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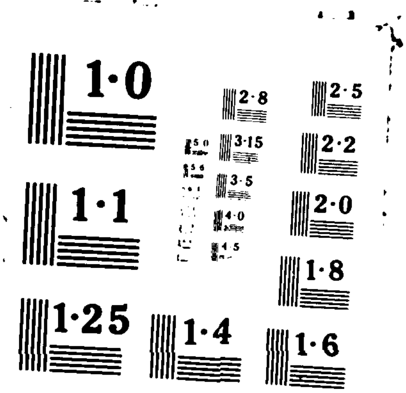
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TECHNICAL REPORT ARCCB-TR-87031

STRUCTURAL INTEGRITY OF METALLIC ARMATURE RAIL GUNS

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NOVEMBER 1987

US ARMY ARMAMENT RESEARCH, DEVELOPMENT AND ENGINEERING CENTER
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The design of a rail system for an electromagnetic gun becomes more complicated when the transfer from a laboratory to a tactical system is considered. In the laboratory, weight and volume are not important and the system must be bolted together in order to be disassembled for study, modification, and repair. The tactical system must be of reasonable weight and volume, self-supporting, safe to use, have a long life, and be factory assembled. This set of design requirements must be reconciled with the function as a projectile

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guide and an electrical conductor. The first crude prototype 'barrel' must be manufactured from available materials which do not have the optimum properties. The design then becomes a series of compromises which are performed in the hope of a successful result.

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INTRODUCTION

An electromagnetic rail gun is rather simple in concept. It consists of two parallel conductive rails with a projectile between them. At the rear of the projectile is an armature which is essentially a 'shorting bar' between the rails. When the rails are connected to an electrical power supply, a magnetic field is set up between the rails which interacts with the field set up by a current in the armature to propel the projectile up the rails and out of the gun. This is an attractive process because the electrical current can chase the projectile up the rails much more efficiently than the hot gasses of a chemically-based gun. In this way much higher projectile velocities can be achieved. However, there are many technical problems which must be overcome in order to create, control, and contain the large energy requirements of a reasonable size projectile. In this case, the high current density required to attain reasonable velocities produces magnetic fields which place substantial forces on the various rail gun structures.

Recent developments in power supplies for rail guns such as the homopolar generator have given promise to the development of a practical rail gun weapon. Therefore, interest was generated in the process of moving from the laboratory rail 'bolted up' system to a more portable rail system or a rail gun 'barrel'. This process seems to require a movement from the square bore of the usual laboratory gun to a round bore. At the same time it seems advantageous to shift from a plasma armature to a solid metallic armature. The solid armature is intended to eliminate the rail damage produced by the hot plasma. The first step in this process was taken earlier by this author in an investigation of square bore guns held together by a composite over-wrap (ref 1).

References are listed at the end of this report.

The requirements for a rail system now become more complicated. It must still guide the projectile and provide a conductive path from the power source, but now the weight and volume become very important. Further, it must be self-supporting in bending so that it can be held in some reasonable turret and pointed in the desired direction. The ability to deliver the projectile in a particular direction will mean that the process of guiding becomes more critical because the projectile must be sent several kilometers to a target rather than a few meters. The one factor which will help is that the plasma armature common in laboratory guns will be replaced with a solid metallic one and the plasma pressure will be gone from the problem.

This report deals with the design of an early prototype of a tactical rail system. The design is driven by the necessity of producing hardware from available materials using the available production machines, and this will be done with insufficient design information. The structural analysis was done largely with the ABAQUS (ref 2) finite element code using nonlinear static analysis. This problem does have serious dynamic considerations; however, the static problem must come first because if the static problem is not solved there is no hope of any control of the dynamic cases.

In this report, the definition of structural integrity will be expanded from the normal notion of relating integrity to some gross failure. Here the failure will also include failure to function, i.e., failure to complete all tasks correctly. The item of primary concern is rail expansion which must be minimized to insure good armature contact and precise alignment of the projectile in the desired direction. A major problem is that the armature design parameters are not available and the detailed design of tactical projectiles is still in the future. No guidelines have been quantified for permissible rail

expansion values. The study must then look at ways to minimize these numbers and thus ease the burden of the projectile designer.

