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TECHNICAL REPORT BRL-TR-3299

BRL

STRUCTURAL DESIGN ISSUES FOR ELECTROMAGNETIC PROJECTILES

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DECEMBER 1991

U.S. ARMY LABORATORY COMMAND

BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

NOTICES

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE
December 1991

3. REPORT TYPE AND DATES COVERED
Final, 1 May 89 - 1 May 90

4. TITLE AND SUBTITLE
Structural Design Issues for Electromagnetic Projectiles

5. FUNDING NUMBERS
PR: 1L162618AH80

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Ballistic Research Laboratory
ATTN: SLCBR-IB-M
Aberdeen Proving Ground, MD 21005-5066

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Ballistic Research Laboratory
ATTN: SLCBR-DD-T
Aberdeen Proving Ground, MD 21005-5066

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
BRL-TR-3299

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)
Many structural design issues in electromagnetic (EM) launch of projectiles can be analyzed by techniques used for conventional powder gun-launched projectiles. We give general design guidance and discuss analysis methods for assessment and management of EM launch loads. This information is distilled from design and analysis experience on saboted-rod kinetic energy (KE) projectiles to survive conventional launch environments. While the physics of EM launcher systems differ radically from conventional systems, many of the barrel/projectile interactions problems are similar to those encountered in conventional systems over the past 15 years. Knowledge on solving conventional KE projectile problems may then benefit the EM community. In-bore loading characteristics of concern are: (1) large axial forces; (2) rapid initial rise times and "jogs" in loading due to EM current changes; and (3) lateral loads. Transient finite element analyses of a 120-mm KE round subjected to EM and conventional loadings are presented. These help illustrate dramatic response differences between the two kinds of propulsion environments.

14. SUBJECT TERMS
electromagnetic launchers; ordnance; structural analysis; kinetic energy projectiles; transient response; projectile response; finite elements.

15. NUMBER OF PAGES
38

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAR

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1. INTRODUCTION

Electromagnetic (EM) launch technology is following a similar evolutionary path to the long history of conventional chemical propulsion gun ("powder gun") technology, only with a drastically accelerated time scale. Conventional gun technology evolved from launching crude full-bore cannonballs and slugs centuries ago to today's complicated sabot-carried kinetic energy (KE) projectiles. The EM gun technology community is attempting to do the same thing in a matter of only a few years. As with conventional systems, the successful development of EM systems requires not only a deep understanding of the physics of EM launch phenomena and related technology, but also an understanding of the structural response and integrity of the projectile during launch. Like their conventional counterparts, projectiles currently under development for EM applications are sophisticated "machines" with many interacting parts, and which must survive extremely high-g launch environments. While the authors' experience lies in the research and development of conventional KE (and artillery) projectiles, we believe that many of the hard lessons learned in that area about design for launch survivability will carry over to EM applications. This report is thus an advocacy of the use of conventional projectile structural design and analysis technology to address some of the complicated mechanical interactions encountered at launch of EM projectiles. The report is a revised and extended version of a paper originally presented at the 1990 5th Symposium of Electromagnetic Launcher Technology (Bannister et al. 1990a) and later published in the January 1990 IEEE Transactions on Magnetics (Bannister et al. 1990b). More detailed discussions of several topics are provided here which had to be dropped from the original papers due to space limitations.

The projectile configuration primarily considered is a KE antitank projectile, consisting of a long rod penetrator, or rod, made from a very dense material (but with small specific strength), fins and a windshield to complete the flight body, and a "sabot." Figure 1 portrays a conventional design of this type, the 120-mm M829 KE projectile, which we have worked with for several years. Based on our experience, we argue that for high performance launch of a design such as this, whether by conventional or EM means, the sabot design must satisfy several difficult and competing requirements stemming from the in-bore launch environment. First, the sabot is the interface between the rod and the launch tube, so its design must satisfy the requirement to provide precise, repeatable launch conditions for the rod at entry

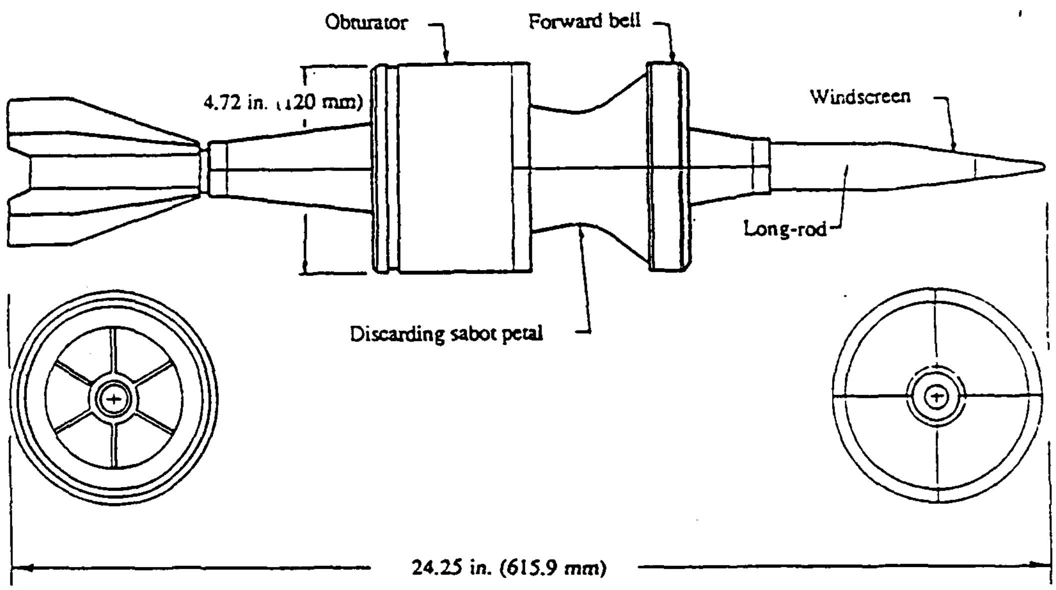


Figure 1. 120-mm M829 Saboted-Rod KE Projectile.

into free flight. Secondly, the sabot is the supporting structure which adds structural integrity to the rod during launch and hence must be structurally robust. Thirdly, the sabot usually must support an obturator to permit ease of seating at origin of the barrel, provide a seal against blow-by of gun gases, and provide a low-friction wear surface contacting the barrel. Finally, since the sabot's portion of the total projectile KE is parasitic after muzzle exit, it must have minimum weight while still satisfying all structural requirements.

Striving for further weight reductions is a worthy long-term venture in the search for a minimum sabot weight, to be sure. We believe, however, that just as in design of conventional KE projectiles, there is some danger that it can be applied too vigorously during initial feasibility demonstrations of EM projectiles. Our experience with conventionally-launched saboted projectiles is that sabot weight reductions, after a certain point in design refinement, are almost always inimical to the margin of structural integrity. Further attempts at reducing sabot weight, especially in new launch environments, can doom initial projectile design efforts. Consequently, during design feasibility studies with EM projectiles, the prudent engineer would be well advised to make use of structural overdesign until a record of repeatedly successful launches has been built up. If at all possible, the tendency to make multiple design changes between shots, in an attempt to speed up solution of a particular design flaw, should be avoided. Important cause-and-effect relationships are often completely obscured by changing too many design features at once. Furthermore, a large enough number of shots of a fixed design must be fired at maximum service load conditions to verify structural robustness. Once a robust design has been identified (but one which remains structurally overdesigned and thus too heavy), it is a candidate for subsequent design modifications to reduce weight.

