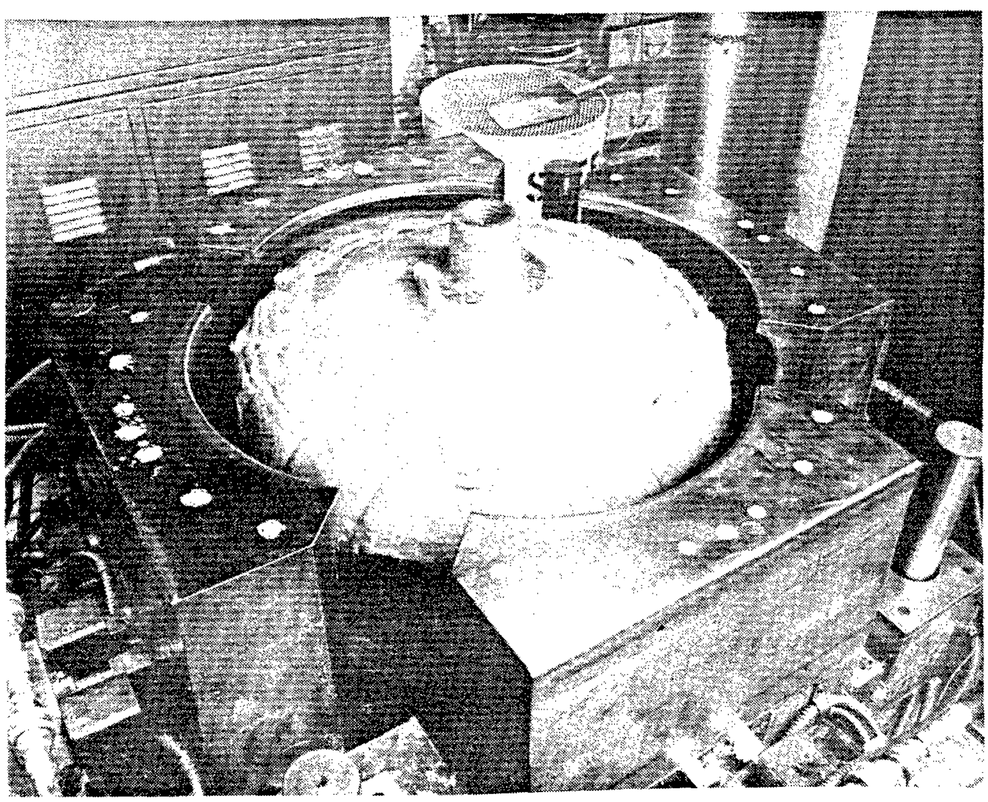


Figure 7.5.4.-1. Bottom Mold Half with Slides Retracted and Roadwheel Preform in Place

The roadwheel preform is cured at 225°F for four to five hours and allowed to cool at least two hours before being removed. A final post curing is performed at 350°F later in a large oven.