DESIGN LIMITATIONS

Early rail gun barrels were designed to take advantage of readily available materials and manufacturing facilities in order to produce hardware on a specific schedule. This, along with the lack of many specific items of design information, has resulted in a design which is far from the optimum. However, there has been time to look at alternate methods and materials in order to increase the design data base. In any case, the initial design parameters are as follows:

1. A circular bore of 0.050 meter diameter and 5.0 meters long.
2. A maximum rail current of 1,500,000.0 amperes.
3. Rails made from OFHC tough pitch copper.
4. A composite-wrapped hoop for overall support.
5. Self-supporting in bending.
6. Metallic armature.
7. Insulating spacers between the rails machined from G-10 glass cloth-epoxy material.
8. Maximum possible contact surface for the armature.
9. The rail geometry may not include acute angles.
10. The rail system must look like a gun, however, an oval cross section is acceptable.
11. Any reasonable weight will do, however, the cost of available composite materials is very high.
12. Electrical insulation must be provided to isolate the two rails.

Of these design goals, the desire for a circular bore combined with goals 3, 8, and 9 provided the most serious limitations. Informal information from Los Alamos National Laboratory placed the maximum rail contact area at 120 degrees of arc in a round bore. Further, the use of soft copper rails and the desire to limit the use of acute angles required that the outer surface of the rail intersect the bore at a right angle. This is a very serious limitation, and if it can be eliminated, many improvements in structural performance are possible.

While not a design limitation, this work has also explored the full use of Standard International Units in the design and analysis. This has been very successful and can be recommended for all engineering work. Therefore, all units in this report are metric using the standard meter, newton second system. Stresses and stiffnesses are given in pascals, or newtons per square meter.

RAIL GUN GEOMETRY

This report is primarily concerned with the design of the basic cross section of the rail system or rail gun barrel. The basic concept is shown in Figure 1 which outlines the seven basic items. The primary components are the two electrically conductive rails (R). The rail spacing is controlled by two insulating spacers (S), which conform closely to the rails and fill in part of the inner bore surface. These four components are held together with a conforming hoop assembly of three more elements. The inner portion of the hoop is an insulating-wrapped composite (I) material to electrically isolate the rails from the structural hoop (H). The structural hoop is that portion which carries the major loads from the magnetic expansion force. The outer element (L) is a layer of composite material which is oriented in the longitudinal direction to provide bending stiffness for the overall structure.

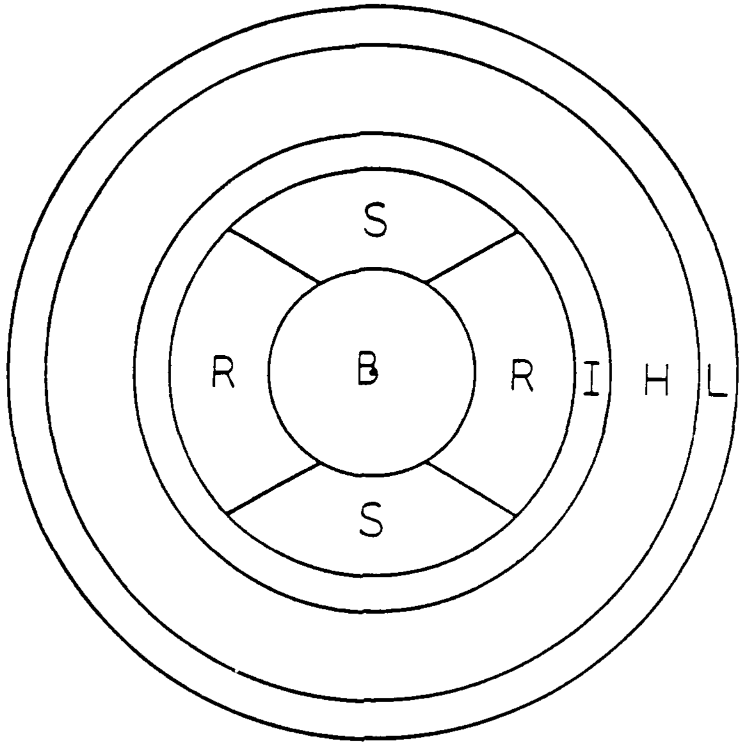

Figure 1. Basic geometry.

Figure 2 shows the finite element grid (a one-quarter section) for one rail gun that was fabricated. The hoop has been flattened to an oval shape for two reasons. First, this reduces the weight and volume of the spacers which serve little structural purpose. Second, the oval shape reduces the length of the loaded hoop in an effort to reduce the expansion of the rails. The oval shape is generated by connecting circular arc segments of two different radii which meet in a smooth manner at the interface between the rail, the spacer, and the hoop assembly. This will insure a smooth transition during the composite-wrapping process. In this report the radius of the outside of the spacer (next to the insulating hoop) is twice that of the outside of the rail.