2. LOADS APPLIED DURING LAUNCH OF EM PROJECTILES

The rational design of any structural component to withstand service loads requires a firm grasp of the type and magnitude of forcing functions acting on the component. While this may appear to be trivially obvious in everyday structures work, the harsh loading environment inside a gun is far from obvious to most structural designers. This unfamiliarity with interior ballistics environments leads to a surprising number of projectiles which are mistakenly overdesigned because the wrong maximum pressure is used. For example, a common mistake is to use maximum breech pressure for design purposes. In fact, because the projectile is seated well forward of the breech, it never sees such high pressures owing to the negative pressure gradient over the distance between breech and the position of the projectile base. This fact, while well known to experienced projectile designers, is often not communicated to inexperienced designers. The point we wish to make here is that the structural engineer working with ballistic launch problems must understand enough of the physical processes involved to correctly determine the nature of forcing functions, magnitudes, and mode of application to projectiles.

The major load acting during launch is the net axial force applied to the projectile from the base pressure. The axial force generates high values of axial acceleration and attendant inertial body forces. These loads are orders of magnitude larger than any others acting during launch. For example, the peak net axial force on the 120-mm M829 KE projectile is in excess of 10^6 lb. This loading is dynamic, having a period of the order 5–10 ms. An important point to make here is that conventional pressure-time histories are smooth, with a gradual buildup to peak pressure and a gradual fall-off thereafter, as shown in Figure 2. For purposes of initial design studies where the exact geometry of the projectile is in flux, structural analysis can be considerably simplified, at least to a first approximation, by ignoring all dynamic effects. One can then quickly check structural integrity of many design candidates by performing quasistatic analysis at peak pressure conditions. Peak pressure conditions are tantamount to peak axial acceleration conditions, thus this combination of external pressure and acceleration yields the "worst case" projectile stress state. Again, we emphasize this analysis strategy only makes sense for rough initial design studies. The actual in-bore loading environment is highly transient, so that at some point in the design cycle, dynamic response effects cannot be ignored and appropriate analyses must be performed.

For the case of a saboted-rod KE projectile, a rational design strategy must be adopted which leads to feasible designs which will both survive the rigors of gun launch and which can be economically manufactured. Given the myriad possibilities for sabot geometries at the outset of a design project and the complex responses and interactions of the sabot and rod during in-bore trajectory, the strategy must necessarily include sophisticated stress analysis techniques. A good example of the kind of problem requiring fairly advanced analysis solution techniques is the calculation of the distribution of interface loads along the sabot-rod interface. We have found two-dimensional (2D) and three-dimensional (3D) finite element (FE) methods to be an indispensable part of rational sabot design work. A brief discussion of FE methods and tools we have found useful for static and dynamic projectile stress analyses will be given in Section 4.

Knowledge of powerful structural analysis techniques alone is not sufficient to create shapes for feasible saboted-rod projectile designs "out of the blue." As in any design exercise, some starting point is needed, whether purely conceptual (a flash of insight in the designer's brain, for example), engineering drawings, or hardware which is known to work for a similar application or under similar conditions. This we recognize as the intuitive or creative aspect of engineering design. In the present context, fortunately, many years of work on designing conventional saboted-rod projectiles has helped us identify at least one generic geometric configuration from which many feasible designs seem to flow (Drysdale and Burns 1988). We believe that knowledge of the principles incorporated in this generic design, a

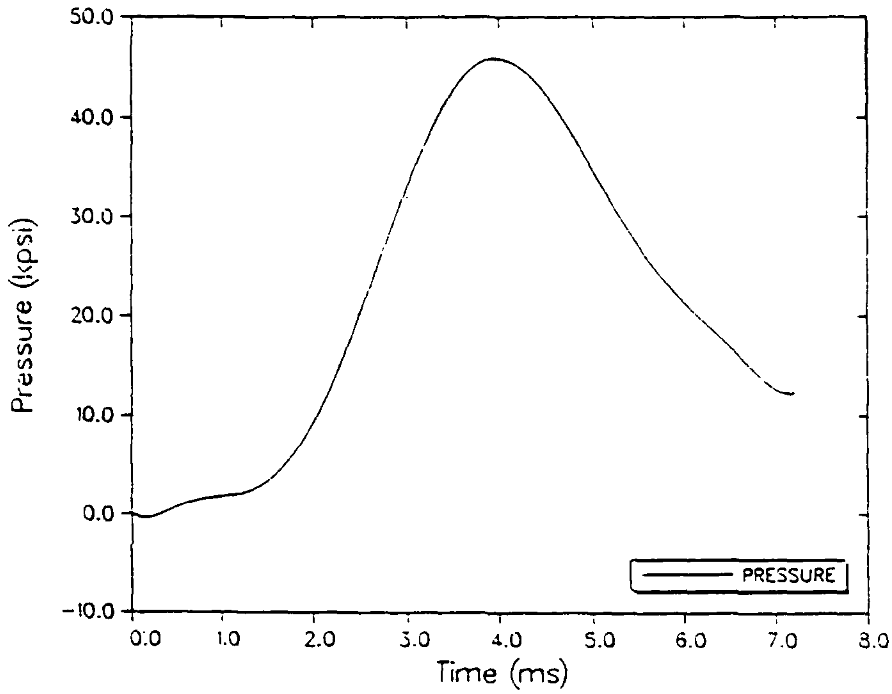


Figure 2. Conventional Base Pressure vs. Time History.

double-ramp sabot structure, may be useful to EM KE projectile designers. Because the double-ramp concept may serve at least as a point of departure in designing EM sabots, a brief description of its features is given in Section 3.

Besides the magnitude of the propulsive forces involved in gun launch, the time scale and method of application are important. It is well known in EM work that the initial loading rise time can be very short and that sharp "jogs" can appear later in the loading history. These are closely related to current waveform discontinuities which can be controlled to some extent with the aid of modern current conditioning equipment. To illustrate the consequences of irregular EM loadings, representative 2D transient FE analyses for the 120-mm M829 KE projectile will be shown in Section 5. For comparison, results for the same projectile subjected to the smooth pressure history shown in Figure 2 will also be discussed. These results dramatically illustrate the effect of a sharp initial rise in axial load on excitation of dynamic stress states in a projectile.

In conventional KE projectile analysis, the smooth base pressure history is applied over the "wetted" surfaces, or rear surfaces of the projectile exposed to the propellant gases during in-bore travel. This base pressure can be applied quasistatically as a static value of peak pressure, or as a time-dependent function, as the analysis requires. The mode of transmission of loads to EM projectiles varies with the design of the launcher system. For example, base-mounted armatures are used extensively in EM systems to provide axial propulsion. The question then arises as to how to construct a "base pressure" function for EM loading conditions which corresponds to a conventional base pressure history. The answer depends on how important the precise details of the interaction of armature and projectile at their interface are to the designer. At some distance away from this interface, say, in the main projectile body, we can expect the structural response will be relatively insensitive to details of what happens at the armature/projectile interface (this follows from consideration of St. Venant's Principle in the theory of elasticity [Timoshenko and Goodier 1970]). Near the interface, however, responses computed with a base-pressure model will obviously be approximate, at best. Preferably, to assess the validity of the base-pressure approach vs. a detailed armature/projectile interface model, we need an analysis method which can compute transient EM body force distributions in the armature. From the body force distributions realistic estimates of displacement and stress fields in the armature and projectile can be obtained. For a more complete treatment of the interface region, the model should also be able to handle sliding contact boundary conditions, with friction and void opening/closure capabilities. What is envisioned here is a modeling capability on a par with existing 3D transient continuum mechanics codes such as DYNA3D (Hallquist and Benson 1986) or PRONTO3D (Taylor and Flanagan 1989). Unfortunately, at the present time, while codes exist to handle certain aspects of the problem, no comprehensive 3D, nonlinear transient coupled electromechanical modeling capability appears to exist.