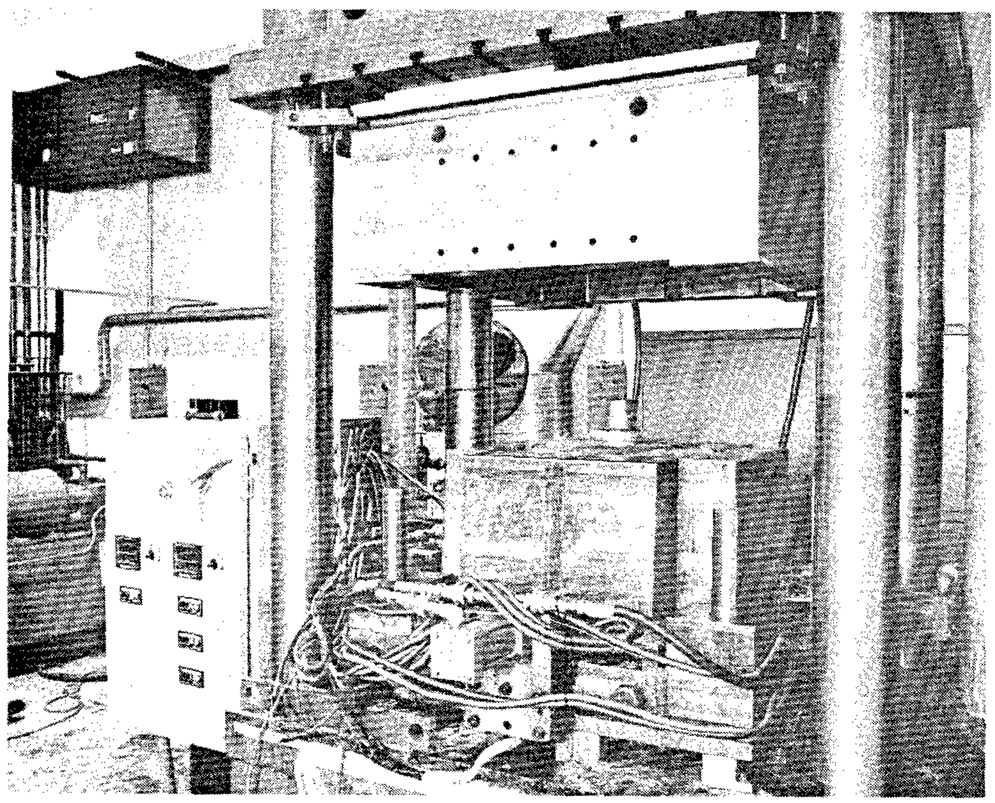


Figure 7.5.4.-2. Complete Roadwheel Mold in 500 Ton Press

7.5.5. Post Processing. Once removed from the mold, the cured roadwheels/mandrel are placed back in the filament winding machine and are cut in two halves with a diamond blade tile saw. This tile saw had a predetermined mounting location which placed the cut down the center of mandrel as the mandrel/wheels were being rotated by the filament winder. After the cut was complete, the wheels could be slid off the mandrel and removed from filament winding machine.

The roadwheels are then machined to bring their hub opening diameter and rim width to their final dimensions. Special fixtures were made to aid in the speed and accuracy of preforming these operations. A diamond edge 4" cutting wheel was used to make the rim width cut and a 5/8" solid carbide end mill was used for the hub diameter. Both operations were performed on a bridgeport mill with a rotary table.

The composite roadwheels were then postcured in a large oven at a final temperature of 350°F for three hours then allowed to cool gradually to room temperature before being sent for rubberizing.

7.5.6. Rubberization. Goodyear Tire and Rubber Company in St. Mary's, Ohio, performed the rubber molding process for the composite roadwheel program. Goodyear had a mold built for this program which was identical to the current production molds except that the composite roadwheel mold provided additional support around the inside diameter of the wheels. Goodyear used a compression molding process and the SM8565 rubber, both which are used on the current aluminum wheels.

After rubberizing, the wheels were returned to GDLS Sterling Technology Center, where the final assembly steps took place. Holes for vehicle mounting and wearplates were drilled with carbide tipped drills. Fixtures with drill bushings were again used which assured quick accurate hole placement.

7.5.7. Wearplates. The wearplates used for the composite wheels are the same as those used on the current production M1A1 wheel. In the composite design, however, it was necessary to drill new bolt holes and use new mounting hardware to compensate for different material thicknesses in the composite wheel versus the aluminum.

After the wear plate assembly, the final processing step is the application of Chemical Agent Resistant Coating (CARC) primer and paint. These paints were applied per the guidelines listed in MIL-STD-171.

7.6. Testing

GDLS has conducted static and rolling drum tests on the composite roadwheel, as well as bearing and torque retention tests. The reason for testing was to satisfy contractual requirements, and also to aid in development of the final wheel design. The following sedtions discuss each type of test performed.