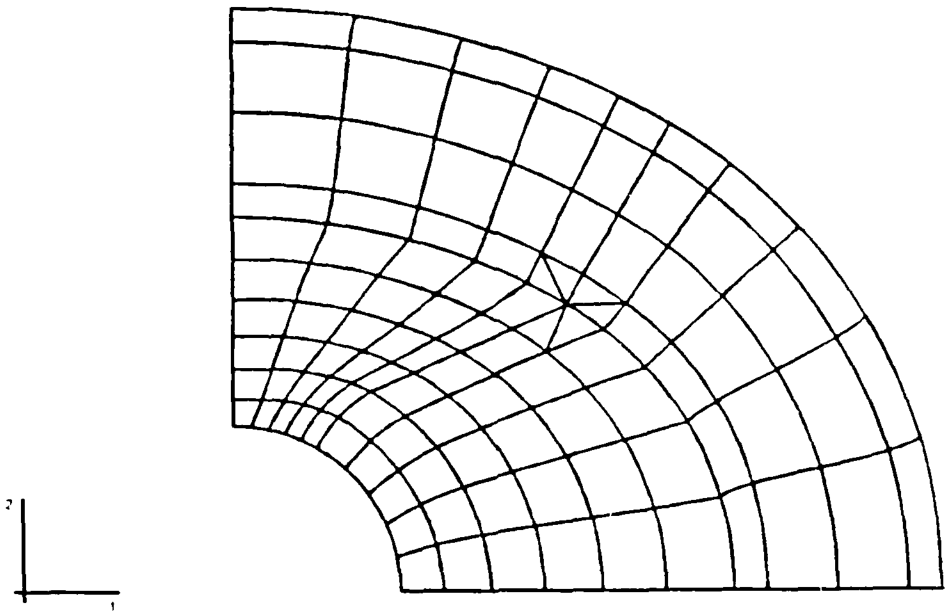

Figure 2. Finite element mesh for a round bore gun.

The rails were designed initially to provide for a round bore rail gun which has presented several problems. The primary concern is that electrical conduction problems prevent the use of acute angles in the rail so the rail sides must meet the bore at a right angle and then curve back to the hoop. At this point it is tempting to interlock the rail and spacer; however, insulating materials with good strength are not easy to come by and this work is limited to available materials. The poor strength of available insulating materials for the spacer also seemed to preclude an acute angle in the spacer at the bore. This idea also reinforced the notion that the rail spacer interface meet the bore at a right angle.

The spacer fills in the volume bounded by the rails, the bore, and the long radius portion of the hoop. In the round bore gun it will be pushed into the bore under the assumed magnetic loads. This appears to be a problem, although the effect will primarily be in back of the projectile. It still seems that it should be controlled, however, and the hexagonal bore configuration shown in Figure 3 illustrates this point.

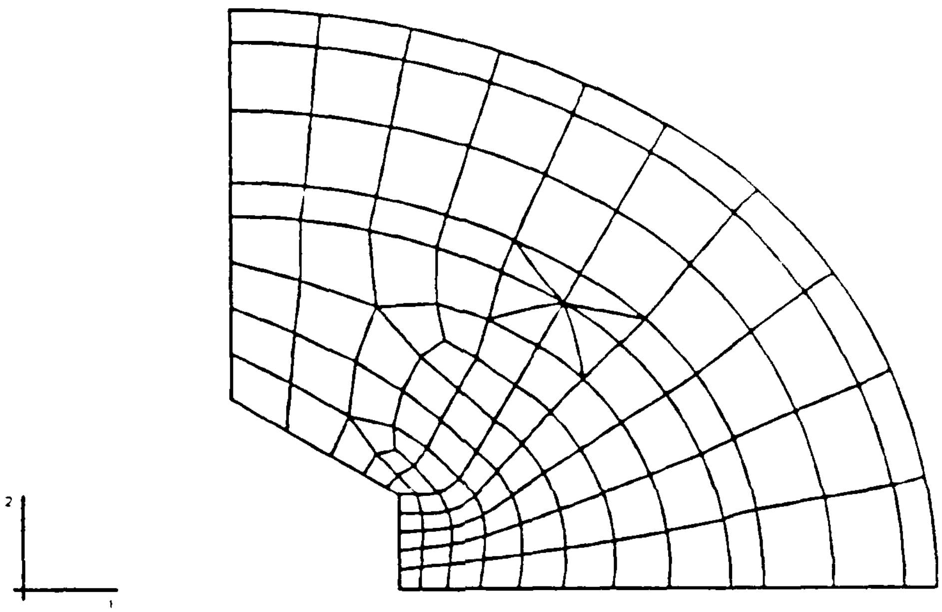

Figure 3. Finite element mesh for a hexagonal bore gun.