Another source of loading commonly observed in conventional projectile work is "balloting," i.e., the side-to-side in-bore motion of the projectile as it travels down the gun tube. Balloting arises from flexibility of the KE projectile and the fact that no gun barrel is ever perfectly straight. Initial clearances between sabot bore-riding surfaces and barrel are also important in the mechanics of balloting. Considerable dynamic lateral loads on the projectile can result from balloting, in some cases sufficient to plastically deform or even break the rod. These forces are applied to the sabot bore-riding surfaces to keep the projectile following the bore centerline profile. Both inherent irregularities in the barrel straightness profile, due to wear and left over from the initial barrel machining process, and gravity droop contribute to the total bore profile. The magnitude and application of the loads depend on the contour of the barrel centerline along the length of the barrel, the velocity of the projectile, and the interactions between barrel and projectile as the latter moves downbore. Because of variabilities in barrel-to-barrel profiles and other factors, we do not use, nor advocate use of "rule of thumb" procedures to estimate magnitudes of lateral accelerations. A common procedure, but one which has no technical substantiation, is to compute the maximum lateral acceleration as a small percentage of peak axial acceleration. The approach we take at the present time, at a minimum, is to resort to modeling of the entire barrel/projectile interaction cycle with the RASCAL (Erline and Kregel 1988) or SHOGUN (Hopkins 1990) gun dynamics modeling codes to extract lateral acceleration data.

Other launch-related loads of relatively less importance exist. These include the aerodynamic loads (significant for hypervelocity launch) on the front of the projectile, which can be estimated from piston theory, and obturator pressures arising from barrel engagement. Torsional loads, while very important in artillery projectile design, are obviously not important in either conventional or EM launches where no barrel rifling exists.

Finally, we consider thermal loads. In conventional guns, very high temperatures are generated by the chemical combustion of the propellant. Thermal loads and deformations can thereby be induced in the projectile and barrel through heat transfer mechanisms. Under service conditions, the duration of time of the thermal exposure of the projectile is short—a few milliseconds during firing of an individual KE projectile. Also, because of the common use of silicon rubber sealants in KE rounds, thermal effects have not been found to be a major problem for conventional gun launches. Projectile parts with thin sections, such as the tail fin blades on KE rounds, may be degraded by exposure to aerodynamic heating, but again this has not been found to be a major problem. We believe that exposure to surface heating from plasmas, such as occur in electrothermal-chemical (ETC) or plasma-armature EM launchers, should be manageable for the same reasons. Heating that occurs in the interior of a solid armature from high current flows (of order megamperes) is potentially a greater problem. The temperature in the interior of the armature, with attendant loss of material strength, might be significant even within the short time duration of a given launch. If this proves to be the case, the strength of an integral sabot/solid armature structure may be severely compromised, especially in highly loaded sabot regions. Again, a thorough assessment of these problems would require a good modeling capability for coupled thermal/current flows in realistic hardware configurations.

3. MANAGEMENT OF AXIAL LOADS DURING EM LAUNCH

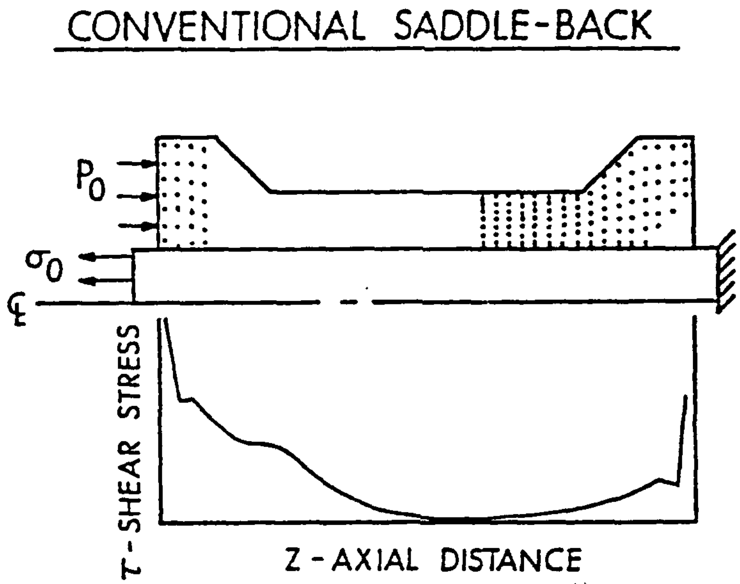
We regard the structural design issues associated with axial loads in a solid full-bore projectile, such as an artillery shell, to be elementary compared to those of a KE projectile. The propulsive force can be assumed to be applied uniformly to the base of an artillery shell. The only material properties of relevance for given shell geometry are then the elastic properties, some measure of material strength, say a maximum allowable stress, and density. Given the large inventory of existing successful artillery shell design solutions to work from, design of a new shell is a straightforward process of geometry layout and material property selection (usually good quality steel) to withstand service loads. Some consideration must also be given to fabrication and manufacturability issues during the design phase.

The situation is completely different in designing KE projectiles. The sabot and rod are joined at an interface, composed of interlocking grooves or thread forms, and therefore must deform compatibly in response to external loads. We point out though that the sabot and rod are fabricated of materials with vastly different elastic moduli and densities. Density differences result in vastly different body force distributions along the interface, given equal accelerations. Elastic modulus differences generate significant stress differences along the sabot/rod interface because of the displacement compatibility requirement. Design of these components thus requires a somewhat more sophisticated analysis capability to accurately compute states of deformation and stress along the interface. In practice, this necessitates the careful use of quasistatic and transient FE-based structural analysis methods, validated by good experimental work, as will be discussed in Section 4.

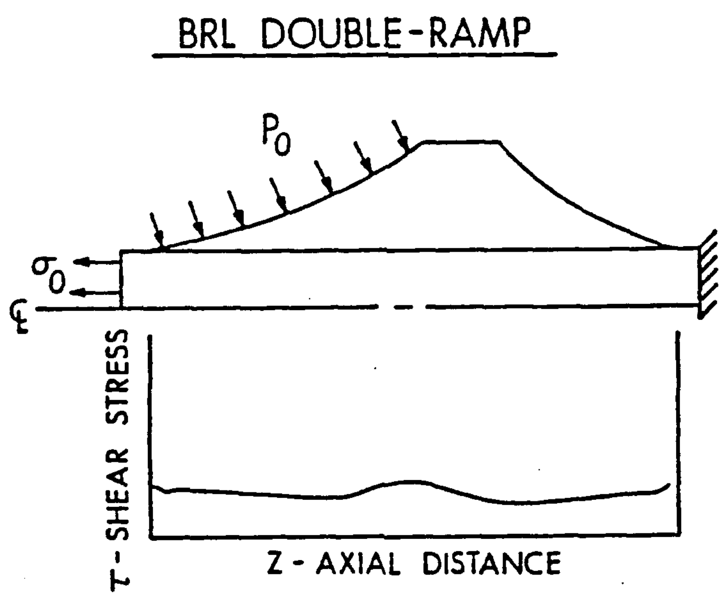
Large discontinuities in geometry or load intensify stresses and strains in projectile components. For example, notches, grooves, and re-entrant corners must be carefully considered because they act as local stress risers. Design features such as these can induce local stresses several times the prevailing globally applied stress. In every day engineering design work, this problem is exemplified by the familiar difficulties encountered in designing "nut-and-bolt" systems to withstand axial loads. The large axial stiffness discontinuity at the juncture of the nut and bolt results in a local shear stress concentration, which tends to aggravate premature failures at the first loaded thread under the nut. It has long been known that the "strength" of the joint can be increased by the simple device of tapering the nut profile, thus spreading the load over several threads and reducing the shear stress concentration.

In dealing with these general load management problems in the design of saboted-rod projectiles, a design philosophy based on the notion of a double-ramped sabot configuration has been successfully built up over the past few years (Drysdale and Burns 1988). Figures 3a and 3b show the results of stress analyses of a conventional flat-based saddle-back and a double-ramp saboted-rod projectile, respectively. The same conventional pressure loading history was applied to both sabots, resulting in the same total axial load being applied in both cases. Also, the loading must be supported by equal-length sabot/rod interfaces by a shear stress distribution. The advantage of the double-ramp concept in smoothing the interface shear stress distribution is immediately apparent in Figure 3b. The very high shear stresses at the aft and forward ends of the saddle-back sabot represent a severe structural integrity problem which is easily alleviated, as can be seen, by incorporating tapered aft and forward surfaces on the sabot.