7.6.1. Bolt Bearing Tests: In order to satisfy the interchangeability requirement, geometry in the roadwheel hub region had to match the current aluminum design. This meant that existing edge margins of 1.2 diameters must somehow be made to work in the composite material. Good composite design typically features 3 diameter edge margins which result in high bearing stress allowables. Since data for 1.2D bearing strength did not exist, a series of tests were conducted on both pure composite and metal reinforced coupons. Metal reinforcement was achieved by interleaving stainless steel sheets between the plies of E-glass composite. Bushings and inserts were not considered since they require a larger hole which results in even less edge margin. All coupons were cut from an E-glass/epoxy panel which had .020 and .005 metal plies strategically placed. Specimen design and testing procedures were determined per a modified ASTM D-953 as recommended by MIL-H-17. All testing was conducted at the GDLS Troy Technology Center and Sterling Technology Center. Test results are shown in Table 7.6.1.-1. A comparison of bearing strengths indicates little significant difference between reinforced and non-reinforced concepts. Failure for the metal reinforced coupons occurred at the metal/composite transition region while the all composite coupons failed in tension at the test pin hole. Based on these tests, it was decided to implement the all composite joint concept. The added risk and complexity of metal reinforcement would result in no noticeable performance improvement.

Previous stress analysis (see Section 7.3.1.) resulted in a -.38 margin of safety. This was based on the composite bearing stress allowable of 30 KSI. Frictional forces due to clamp-up were not included but are a substantial load reaction path at the hub. GDLS conducted testing to determine the coefficient of friction for the composite/steel interface. This was done by slotting the end of bearing coupons and measuring the force required to cause slippage while clamped at a known preload. Several methods of surface preparation were tried. The best result was obtained using a sandblasted surface with acetone wipe prior to installation. This procedure resulted in a static friction coefficient of .33.

Table 7.6.1.-1 Bearing Strength Test Results

SPECIMEN	THICKNESS (IN)	STRENGTH (PSI)	BEARING "B" ALLOWABLE
Pure Composite			
1	.480	37,000	30 KSI
2	.485	34,167	
3	.480	36,333	
.020 Shim			
1	.4930	35,050	28 KSI
2	.5030	31,650	
3	.4995	32,753	
.005" Shim			
1	.5260	32,740	32 KSI
2	.5210	39,002	
3	.5255	39,581	

Pin Diameter = .625 in.

7.6.2. Torque Retention Tests. Bolt torque retention testing was conducted by GDLS to determine torque loss due to time and temperature. The bolt torque retention test specimen was a 12" x 12" x 1" panel consisting of 63 layers of 18 oz. CoFab E-glass at 60% fiber volume resin as Dow Tactix 123/H41. The bolt used was the same 15/16" stud currently in use on M1A1. These tests were performed prior to availability of a completed roadwheel so that early data could influence material selections prior to design finalization. All testing took place at GDLS STC facility.

Test results show that 93% of torque was retained as a minimum, and 100% retention could be obtained by retorquing after initial installation. Results are shown in Table 7.6.2.-1.

Table 7.6.2 Bolt Torque Retention Test Results

TEST #	CONDITION	MEASURED INITIAL TORQUE (FT-LBS)	MEASURED BREAKAWAY TORQUE (FT-LBS)	ANGULAR RETORQUE NUT ROTATION	% TORQUE RETENTION
1	24 HRS R.T.	350	325	7.1°	93%
2[1]	72 HRS R.T.	350	NO MOVEMENT	0	100%
3	48 HRS R.T.	350	325	6.6°	93%
4	100 HRS R.T.	350	325	22°	93%

[2]Continuation of Test 1

7.6.3 Flammability Tests. There are two principle components pertinent to the roadwheel assembly, the fiber reinforced resin system and the vulcanized rubber tire. While GDLS has no data for epoxy systems with the exact glass/graphite reinforcement percentages of the roadwheels, Tactix 123 epoxy systems containing only E-glass reinforcement have been studied. Because of the high temperature capabilities of the graphite, GDLS believes that its presence would not alter the basic conclusions of this analysis.