Most laboratory rail guns have a square bore because the rails are rectangular copper bars. Several round bore guns have been produced at Los Alamos National Laboratory (ref 3), however, they have presented many difficulties. Here a hexagonal bore gun is suggested because of its ability to control spacer motion into the bore region. There is precedent for hexagonal bore guns as the Whitworth gun was used successfully by the Confederate Army during the Civil War. In this case, the hexagonal bore provides for a right angle corner in the rail at the bore and a short contact surface to control spacer movement into the bore. Control of the spacer movement will be shown to be important in the

control of rail expansion, however, the bearing stresses between the rail and the spacer become very large.

RAIL GUN MATERIALS

The materials for this work were, for the most part, defined by availability and past experience of other rail gun builders. It was assumed that high electrical conductivity was a mandatory requirement for the rails, which made copper the material of choice. A high purity copper was selected in the half-hard condition.

Copper:

Tensile Modulus - E = 110.33 E09

Poisson's Ratio - M = 0.330

Yield Strength - Y = 170.6 E06

The spacer material was selected because of its use in other rail guns and because it is readily available in large blocks. It is a standard insulating material called G-10. It is manufactured as a stack of fiberglass cloth layers bonded together with an epoxy matrix. In this gun the wrap direction (ref 3) runs parallel to the rails, the filler runs between the rails (ref 1), and the stacking runs out from the bore (ref 2). The following three-dimensional orthotropic properties were used.

G-10:

Tensile Moduli - E1 = 26.36 E09, E2 = 15.35 E09, E3 = 30.77 E09

Poisson's Ratio - M12 = 0.4455, M13 = 0.1050, M23 = 0.1448
M21 = 0.2594, M31 = 0.1226, M32 = 0.2903

Shear Moduli - G12 = 8.66 E09, G13 = 6.62 E09, G23 = 6.17 E09

The insulating layer of the hoop is assumed to be a fiberglass-epoxy composite material wrapped in the hoop direction. The analysis, which used properties assuming a standard fiber volume fraction of 60 percent, resulted in the following properties:

S-Glass:

Tensile Moduli - E1 = 12.85 E09, E2 = 12.85 E09, E3 = 52.85 E09

Poisson's Ratio - M12 = 0.3584, M13 = 0.0628, M23 = 0.0628
M21 = 0.3584, M31 = 0.2582, M32 = 0.2582

Shear Moduli - G12 = 4.73 E09, G13 = 6.00 E09, G23 = 6.00 E09

The outer bending layer of the hoop is assumed to be an IM-6 graphite-epoxy composite with a fiber volume fraction of 0.60 which produces the following material properties.

IM-6:

Tensile Moduli - E1 = 8.870 E09, E2 = 8.870 E09, E3 = 175.1 E09

Poisson's Ratio - M12 = 0.3618, M13 = 0.0131, M23 = 0.0131
M21 = 0.3618, M31 = 0.2588, M32 = 0.2588

Shear Moduli - G12 = 3.26 E09, G13 = 5.51 E09, G23 = 5.51 E09

The material for the structural portion of the hoop is a major concern of this study and will be covered in detail in the remainder of the report. However, the structural hoop will always be one of three classes of material. First, is a continuous fiber composite such as graphite-epoxy. The actual rail guns which have been fabricated or scheduled are glass or graphite composites. When these materials began to show large deformations, the analysis was changed to standard metals such as aluminum. Finally, as a projection into the future, some runs are reported using laminates of metal sheets (aluminum or titanium) separated by glass cloth-epoxy insulating layers. As will be seen, these choices can produce strong variations in the maximum rail expansion. In the initial part of this work, a plane hoop wrap was assumed, however, this evolved into a plus and minus 7.5 degree winding pattern. This will show up as a slight variation in the hoop stiffness of wrapped composite cases.

DETAILS OF THE ANALYSIS

The analysis was performed using the ABAQUS finite element code. Eight-node generalized plane-strain elements were used in conjunction with three-node per surface interface elements. There are three interface surfaces in this geometry: the rail-hoop interface, the spacer-hoop interface, and the rail-spacer interface. These three surfaces must be separated so that they may act independently. This has been done by using collapsed quadrilateral elements at the intersection point. In these elements, one side has been given zero length, while all three nodes are allowed to deform independently. This will keep the contact surfaces independent while allowing a 1/R singularity at the intersection point. This singularity is necessary to model the discontinuity of the sharp corner of the rail contacting the insulating layer of the hoop. In an actual system the soft copper rail will deform and eliminate this problem, however, for this analysis it is not necessary.