Despite the advantage in smoothing out the distribution of shear stress along the sabot/rod interface offered by the double-ramp sabot concept, EM projectile designers appear to frequently adopt a flat-backed sabot geometry as an initial design configuration. This is done apparently to ease integration of the projectile with a flat-front solid armature. If this tack is taken, then we argue that a detailed analysis of the projectile/armature interface should be included as part of the stress analysis. The reason for this is that the interaction of these parts cannot be known a priori without solving what is a very difficult deformation mechanics problem. The problem is made even more difficult if we include the sliding contact surface between armature and projectile, for then the problem is highly nonlinear. Strictly speaking, it is not possible, even if desirable, to apply the accelerating force from a solid armature as a uniform pressure over the rear surface of the projectile body. Likewise, a "rigid" pusher plate accelerating the projectile body is an equally unwarranted and unrealistic assumption of the



(a) Conventional Saddle-Back Contour



(b) BRL Double-Ramp Contour

Figure 3. Interface Shear Stress Profiles Showing Dependence on Sabot Contour.

nature of the mechanical interactions at the interface. Finally, the high shear state at the sabot/rod juncture just forward of the armature/projectile interface (see Figure 3a) remains a potential design problem. These difficulties again point up the need for a good EM projectile modeling capability.

4. TOOLS FOR THE ASSESSMENT OF STRUCTURAL INTEGRITY

In this section, we discuss numerical modeling methods and tools we have found appropriate for conventional KE projectile stress analysis. For the complicated projectiles being considered, consisting of arbitrarily shaped interacting components with vastly different material properties, the FE method can be used to gain insight into structural integrity problems. While free-body diagrams and elementary "strength of materials" approaches are useful for first-cut studies, in general, they cannot solve realistic dynamic interaction problems of the kind encountered in KE projectile design. For example, the results shown in Figure 3 could not have been obtained by elementary methods. Static linearly elastic 2D FE codes can be used to study the projectile response at peak axial load conditions. NIKE2D (Hallquist 1986), SAASIII (Crose 1971), SAPIV (Bathe 1973), ABAQUS (Hibbett 1985), and ANSYS (DeSalvo 1987) are codes that provide good static linear elastic analysis capabilities. Dynamic nonlinear 2D FE analyses require more computer resources, but important effects of dynamic response and material and geometric nonlinearities are captured. NIKE2D, ANSYS, ABAQUS, DYNA2D (Hallquist 1984), and PRONTO2D (Taylor and Flanagan 1987) provide good capabilities for this class of problems. DYNA2D and PRONTO2D are especially useful for projectile response work because of their ability to handle highly transient phenomena such as wave propagation. Capability to handle multiple materials and nonlinear material behavior are also very important. For example, plastic obturators are often used in 120-mm KE projectiles. Plastic material properties are temperature-dependent and sensitive to strain and strain rate. Accurate modeling of plastic obturators during barrel engagement requires constitutive models which cover large strains, significant strain rate effects, and temperature dependence. Two-dimensional rezoning, available in DYNA2D and NIKE2D, greatly aids accurate tracking of the changing shape of the obturators in calculations of this type. Boundary Element Methods (BEM), based on older classical boundary integral methods, can also be used to solve these problems. However, at the present time, in our view at least, commercially available BEM codes are not as general, robust, or user-friendly as FE codes for solving in-bore structure mechanics problems.

When we move to 3D launch modeling (e.g., simulating dynamic axial, lateral, and spin [torsional] environments of the projectile, including tube gravity droop and inherent nonstraightness, eccentric breech masses, and sabot petal asymmetry), then we must resort to good 3D dynamic nonlinear FE codes. Codes such as DYNA3D (Hallquist and Benson 1986), PRONTO3D (Taylor and Flanagan 1989), ABAQUS, ANSYS, and NIKE3D (Hallquist 1984) have many of the 3D modeling features needed for this purpose. Of these, DYNA3D and PRONTO3D appear to have the specific transient response analysis and postprocessing capabilities needed for barrel/projectile analyses of the kind discussed here.

In order to reach correct conclusions about structural integrity based on a projectile stress analysis, it is important to model the entire relevant system. The beauty of the FE method is that, for the cost of a few extra elements, very fine details of the interactions at any armature/projectile/sabot/rod interfaces can in principle be modeled. We hasten to point out, however, that because the armature and projectile may slide relative to each other or separate along the interface, the problem is basically a nonlinear contact problem. This means that in choosing an FE code to solve the problem, the analyst should be sure the code formulation includes adequate contact ("slide line") algorithms. In any case, with such an FE code it is not necessary or desirable to make simplifying assumptions about the nature of the armature loading upon the projectile, or any interactions arising therefrom; model the entire system!

That point emphasized, it should be noted that the cost of FE calculations is strongly dependent on the number of elements (or nodes) in the mesh used. In view of this, one then ought to use the simplest applicable FE model. Thus, to assess the structural adequacy of a conventionally-launched KE projectile subjected to high axial loads, a 2D axisymmetric FE analysis is sufficient in most cases. Only when balloting (lateral vibration) behavior must be considered will it be necessary to perform a full 3D analysis. Furthermore, if the stresses in the projectile are kept below the prevailing material yield stresses, except perhaps in isolated localized regions, linearly elastic material properties may be used. In contrast, when extensive plastic deformation occurs in a cross section of the projectile, an elastic-plastic or even elastic-viscoplastic material model may be required. As might be expected, going from a

2D to a 3D FE analysis, or adding nonlinear material effects, is costly both in computer and analyst time. A decision to go to 3D modeling should never be taken lightly. In addition, the question of whether a quasistatic or dynamic analysis is warranted is very important, as will be discussed in Section 5. Consideration of how to apply EM forces will be covered in Section 6.

5. QUASISTATIC vs. DYNAMIC MODELING

As with FE modeling of conventional artillery and KE projectiles, the issue of whether a quasistatic or dynamic analysis is appropriate applies to EM projectiles. We assume otherwise that fully nonlinear 2D or 3D analyses will be the norm, and that fairly long flexible KE-type configurations are of interest. We also make the perhaps drastic assumption that computer and manpower costs are not critical. In reality, of course, there is little question that cost considerations favor quasistatic over dynamic analyses, and, moreover, 2D analyses are preferred over 3D analyses! Of course lack of access to good, general-purpose nonlinear dynamic FE software is often a key limiting factor. In solid structural modeling at large, criteria such as strain rate or duration of load vs. fundamental periods of vibration of the structure are used to decide which analysis approach to follow in practice. Our approach in KE projectile studies in recent years has been to first conduct quasistatic 2D axisymmetric analyses to check basic structural survival of the projectile under peak acceleration loads (typically in the range of 50,000–100,000 g's). Dynamic 2D or 3D analyses are then conducted as required. The availability of robust dynamic FE software in recent years has made the dynamic analysis step very nearly automatic. It turns out that there are, in general, several compelling reasons to perform dynamic analyses:

(1) quasistatic analyses are at best approximate representations of the true in-bore response, which is fundamentally dynamic;

(2) pressure waves and solid phase propellant grain impacts on the projectile may be present during propellant burning;

(3) engraving processes of KE round plastic obturators lead to high strain rates (of order 1,000 s);

(4) in artillery projectiles, tube wear/erosion leads to torsional impulse on the projectile (torsional impulse is defined as an unexpected large torsional acceleration near time of shot start);

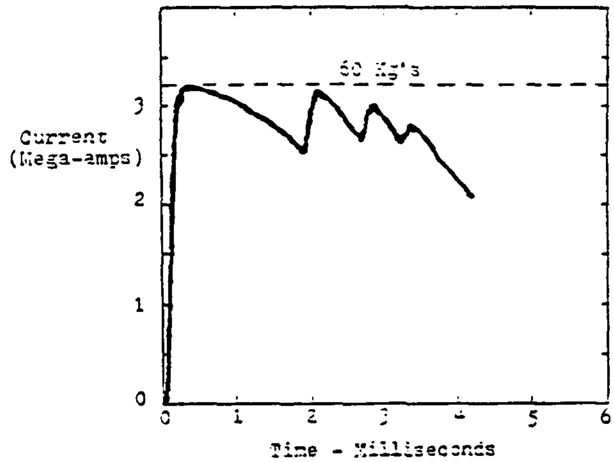
(5) projectile/barrel interactions due to tube crookedness and lateral asymmetries lead to significant lateral accelerations; and

(6) the projectile undergoes rapid unloading at muzzle exit.