The results of the Tactix 123 system studied are shown in Table 1. The fiber weight content (75.2%) is comparable to the roadwheel assembly (71.5%). Thermal decomposition, which generally proceeds combustion, occurs only with difficulty as evidenced by the high thermal decomposition temperature. In the horizontal burn test, the sample extinguished itself before its rate of burn could be required to sustain combustion, shows that at 150°F more oxygen than exists in a normal atmosphere (22.5% vs. 21%) would be needed to sustain combustion. The smoke density and constituent analysis results are not directly applicable to self extinguishing properties, however are included for the sake of completeness. For an exterior applications, smoke is less important, however the data show that the Tactix 123 system studied is a low smoke generating system. While many by-products are produced in combustion, only three of the more toxic material were tested for; all of these materials were produced in small quantities which offer no jeopardy to surrounding personnel.

No testing was performed on the vulcanized rubber tires, however, this is the same composition which is used on the current configuration. Given this, the fire risk associated with the dense rubber tire should be independent of the roadwheel composition.

The above tests indicate the epoxy system similar to the roadwheel system did not continue to burn when ignited, and required more than the amount of oxygen present in the atmosphere to force it to burn. Given this and the other flammability test results, the composite roadwheel assembly meets the requirements of self extinguishg.

Table 7.6.3.-1 Flammability Results

Fiber content		75.2%
Thermal Decomp. Temp.(C)		436
Burn Rate		0 inches
Oxygen Index		
R.T./150F/575F	24.5/22.4/19.9	
150F	22.4	
575F	19.9	
Smoke Density		
Smoldering/Flaming		
D(m) (20 min.)	30/176	
D(s) @ 4 (min.)	0.3/11	
D(s) = 16 (min.)	16/5.3	
Trace Gases ·(PPM)		
NO2	5.5	
HCl	0	
HCN	11.5	

7.6.4. Roadwheel Testing. GDLS has conducted a series of static tests on the composite roadwheel. Some of these were development tests performed on pre-production wheels in order to aid in material and design optimization. The goal as stated in the contract was 79,000 pound radial load held for five minutes.

All static testing was conducted at the GDLS STC facility in Sterling Heights. The roadwheel was mounted into a specially designed fixture which was then placed into a 120 kip Tinius Olson machine. This test setup is illustrated in Figure 7.6.4.-1. The test fixture was a weld assembly fabricated of 1 inch high strength low alloy steel plate.