The magnetic load was applied as a uniform pressure on the bore surface of the rail with a total expansion force of 4.38 E+06 newtons per meter of rail. This figure was the initial estimate of the total expansion force for a 1.0 E+06 ampere current and an inductance gradient of 0.40 E-06 Henry. During the duration of this study, several different methods of calculating the rail expansion force from current distribution models were tested. However, none were better than the original crude estimates. This is also true of the distribution of load on the rail, where the application of load as a general body force did not result in significant changes in rail expansion.

The final analysis details relate to the required constraints. The finite element grid is a one-quarter section model which used symmetry constraints on the coordinate axes. Further, it uses generalized plane-strain elements which

were constrained to keep the normal strain constant for all elements. However, this strain was allowed to be any value which produced a net axial force of zero.

A secondary analysis was performed to determine the droop of the gun when supported as an overhanging beam. In this case, a 5 meter-long barrel was assumed which was supported at one end and at a point 2 meters from that end. The tip deflection was calculated at the free end using simple beam theory. In order to calculate the section modulus (EI) of this complex section, a simple program was generated. This program used the ABAQUS finite element mesh to calculate the area and inertial properties of the section. These were then multiplied by the appropriate material modulus and summed to produce the overall composite section modulus. The same basic method was used to calculate the appropriate mass-per-unit length of the gun to use as a distributed load.

RESULTS

Figure 4 shows a typical deformed grid plot for the round bore gun with the deformation magnified by a factor of 10.0. Two primary problems are demonstrated. First is the rail expansion under load, and second is the spacer contraction due to sliding along the rail-spacer interface. The sliding has been allowed because of the small (0.02) value for the coefficient of friction. This is the general condition for the first two rail guns to be built. In contrast, the hexagonal bore model shown in Figure 5 still has a large rail expansion, but now the spacer contraction has been controlled and the gap in the rail-spacer interface has been replaced by a small region of high contact stress. This contact at the bore will have the effect of producing a bore seal against contaminants and any casual plasma which may exist. However, the price

is a high contact force which must be carried by the soft rail material and the weak insulating spacer.

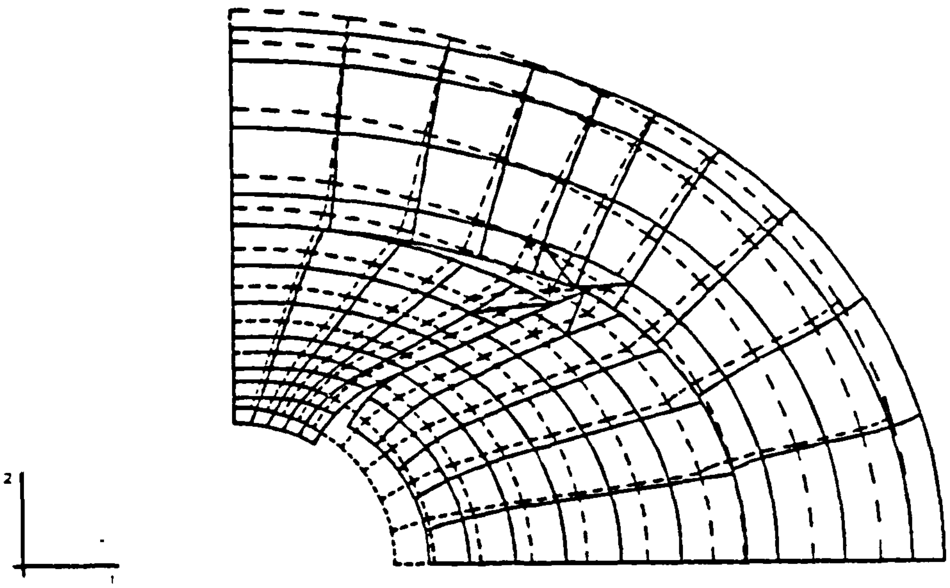

Figure 4. Deformed mesh for a round bore gun.