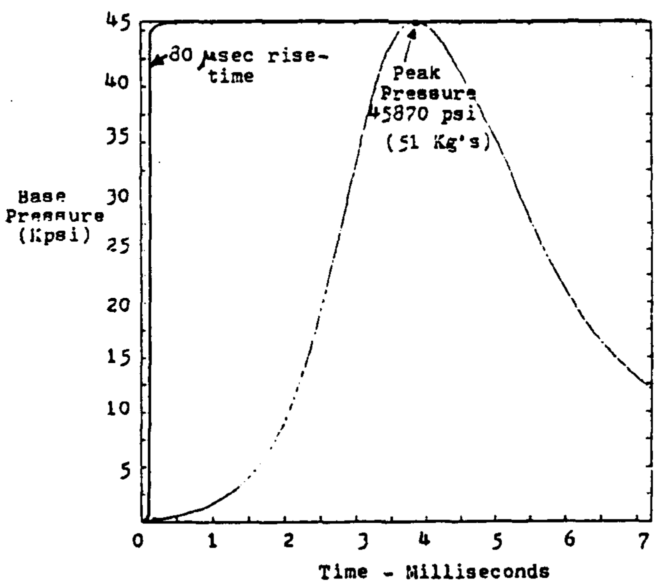
Of these, reason (5) is especially important for flexible KE rounds (and thus, similarly for EM rounds); lateral motions induced in-bore persist after muzzle exit and affect accuracy on the target. For EM launch, any power supply-induced current oscillations, as well as transient diffusion effects, may possibly generate phenomena similar to those described in (2) above.

Figure 4a shows a sample armature current-time history for an EM launcher (adapted from LTV Corporation 1989). We assume, in this case, that axial acceleration body forces are proportional to the magnitude of the current by scaling the peak current to an acceleration of 60,000 g's. This time-history is presented only for the sake of discussion, and is by no means typical of the current waveforms available from the wide variety of electrical launching systems now under development. Other types of experimental EM launchers may have different current-time characteristics. As mentioned in Section 2, some systems allow control over the shape of the current-time history. A chemical propulsion phase may be used to preaccelerate the projectile before it enters the electrical propulsion phase. The value of the latter systems is that the very rapid initial rise time and the oscillations can be mitigated. The conventional base pressure history of Figure 2 is redrawn in Figure 4b to illustrate the much smoother time dependence of this loading in comparison to the jagged EM curve.

In Figure 4b, an 80 μs (< 0.1 ms) rise-time P–t curve is overlaid on the conventional P–t history. This curve reflects the unusually rapid early rise-time characteristic which, out of all the possible EM loading histories which can be envisioned, is an entirely admissible candidate for study. The EM P–t curve is assumed to be flat after the initial rise, and has a maximum pressure value matching that of the powder gun, 45,870 psi, and the same maximum axial acceleration of 51,000 g's. Of particular interest in the dynamic stress analysis is the



(a) Sample EM Current-Time History.



(b) Conventional and Simulated EM Early Rise-Time Pressure-Time Histories.

Figure 4. Base Pressure-Time Histories.

projectile's response to the sharp rise time (< 0.1 ms) evinced in the EM loading history. To be sure, the strong oscillations we see later in the EM history shown in Figure 4a are indeed of concern, but the projectile must first survive the initial rapid pulse loading. This sharp initial pulse has a dramatic effect on the transient response of the projectile, as will be shown in Section 6. From the modeling standpoint, it also means that dynamic (transient) rather than quasistatic FE analysis techniques must be used.

6. APPLICATION OF EM FORCES

To illustrate the differences in modeling structural responses of KE projectiles to rapid pulse loadings, dynamic FE analyses of a representative 120-mm KE round (the M829 design shown in Figure 1) were performed using the DYNA2D FE code (Hallquist 1984) and the loading curves shown in Figure 4b. We were particularly concerned with the effect of the initial rise time of the EM loading history shown in Figure 4, which for our purposes was taken to be 80 μs. Strictly speaking, the EM base loading is not an axisymmetric pressure boundary condition as we have assumed, but is, in fact, a complicated 3D, electrically-induced body force distribution. In general, the electrically-induced body force density, f, for given armature current density, J, and magnetic field, B, is given by the vector equation

$$f = J \times B,$$

where we take the axial (z-component) or down-bore component of the force, f, as the major driving force which propels the armature/projectile combination. The precise nature of how the forces are applied to the base of the projectile by the armature needs further comment. The propulsive forces are generated by the current flowing through a magnetic field, and so should be calculated by solving the transient 3D electrical boundary value problem. Even for seemingly simple 2D axisymmetric projectile geometries launched from rail gun systems, the current will flow from rail-to-rail, i.e., across the diameter of the projectile, so that the EM body forces will take on some complicated 3D distribution. We need to keep in mind, therefore, that the axisymmetric modeling approach we have employed here can only be viewed as approximate.

From the standpoint of FE modeling of fully coupled transient 3D EM-mechanical effects, the U.S. Army Ballistic Research Laboratory (BRL), at the present time, has no readily available computational tools. What is needed is an accurate numerical means of modeling the transient 3D J and B fields for a given EM launch environment, armature/projectile configuration, and choice of materials. Work is progressing at BRL on the development of 2D transient analysis techniques which treat a rectangular armature in a realistic manner (Powell 1990). Work is also underway at the University of Texas-Austin Center for Electromagnetics (CEM) on an FE analysis capability for transient 3D EM effects and future CEM efforts will be directed at developing a 3D transient coupled electromechanical model (Price 1990). For the present purpose, this means that precise details of the transient 3D body force distribution are not known. To get around this difficulty, we have assumed that since the function of the armature is to transmit the total axial load to the base of the projectile, then the existing DYNA2D FE methodology developed for conventional base-pressure loaded KE rounds can be used. In the DYNA2D calculations, the pressure-time curve in Figure 4b denoted "80 μs rise time" was used to simulate the net effect of the EM loading environment on the KE round. A companion DYNA2D calculation was done for the conventional P–t history curve in Figure 4b for comparison purposes.

Figure 5 shows the simplified version of the 120-mm projectile portrayed in Figure 1 used in the calculations reported here. The grid shown in the lower portion of Figure 5 was employed in the transient DYNA2D calculations. Figure 6 shows the resulting axial stress histories for the conventional case. These stress histories are taken at points A, B, and C on the rod centerline, as indicated. It can be seen from Figure 6 that the response to the conventional P–t history is relatively smooth and well-behaved. This is expected, given the smooth shape of the applied base pressure history. A maximum compressive stress of approximately 80,000 psi was attained at about the time of peak loading (4.0 ms) for the smooth P–t history. In contrast, in Figure 7 we see that the sharp rise-time EM loading response at point C (the worst of the responses at the three points A, B, and C) appears to generate very large amplitude stresses (220,000 psi, which is well above the rod material yield stress) and subsequent wild oscillations in time. For direct comparison, the conventional response curve for point C from Figure 6 is superimposed on Figure 7. The strong oscillations can most likely be attributed to stress waves being generated in response to the initial pulse (which has a rise time roughly equal to the wave transit time in the rod) and then

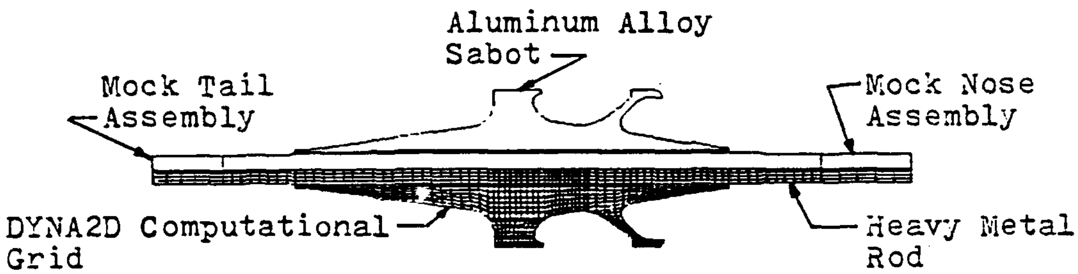


Figure 5. DYNA2D Model of 120-mm M829 Saboted-Rod KE Projectile.