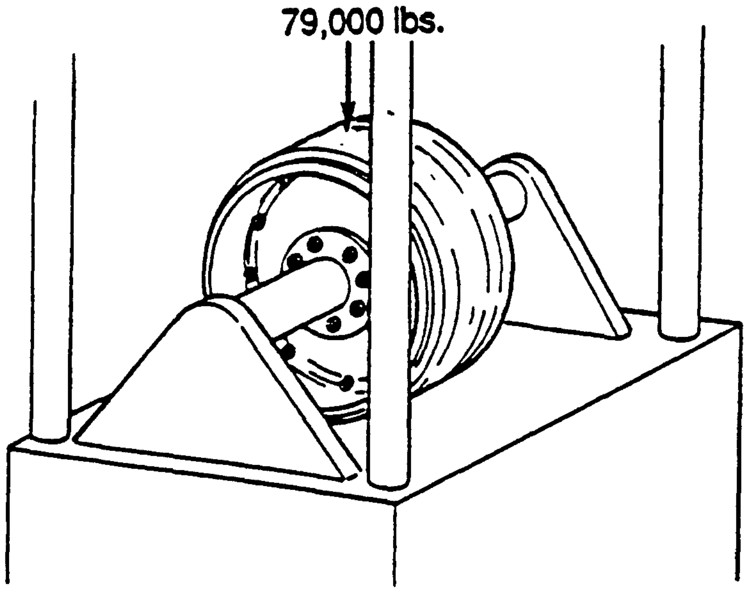


Figure 7.6.4.-1 Static Test Setup for Composite Roadwheel

The GDLS composite roadwheel (final design) achieved 90,000 lbs. during static testing, surpassing the contractual goal of 79,000 lbs. by 14 percent. This result was obtained using a fully assembled, rubberized, ready to install unit. Developmental testing of unfinished subassemblies was also performed earlier in the program to aid in the design. Load versus deflection plots for static testing are shown in Figure 7.6.4.2. The first loud noise during each test was due to delamination growth in the rim area (as near as we could tell) and typically change in the load versus deflection plots. The lone exception to the rule was a specially modified roadwheel (22B) which featured an aluminum ring c-clamped to the composite wheel inner diameter. This ring did not reduce loading on the roadwheel but it provided an order of magnitude stiffness increase at the rim free edge. This resulted in a much stiffer wheel which nearly without any damage, demonstrated the importance of rim stiffness in achieving maximum strength. Because of this test, the composite wheel rim was thickened from 1.25 inch to 1.45 inch.

Between January and March of 1991, a total of eight composite roadwheels underwent vehicle testing at Yuma Proving Grounds, AZ (4 wheels) and Fort Greeley, AK (4 wheels). At each site, the wheels were run as pairs at various stations on the vehicles. Testing continued until at least one wheel from each pair showed significant visual damage at which point both wheels were removed from the vehicle. Table 7.6.4.-1 gives a brief summary of the test results.

TEST SITE	WHEEL NO.	MILES LOGGED	DAMAGE TYPE	REMARKS
AZ	33	28.5	90% Tire Loss	
AZ	39	28.5	None	
AZ	29	82.5	95% tire loss	Some very minor composite
AZ	36	82.5	Loss	damage-delamination
AK	27	203.8	5% tire loss	Some delamination
AK	35	203.8	95% tire loss	Moderate composite damage (delamination)
AK	31	439	50% tire loss	Minor delaminations
AK	38	439	None	Minor delaminations