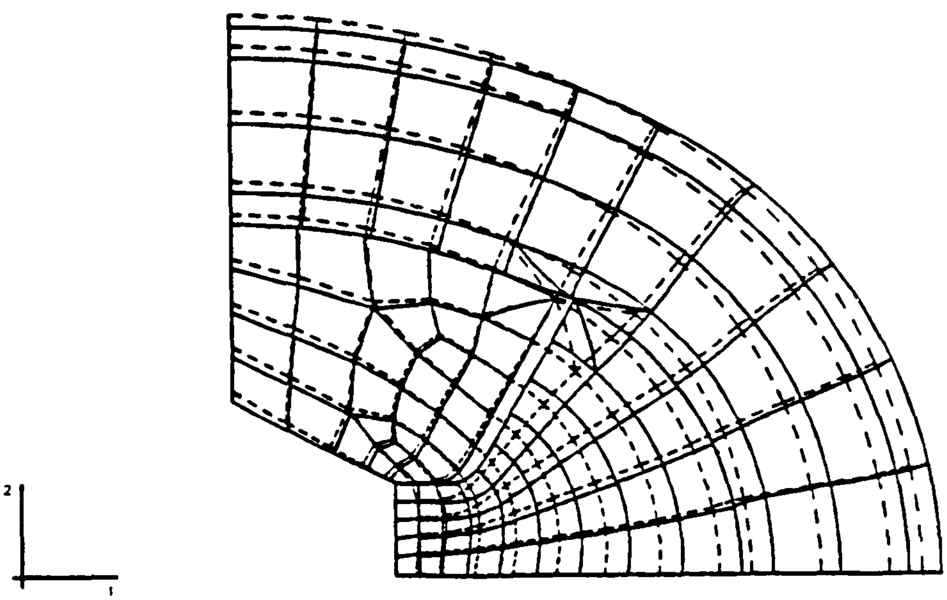

Figure 5. Deformed mesh for a hexagonal bore gun.

Figure 6 is a stress contour plot of the minimum principal stresses where the structural hoop is S-glass composite. The single most prominent feature is the contour loops near the rail-spacer-hoop intersection. These compressive stresses are the result of the sharp corner of the rail pressing on the hoop. This is due in part to the mathematically sharp corner modeled by the singular elements. Three factors will reduce this effect: real corners have a radius, the rail deforms locally, and better hoop materials reduce overall system deformation.

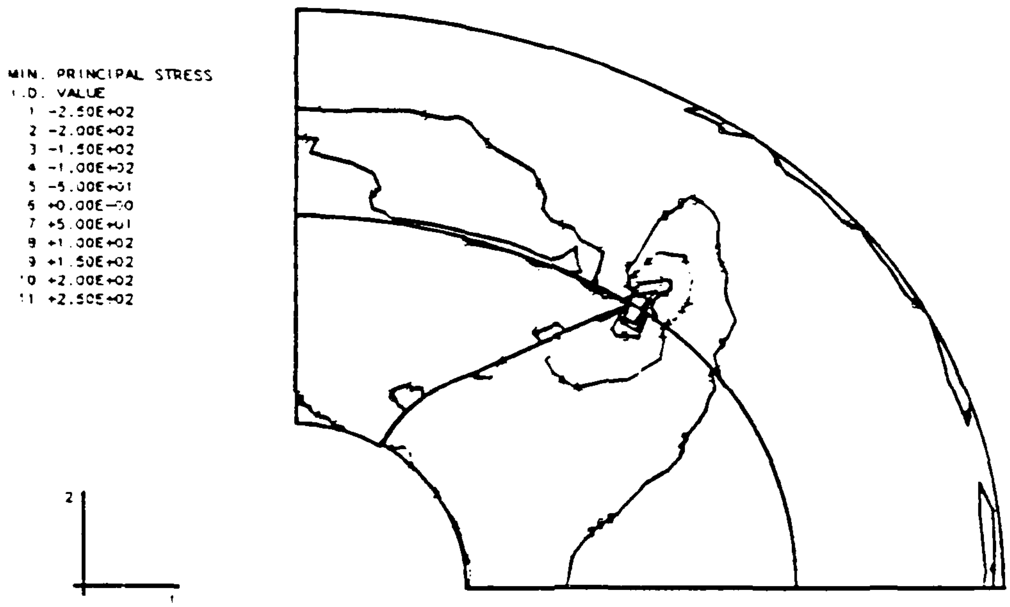

Figure 6. Minimum principal stress contour plot.

Figure 7 is a stress contour plot for the case of an IM-6 graphite composite hoop. Here the contours are lines of constant maximum principal stress. The thing to note here is that the maximum tensile stress is in the hoop above the spacer. Such stress is the highest near the insulation layer and decreases rapidly through the thickness of the hoop. This is a result of poor stress transfer in this class of materials because of low transverse and shear stiffnesses. Similar effects have been noted by Mansfield for pin-loaded composites (ref 4) and this author for thick-wall cylinders (ref 5).