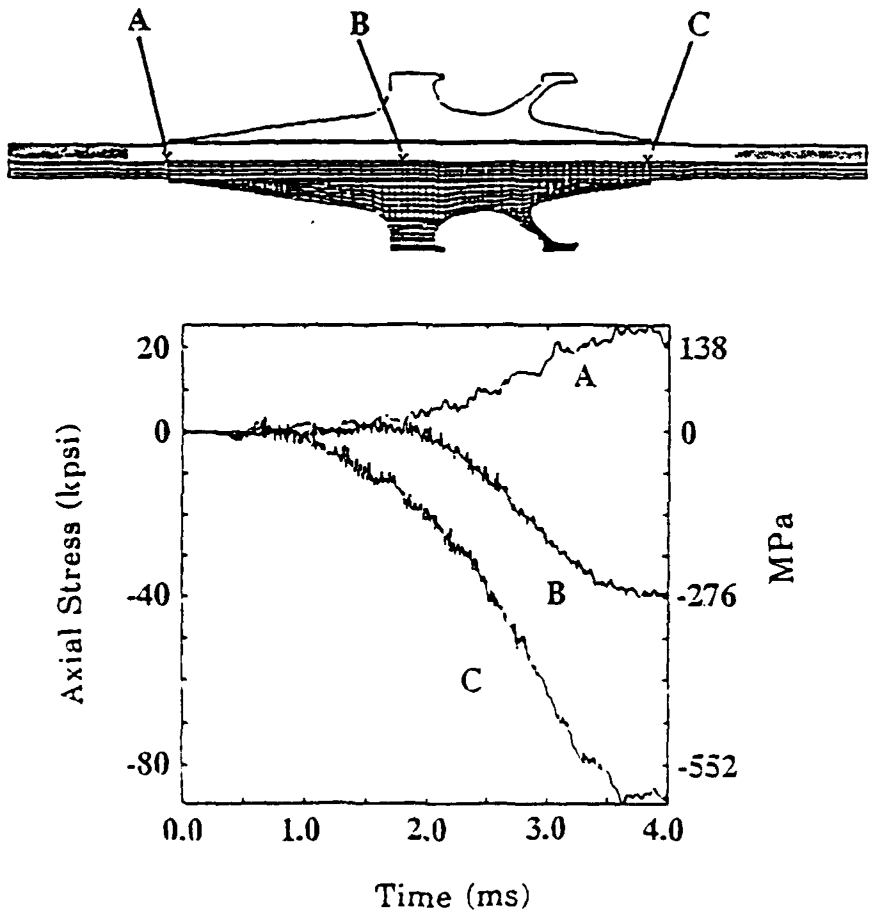


Figure 6. DYNA2D-Computed Axial Stress Histories in Response to Conventional Base Pressure History.

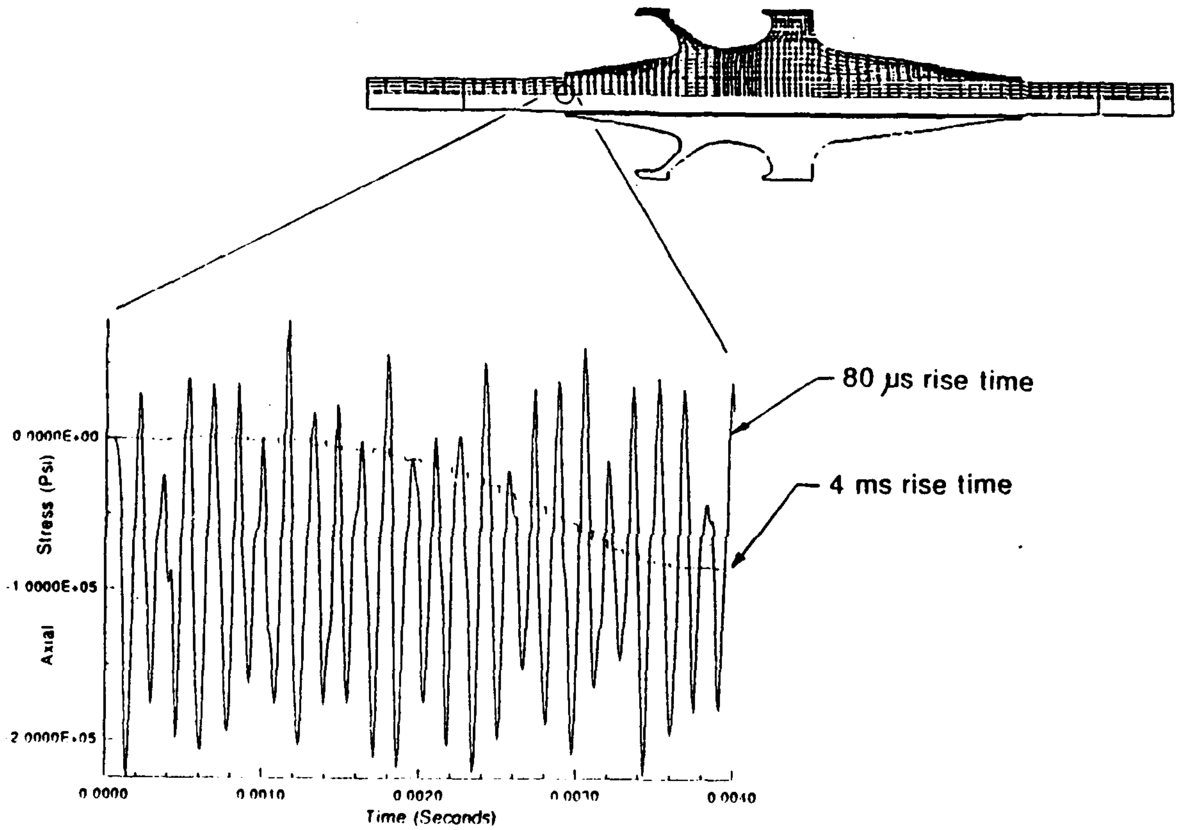


Figure 7. DYNA2D-Computed Axial Stress History at Point C in Response to Sharp Rise-Time EM Loading.

propagating along the rod. No damping is provided, so the waves continue to propagate back-and-forth along the rod. This is why the oscillations do not decay away, even at times long after the pulse flattens out.

These results suggest that drastic differences exist between the effects of the two kinds of loading histories. They also point up the fact that rapid loading rate and load oscillation problems need careful attention using dynamic FE analysis techniques. It would appear that smoothing of the initial pulse in EM loadings, and the elimination of later current oscillations, would greatly simplify the task of designing EM projectiles to survive launch. Clearly, if the response environments differ by the margins shown here, a great deal of work remains to be done in analyzing and designing EM projectiles.