Table 7.6.4.-1 Vehicle Test Results

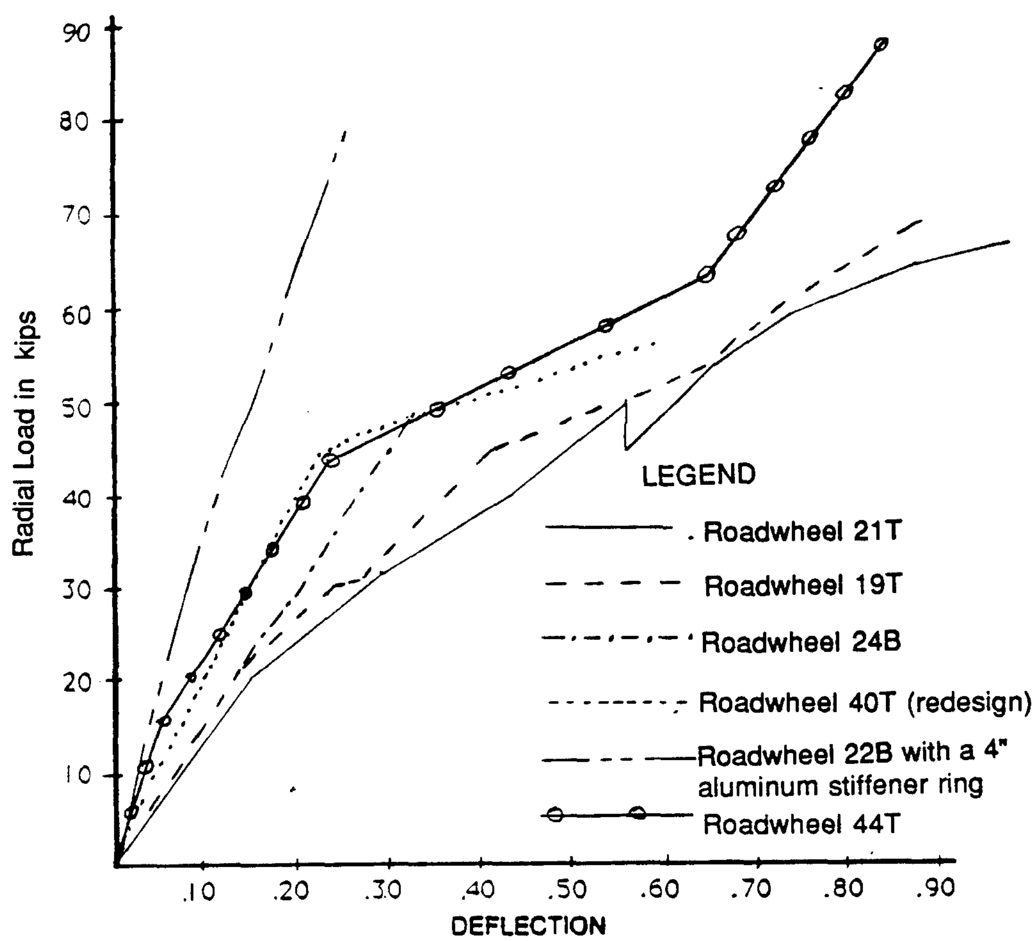


Figure 7.6.4.-2 Composite Roadwheel Static Test Result

7.6.5. Rolling Drum Test. Rolling drum testing was performed at Goodyear in St. Marys, Ohio. The applied loads during the test are listed in Table 7.6.5.-1.

Table 7.6.5.-1 Rolling Drum Test Plan

	Test #1	Time (hrs.)	Load (lbs.)
Rotating Drum	30 mph	0-2	2725
Low Load		2-4	2998
RT		4-6	3270
	Test #2	Time (hrs.)	Load (lbs.)
	10 mph	0-48	6200

Test #1 was successfully completed. Test #2 was interupted after 1 hour due to premature rubber failure. There was no evidence of structural failure in the composite itself. Concurrent testing of an existing aluminum roadwheel revealed significant temperature differences in the rubber tire (the composite wheel running hotter). GDLS feels this is a solvable secondary issue which will not adversely affect development of the M1A1 composite roadwheel.

7.7 Economic Analysis

This economic analysis was performed to estimate the potential production costs of the Composite M1A1 Roadwheel. This cost analysis was based on a production rate of 750 tanks (24,000 wheels) annually on a one-shift, 8-hour, 5-day work week (1-8-5). All costs are expressed in FY89 dollars using 1 January 1992 as the production start-up date and 31 December 1997 as the production end date. All research and development costs were considered "sunk" and not included in the analysis. All other assumptions made in the economic analysis for each cost element are stated in the calculations.

The bottom-up cost estimating model was used in the economic analysis for the composite roadwheel. This approach is derived from standard pricing methodology where each cost element is identified and defined. The unit cost and labor associated with each element were then estimated and an average unit cost derived.

Material costs were calculated from current vendor prices and actual materials used in developmental part fabrication. Labor and tooling were determined from the knowledge and experience gained in the research and development of the composite roadwheel and other similar programs.

7.7.1. Non-Recurring Costs. This element is comprised of the non-recurring costs which are necessary to initiate and support production of the Composite M1A1 Roadwheel. This element includes the cost of capital equipment, non-recurring tooling and non-recurring labor.

The primary capital equipment required to support production is listed below. Based on a total production of 144,000 units, the cost of capital equipment per unit is $8.87.