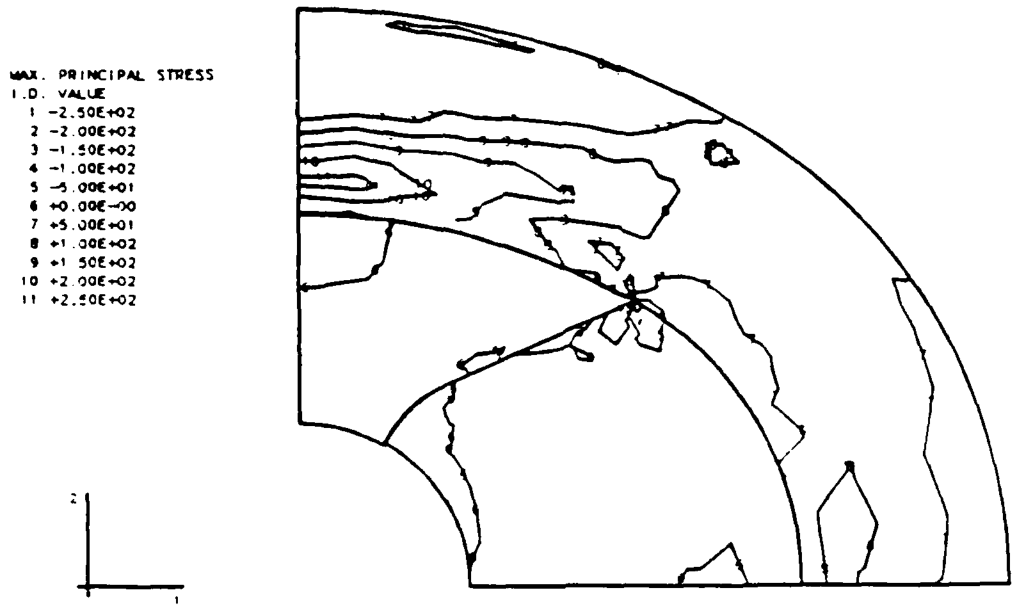

Figure 7. Maximum principal stress contour plot.

The general level of stresses in all of the cases reported here is low. All of the data was plotted using 11 contours over a range of -250.0 E+06 to 250.0 E+06 pascals. These stresses are acceptable to all of the structural materials involved (not the G-10). These generally low stresses had two notable exceptions. First is the high compressive stress at the mathematical singular point, and second is the high contact stress in the hexagonal bore configuration.

The primary result of this report is the analysis of the rail expansion for different materials in the structural portion of the hoop. The materials may be isotropic metals such as steel or aluminum, organic composite materials such as S-glass or graphite, or a metallic and composite laminate of glass cloth-epoxy layered with aluminum or titanium. Further, the round or hex bore configuration may be used with little difference in result. All of these are plotted as the radial displacement of the bore surface of the rail against the hoop stiffness of the particular materials. These are shown in Figure 8 for the following materials:

Isotropic:

1. Steel

2. Titanium

3. Aluminum

Fiber-wrapped composite:

4. S-glass - epoxy

5. IM-6 graphite - epoxy

6. Steel wire - epoxy

Metal and composite laminate:

7. Titanium - G-10

8. Aluminum - G-10

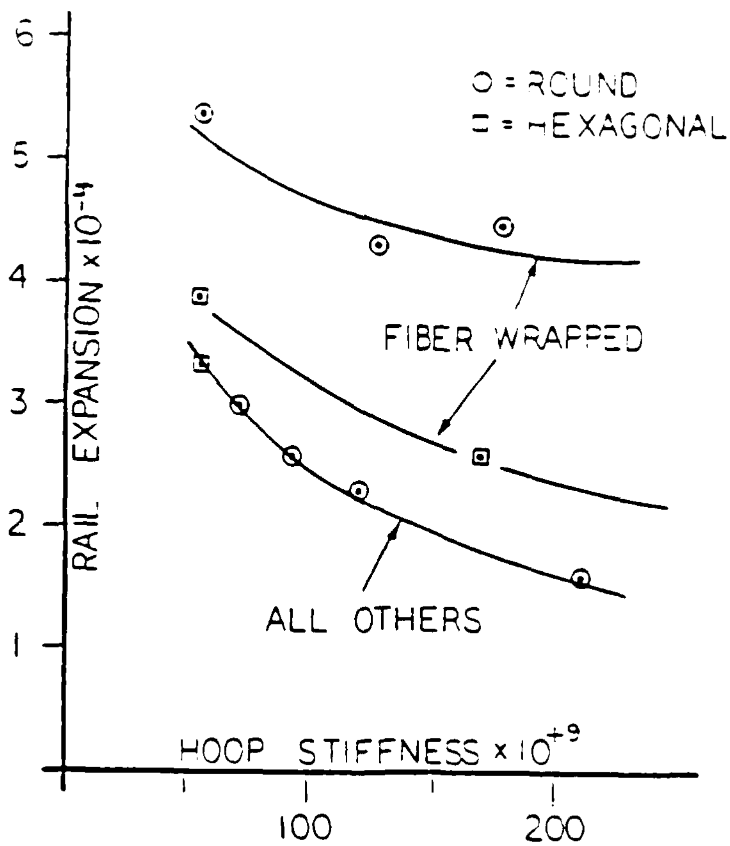

Figure 8. Rail displacement versus hoop stiffness.

Note that there are two different families of data on this plot: the fiber-wrapped composites and everything else. The numeric data is shown in Table I.

TABLE I. RADIAL DISPLACEMENT DATA

Configuration of the Bore	Material Number	Hoop Stiffness	Displacement Meters
Round	1	206.8 E9	0.000154
Round	2	119.9 E9	0.000213
Round	4	52.85 E9	0.000518
Round	5	175.1 E9	0.000443
Round	6	125.4 E9	0.000414
Round	7	90.52 E9	0.000256
Hexagonal	3	68.95 E9	0.000294
Hexagonal	4	51.22 E9	0.000383
Hexagonal	5	167.5 E9	0.000257
Hexagonal	7	89.09 E9	0.000261
Hexagonal	8	55.18 E9	0.000329

The beam bending analysis was only performed for the S-glass and IM-6 structural hoop materials. They produced a mass of 101.3 and 95.3 kilograms per meter because the graphite fiber is lighter than the glass. However, because the transverse stiffness is nearly the same for both materials, the section moduli were close in value. These gun sections have two principal inertial axes and deflections were calculated for both. The results shown in Table II are barrel droop due to gravity when supported at two points 2.0 meters apart. In all cases the deflections seem to be rather small which verified the bending

stiffness of this design. Further analysis demonstrated that the axial graphite in the outer layer of the hoop is about 5 percent of the total mass of the round bore barrels and accounts for about 50 percent of the bending stiffness of the overall section.

TABLE II. RAIL GUN BEAM BENDING DATA

	Unit Mass (kilograms)	Section Modulus	Deflection (meters)
S-Glass	101.3	5.182 E+06	0.00347
	101.3	2.978 E+06	0.00604
IM-6	95.3	5.020 E+06	0.00337
	95.3	2.861 E+06	0.00592

DISCUSSION

The first thing to note in this report is that the first gun to be manufactured will be a round bore gun with an S-glass epoxy containment hoop. This is far from the best design, however, it does have the advantage of fitting into the limitations of time, cost, materials, and available equipment. The second gun will use an IM-6 graphite structural hoop which is stronger; however, it will do little to improve the rail expansion problem.

There are several things which would help reduce rail expansion. First would be the use of an isotropic structural hoop which would present many fabrication problems. The laminated hoop could be fabricated from thin plates, die cut into oval rings, and stacked with matching glass cloth-epoxy rings. The stack could then be cured into solid sections and assembled over the rails. This would be a time-consuming and expensive process, however, it may also have some magnetic advantages.

Another way of reducing the expansion would be to find an insulating material which would be able to tolerate higher stresses. This, in conjunction with a higher strength rail material, would allow the rail and spacer to be interlocked and some loads transferred over a shorter path near the bore. This leads to the conjecture of using the new high temperature superconductors for the conductive path. In this case the definition of an insulator may change.

Last is that if the bore contact circumference necessary for conduction to the armature could be reduced, some compromise between the round and hexagonal bore configurations would be possible. This type of improvement would also lead to an improved magnetic field in the bore. This is because the current round bore configuration tends to interfere with the development of the magnetic field between the rails.

CONCLUSION

If the definition of structural integrity is extended to include the concept of 'failure to function' as well as catastrophic failure, then these early rail guns may have a problem because the bore expansion could compromise the projectile guiding function or make the armature contact problem more difficult. However, reasonable solutions are possible using currently available materials. The nature of future guns will depend on developments in armature design, high strength insulators, high strength conductors, and structural composite materials. In currently available fiber composite materials, the low transverse and shear stiffnesses do present problems in this three-dimensional loading.

The state-of-the-art in the calculation of the correct loads for use in the structural analysis is a weak point in the analysis. This is a time-dependent two- or three-dimensional problem with the interaction of current flow and the magnetic field. The problem will have to be resolved somewhat before more detailed structural analysis is performed.

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