7. EM LAUNCH TUBES AND TRANSVERSE LOADS

As discussed in Section 2, the second largest load applied to a projectile, after the axial propulsive force, is that due to balloting or transverse motion of the projectile and resulting interactions with the gun barrel. The causes of this transverse motion are the initial clearances between the projectile and barrel and the nonstraightness of the barrel, a characteristic of all real gun barrels. The projectile, being an elastic body, undergoes dynamic bending as it attempts to follow the shape of the barrel. Of course, the barrel itself is an elastic body and moves as the projectile travels along it. A very complicated dynamic elastic motion results from this projectile/barrel interaction which is amenable to at least two modeling approaches which will be discussed shortly. We now consider the problem of estimating the lateral acceleration.

A reasonable approximation of the transverse acceleration component can be obtained as follows. For the moment, consider the projectile and gun barrel to be rigid. Under this assumption, and ignoring projectile length effects, the projectile motion can be described by a point mass moving along the centerline curve of the barrel. At a given point on the barrel centerline curve, the local shape of the curve can be accurately approximated by an arc of a circle whose radius is the local radius of bending curvature, R. Then a good estimate of the transverse acceleration, a, can then be gotten from the radial acceleration of the point mass as it moves on the perimeter of the circle of radius, R, as follows

$$a = R\,\omega^2;\ \omega = \text{angular velocity};$$

where the velocity of the point mass, v, is given by

$$v = R\,\omega,$$

so that we have, after eliminating ω,

$$a = v^2/R.$$

For projectiles launched in a particular tube, the lateral acceleration is seen to depend on the square of the projectile velocity. More accurate analyses show that this relationship is useful even when elastic deformations are considered. Hence, the hypervelocity conditions normally associated with EM gun firings will tend to further exaggerate the lateral loads.

We argue that, just as conventional gun barrels have variable bore straightness, EM barrels have similar problems. The current so-called "Task B" EM guns utilize copper rails which are 8–10 m in length. The extreme length of these rails makes manufacturing and installation of truly straight rails difficult. In addition, the high erosion rates of the rails leads to uneven wear, which increases the probability for rail misalignment. To date, no straightness measurements have been made on the rails of Task B guns.

Projectile/tube interactions are strongly affected by the bending and radial stiffnesses of the tube, which are obviously different for a conventional and an EM barrel. A typical barrel cross section of an EM launcher is shown in Figure 8. The copper rails (current conductors) and fiberglass sidewalls (insulators) form the barrel walls and are enclosed by a ceramic disk, which, in turn, is encased in steel. Radially, the reduced stiffness of the copper/fiberglass, due to the materials' compliancy, could result in increased lateral motion of a projectile. Also, the deviation of the axial stiffness from that of a conventional steel barrel will change the dynamic bending response of the barrel resulting from interactions with the projectile as it travels downbore.

Several techniques are currently available to model the effects of tube straightness and stiffness on the projectile's lateral loading; all of which share certain requirements. All methods require accurate measurements of the barrel centerline profile, with the barrel mounted as for firing, including gravity droop and inherent machining variations. Accurate measurements are required as it turns out that even small variations from true straightness, say on the order of only a few thousandths of an inch, will impart severe lateral loads at high projectile velocities. Bore centerline data of this kind are easily obtained in conventional barrels by using a laser beam to establish a straight line between the muzzle end and breech face (rear) of the barrel. A bore-riding "target" is then pulled through the tube, while measurements of the deviation of the target from straightness are taken at fixed axial stations (Miller 1990). The launch tube model must accurately reflect the actual stiffness due to construction of the tube and constraints due to mounting and recoil mechanisms. Finally, a consistent model reflecting the flexibility of the round is needed, especially for long KE projectiles.

The most elementary technique we have for dynamic projectile/tube interaction modeling is based on the use of structural beam models for the tube and projectile (Erline and Kregel 1988). Stiffness and mass properties for the beam elements representing the barrel and projectile are obtained by integrating over the appropriate element areas and volumes. The projectile is constrained to follow the instantaneous curved tube profile by means of springs at the projectile/tube contact points. For a KE projectile, these contacts are generally the forward bore-rider and the plastic obturator near the middle of the sabot. Determining the correct spring constants for these contact springs is nontrivial, and requires either 3D FE analyses or carefully conducted experiments to extract force-deflection data. The spring values can then be obtained by curve fits. This elementary beam element modeling approach has been found useful and relatively accurate, with solutions readily obtained in a short time by means of a personal computer (PC). It is also possible to study the effects of wide ranges of several parameters on transverse projectile motions with this PC-based method, i.e., conduct parametric design studies.

At the other extreme of modeling sophistication for the projectile/tube interaction problem is the full 3D transient FE approach, wherein the basic nonlinear governing equations of the dynamic problem are solved in time. This method requires a much larger effort than the beam-based approach, since computational grids must first be developed for the projectile and tube to describe their geometry, materials, and boundary conditions. The main FE code being used for 3D analyses at present is DYNA3D (Hallquist 1986). Figure 9 shows a DYNA3D FE code grid for a KE projectile seated in a conventional tank gun barrel. To accomplish the same level of modeling of an EM tube, for example a barrel with the cross section shown in Figure 8, would require a more complex grid to describe the rails, ceramic insulators, steel casing, and other hardware items. The problem portrayed in Figure 9 requires 8–10 hours of CPU time on a Cray YMP supercomputer (Rabern 1989) to carry the DYNA3D FE solution from shot start through to muzzle exit of the projectile. Although this model does indeed give a very faithful prediction of the total projectile/barrel interaction event, the great amount of work needed both to set up the input data and to interpret the results, plus the large amount of computer time required, make it difficult to use for parametric studies.

Designers of projectiles are presently handicapped by not having lateral loading information on any of the existing EM launch systems. The inability to accurately model the loading input can result in either underdesign of the sabot, leading to structural failure, or overdesign, meaning increased parasitic sabot mass and thus reduced round velocity and effectiveness on the target. A concerted effort should be made by the community to initiate EM barrel straightness measurements and sponsor appropriate modeling efforts to determine the lateral loading on projectiles, so as to ensure designs which have structural integrity and which are the most mass-efficient.

8. CONCLUSIONS

We believe that it would help designers of EM launch systems to become familiar with the hard-won "lessons learned" which have been accumulated in recent years in the successful design of conventionally launched KE projectiles. For instance, the partitioning of axial load between sabot and subprojectile can be managed by use of double-taper sabot geometries. With such a geometry, we recommend the use of two bore-riding surfaces, and not the use of a single midriding surface. To do otherwise may introduce severe problems in armature design and armature/projectile integration. However, to attempt getting around these problems by means of a flat-backed projectile (with accompanying stress concentrations at interfaces) could merely shift the difficulty from electrical to structural. Determination of the

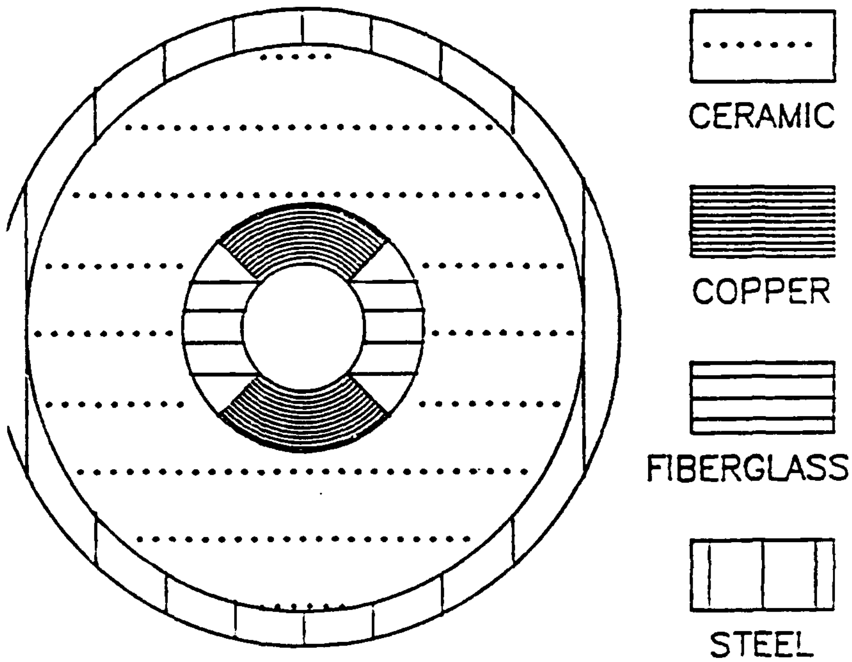


Figure 8. Schematic of Cross Section of Typical Task B EM Launch Tube.