CNC Bridgeport Mills	(4)	($ 36,000 ea.)	$144,000
Filament Winders	(6)	($ 40,000 ea.)	$240,000
Hydraulic Press	(6)	($125,000 ea.)	$750,000
Custom Cherry Picker	(2)	($ 4,000 ea.)	$8,000
Tile Saw w/Powerfeed	(1)	(5,000)	$5,000
Post Cure Oven	(1)	($100,000)	$100,000
Paint Hood, Guns, Mixer, etc.	(2)	($ 15,000 ea.)	$ 30,000
Total Capital Equipment Costs			$1,277,000

In addition to the major capital items listed above, other items such as powered wrenches, work benches, orbital sanders and miscellaneous hand tools would also be required to initiate and support production.

Non-recurring tooling cost make the following assumptions in the development of the tooling costs:

- Production tools (molds, fixtures, etc.) will last for the complete production run.
- The molds will be chrome plated to minimize tool wear and cleanup time.
- Tooling costs will be amoritized over the complete production run on a per unit basis (144,000).

The estimated cost of non-recurring tooling is summarized below. These costs include all labor and materials used in the fabrication of that tool. Based on production of 144,000 units over 6 years, the average cost of tooling per unit is approximately $6.07.

Winding Mandrels	(13)	($ 12,000)	$156,000
Compression Molds	(6)	($110,000)	$660,000
Mill Fixtures	(2)	($ 15,000)	$30,000
Drill Fixtures	(1)	($ 10,000)	$10,000
Check Block	(1)	($ 18,000)	$ 18,000
Total Non-Recurring Tooling Costs			$874,000

The non-recurring labor is the labor required during the pre-production phase of the composite M1A1 Roadwheel program. This labor category, which represents both engineering and the skilled labor, is detailed below:

The estimated non-recurring engineering labor (shown below) is the engineering labor required to initiate the plant facilities set-up. Based on a total production of 144,000 units and a labor rate of $45/hour, the cost per unit is $1.00.

Equipment and Tooling Acquisition	2,000 Hrs.
Facilities Engineering	1,000 Hrs.
Design Engineering	200 Hrs.
Total Non-Recurring Engineering Labor	3,200 Hrs.

The non-recurring labor is non-engineering labor required to initiate production of the composite roadwheels. Based on production volumes of 144,000 units over 6 years and a $40.00/hour, the estimated non-recurring labor cost is $0.81 per unit. These labor costs are summarized below.

Facilities Set-up	700	Hours
Equipment Installation	700	Hours
Tool and Equipment Tryout	1500	Hours
Total Non-Recurring Labor	2900	Hours

7.7.2 Recurring Costs. The recurring cost element includes costs associated with the fabrication of the Composite M1A1 Roadwheels. These costs are divided into the following categories: labor, materials and tooling.

The labor costs consist of both direct and indirect expenses associated with the composite fabrication process.

The direct labor hours required to fabricate the first production composite roadwheel is detailed below.

Filament Wind Roadwheel Preform	8.0	
Cure and Post Cure*	1.0	
Separate, Mill and Drill	1.5	
Assemble Wear Plates	.2	
Clean and Prep Compression Mold and Mandrel	2.0	
Total Direct Labor Required	12.7	Hrs/2Wheels
	6.35	Hrs/Wheel

*The 1.0 hour to cure and post cure the roadwheel represents the actual labor time required.

Based on a 95 percent learning curve, Table 7.7.2.-1 shows the projected labor hours and efficiency improvements for the first unit and at the start of each year during the program.

Table 7.7.2.-1. Labor Hours and Efficiency Input

Production Date	Labor Hours Per Wheel	Percent Efficiency Improvement from First
Jan 1, 1992	6.35	First Wheel
Jan 1, 1993	3.01	52.6
Jan 1, 1994	2.86	55.0
Jan 1, 1995	2.78	56.2
Jan 1, 1996	2.72	57.2
Jan 1, 1997	2.67	58.0

Using the January 1, 1995 projected 2.78 labor hour figure, with a $35/hr. rate, the estimated direct production labor cost is $97.30 per wheel.