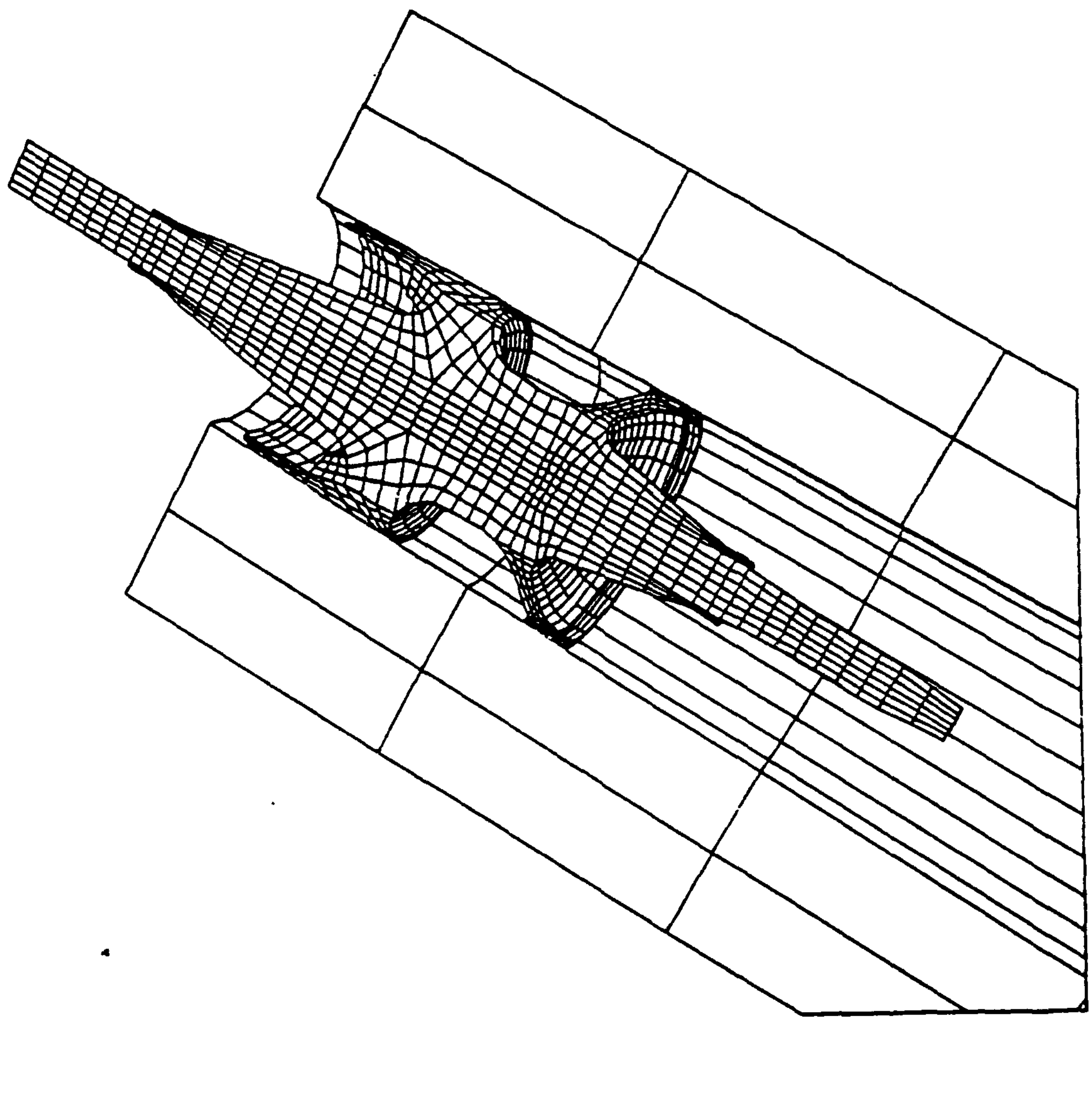


Figure 9. DYNA3D Model of 120-mm M829 Projectile Seated at Breech End of Barrel.

real structural benefits or burdens from a design change can only be done by careful analyses of the new configuration based on the mechanics of deformable solids. We regard approximate structural theories, with their customary appeals to simplified rod, beam, and cylindrical shell models, as being useful only for initial sizing studies or rough, first-cut design work. Such models give an idealized and oversimplified view of the true deformation and stress-and-strain fields in deformable bodies, and say nothing about important local effects arising from material and geometric discontinuities. This mode of thinking stems from the well-known "St. Venant's Principle" often invoked in elasticity theory to simplify solutions. We prefer to use FE methods to cope with the problems of detecting local stress concentration generated by sharp corners and material discontinuities. A good example of where such problems can interfere in the design of saboted EM projectiles is the high shear stress region which occurs along the interface of sabot and penetrator in a flat-backed sabot design. This is also clearly a situation where at least a 2D axisymmetric FE analysis should be used. In addition, even though robust numerical models of the transient 3D, fully coupled EM-solid mechanics problem do not yet exist, much can be done with existing FE methods to at least solve the structural response problem. This assumes that reasonable representations of the external loadings and body forces can be agreed upon. Even relatively approximate analyses, for example 2D FE treatments, with EM body forces replaced by surface "pressures," can illuminate quite well the key solid mechanical interactions during the in-bore travel phase.

Two examples of potential structural burdens have been discussed, namely, rapid loading effects and lateral accelerations. Excessively fast load rise times may generate stress waves of large magnitude. Without a validated dynamic material failure criterion, this effect on structural integrity can only be surmised. However, if it is within the capabilities of the electrical launch system to mitigate the sharpness of the rise times, perhaps by current shaping or by preacceleration of the projectile by chemical propulsion, then this should be done. By reducing or eliminating propagating stress waves from the projectile, the probability of successful launch is greatly increased. Likewise, requiring a projectile to withstand arbitrary levels of lateral acceleration will not necessarily increase its ability to survive launch, but will certainly increase its weight. Dynamic models which will give realistic estimates of lateral loads, based on actual bore profile data and launch conditions, are available for use in EM design. If the projectile is unable to withstand these lateral loads, despite best efforts at design (including even a second look at a midriding sabot), perhaps more stringent bore straightness requirements must be invoked. Only rigorous projectile/barrel interaction analyses will show if this is needed in a given hypervelocity launch situation.

When a concept, say a projectile, leaves the research phase and enters engineering development where it begins integration into a combat-ready system, the process from there on to completion is one of "weaponization." It is during weaponization when incidental problems of the underlying technology, such as structural robustness, reliability, and safety are addressed. This is also the first time in the item's development, if it is gun-launched hardware, where structural integrity becomes an important component of success and so comes under close scrutiny. Structural integrity is often overlooked in the early research phase because laboratory prototypes are often designed to avoid unnecessary structural complications. In gun-launched hardware, many ballistics technologies are represented in a weaponized system. Interior ballistics, aeroballistics, terminal ballistics, and vulnerability studies are all involved. If each of these disciplines is not well integrated into the final hardware design (i.e., projectile), then the system is very likely to fall short of some of its performance requirements. In the case of projectiles, and KE projectiles specifically, poor integration of structural integrity into the design process can lead to catastrophic in-bore failures, with often devastating effects on hard-to-replace launch tubes. In conclusion, our experience in developing conventionally-launched KE projectiles has been that the earlier in the development process that personnel knowledgeable in the several ballistics disciplines are brought onboard, the more likely the benefits of their expertise will be felt, and the more likely a successful design will result early (rather than later!).

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