The indirect labor cost element is comprised of both engineering labor and skilled labor. The cost for each of these labor categories is detailed below.

Recurring Engineering includes the cost of all engineering efforts in support of production. The labor required which is detailed below, costs $2.70 per unit based on a $45 per hour labor rate for the six year production run.

Maintainability Engineering	40 Hrs/Mo.
Production Engineering	80 Hrs/Mo.
Total Recurring Engineering Labor Hours	120 Hrs/Mo.

This skilled labor cost element includes this labor costs of tool maintenance and quality control. Each of these two cost categories are detailed below.

Tool maintenance costs include labor associated with normal tool (mold) maintenance for each of the winding mandrels, compression molds, fixtures and check blocks. Based on the 6 year production run and a $40 per hour labor rate, the average cost of tool maintenance will be $1.45 per wheel. The estimated labor required is detailed below:

Winding Mandrels	(13)	(3 Hrs/Mo ea)	39 Hrs/Mo.
Compression Molds	(6)	(5 Hrs/Mo ea)	30 Hrs/Mo.
Mill Fixtures	(2)	(1 Hrs/Mo ea)	2 Hrs/Mo.
Drill Fixtures	(1)	(1 Hrs/Mo)	1 Hrs/Mo.
Check Block	(1)	(.5 Hrs/Mo)	.5 Hrs/Mo.
Total Tool Maintenance Labor			72.5 Hrs/Mo.

Quality Control costs include the labor required to perform all functional checks, reliability testing and incoming material inspection. Based on the 6 year production total of 144,000 units and a $40 per hour labor rate, the cost to perform the Quality Control functions is $2.00. The estimated labor hours for this cost item is detailed below.

Dimensional Check	40 Hrs/Mo.
Reliability Testing	40 Hrs/Mo.
Incoming Inspection	20 Hrs/Mo.
Total Quality Control Labor	100 Hrs/Mo.

The materials cost estimate includes the cost materials both directly and indirectly associated with the manufacture of the Composite Roadwheel. These material costs are detailed below:

Cost Item	Amount	Unit Cost $	Cost $
Resin	14.6 lb.	1.69	24.67
Hardener	2.9 lb.	3.00	8.70
E-glass Roving	26.2 lb.	.93	24.37
Carbon Fiber Roving	17.9 lb.	10.00	179.00
Mold Releases	.01 gal.	25.46	.25
Wear Plates	1 Wheel	49.42	49.42
Rubberizing & Painting	1 Wheel	64.64*	64.64
Total Material Cost Per Unit			$351.05

*The $64.64 for rubberizing and painting includes labor.

The cost of recurring production tooling is detailed and summarized below. Based on production of 144,000 units over 6 years, the average cost of recurring tooling per unit is $3.66.

Sanding Disks	$ 11,200
Drill Bits	$156,000
Mill Bits	$250,000
Saw Blades	$109,565
Total Recurring Tooling Cost	$526,765

7.7.3. Cost Summary. Table 7.7.3.-1 is a cost summary of the various material and labor costs associated with producing Composite M1A1 Roadwheels. The wear plates, assembly hardware, rubberizing and painting are treated as purchased parts/services.

Table 7.7.3.-1 Cost Summary

Item:	Cost per Unit ($):
<u>Non-Recurring Costs</u>	
Capital	8.87
Tooling	6.07
Labor: Engineering	1.00
Labor: Skilled	0.81
<u>Recurring Costs</u>	
Direct Labor*	97.30
Indirect Labor: Engineering	2.70
Indirect Labor: Non-Engineering	
Tool Maintenance	1.45
Quality Control	2.00
Materials	351.05
Recurring Tooling	3.66
Total Estimated Roadwheel Cost (ea.)	$474.91

*The 2.82 hours for direct labor represents the estimated time to produce one roadwheel at the half-way point (Jan 1, 1995) in the six-year production run.

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