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AUTHOR(S): Rich F. Davidson
William A. Cook
Don A. Rabern
Norm M. Schnurr

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Los Alamos Los Alamos National Laboratory
Los Alamos, New Mexico 87545

PREDICTING BORE DEFORMATIONS AND LAUNCHER STRESSES IN RAILGUNS

R. F. Davidson, W. A. Cook, D. A. Rabern, N. M. Schnurr

Abstract - The structural responses of launchers are important because they affect the projectile performance and the operating limits of the railgun system. Structural analysis makes it possible to make better decisions in launcher design. Example analyses of the Los Alamos HIMASS and Lethality Test System launchers are presented in this paper. Also, a discussion of the benefits and limitations of these analyses is included.

INTRODUCTION

Of the many components in railgun systems, the major ones are the power supply, the switching, the launcher, and the projectile. The analyses presented here concern the design of the launcher portion of the railgun system. Design considerations for the launcher include the firing loads and projectile/bore interaction.

The firing loads in the launchers are often very large. For example, plasma pressures of 30 kpsi and magnetic rail forces of 30 klb/in. are common. Large firing loads are desirable because they allow shorter launchers or higher projectile velocities. The opposing design goal is to minimize damage in the launcher.

The success of a railgun system is also affected by projectile/bore interaction effects such as plasma blow-by, projectile pinching, and armature contact (for solid armatures). Minimizing the motion of the bore components of a launcher is beneficial in all these respects.

Launcher design has the additional complication that two portions of the bore must consist of conducting materials that are separated from each other and surrounded by insulating materials. This requirement prevents the use of simple, homogeneous, continuous cylindrical bores (as in conventional powder guns). The two rail-containing methods commonly used in launchers are fiber-wound and bolted-anvil designs.

This paper discusses some methods that can be used to determine the structural performance characteristics of railgun launchers. Specific examples are used to illustrate the methods of analysis and types of results obtained. The benefits and limitations of these methods of analysis are also presented. The examples are the Los Alamos HIMASS and Lethality Test System (LTS) railgun system launcher designs. These designs are shown in Figs. 1 and 2, and their performance and physical characteristics are summarized in Table 1. The HIMASS and LTS launchers use fiber-wound and bolted-anvil containment designs, respectively.

FIBER-WINDING ANALYSIS OF A FIBER-WOUND SHELL DESIGN - HIMASS II

An analysis of the fiber-winding operation was performed to determine the preload in the bore components and to assure that the inner fiber windings were not crushed. In launcher design, the larger the

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The authors are with Los Alamos National Laboratory, P. O. Box 1663, Los Alamos, NM 87545.

Fig. 1. HIMASS II launcher cross section.

Fig. 2. LTS launcher cross section.

preload, the better the design; however, our experience indicates that it is difficult to achieve high preload with fiber windings. At high winding tensions, strand breakage is a major problem. Also, the winding tension in the outer layers reduces the preload in the inner windings. If the winding tension in the outer layers is too large, the inner layers are crushed. The resulting buckled fibers are ineffective in resisting the firing loads. When HIMASS I was manufactured, the inner windings collapsed during the winding process. The winding of HIMASS II was more successful, but the preload achieved was smaller than desired.

TABLE I

HIMASS AND LTS RAILGUN CHARACTERISTICS

	HIMASS	LTS
Bore Diameter (in.)	4	1
Launcher Length (ft)	5	72
Projectile Mass		
(lb)	1.2-2.5	0.03-0.06
(g)	600-1200	15-30
Projectile Velocity		
(ft/s)	3000-6000	40,000-50,000
(km/s)	1-2	12-15
Structural Containment	Kevlar wrap	Bolted steel anvil
Typical Bore Pressure		
(kpsi)	40	30
Typical Rail Force		
(klb/in.)	170	25
Peak Current (MA)	3.0-4.0	1.0-1.3
Power Source	High-explosive helical generator	A staged railgun using transformers charged by traction motors

The fiber-winding problem was solved by using a plane strain Finite Element Method (FEM) model of the launcher cross section (Fig. 3). This method provided the final fiber tensions, the internal component stresses, and the rail/sidewall preload. Each successive winding layer was artificially cooled by an appropriate amount to model its winding tension. The artificial temperatures were used to simulate the tensions in each layer were determined from the winding tension for that layer by means of trial and error.

The resulting stress distribution through the winding layers, after adding the first three winding-layer forces, is shown as the Step 3 result in Fig. 4. The location of this stress distribution is marked "A" in Fig. 3. Step 9 in Fig. 4 shows the final stress distribution after all nine winding-layer forces were activated in the model. Note that the final stress distribution is not simply the winding

Fig. 3. HIMASS II FEM model. (The letters A-E are the locations of responses discussed in the analyses sections.)

Fig. 4. Winding layer stress distribution for load Steps 3 and 9. (Along Line A in Fig. 3 from inside to outside.)

tension on each layer. The maximum preload obtained on the rail/sidewall interface (D in Fig. 3) was 38 klb/in. This is small compared with the maximum applied loads of 170 klb/in. magnetic rail force and 30 kpsi plasma pressure. This final prestress distribution was used as an initial condition for the firing loads structural analysis.

PRELOAD ANALYSIS OF A BOLTED ANVIL DESIGN - LTS

The bore components of a launcher are usually separate rail and insulator pieces. The bolted anvil design is a common method used to hold these parts together under firing loads. The Los Alamos LTS (Fig. 2) is an example of such a design. The object of this design concept is to use the bolt preload to hold the components in such intimate contact that no separation can occur during firing. If separation occurs, plasma can penetrate into the launcher structure and possibly cause an electrical short between the rails. Furthermore, the rebound loads are much higher when the internal components are allowed to separate than when they are held in intimate contact. An analysis was done to determine the maximum bolt preload that can be obtained without causing the internal components to fail. This will enable us to determine the largest possible firing loads that can be applied to the launcher components and still prevent separation of these components.

A two-dimensional plane strain FEM model was used in this analysis (Fig. 5). The bolts were artificially cooled to simulate the bolt tension. The stress distribution on the rail/sidewall interface (Location A in Fig. 5) and the stress level in all the internal components were monitored.

The goal of this preload analysis was to develop a uniform normal stress distribution on the rail/G-10 interface. A uniform stress distribution provides the largest preload that can be applied at incipient failure in the G-10 sidewall. A small chamfer was cut into the G-10 sidewall to obtain a more uniform stress distribution. Figure 5 shows the prestress distributions on the rail/sidewall interface with and without the chamfer. Note that the chamfer reduced

Fig. 5. LTS FEM model. (The letters A and B are the locations of responses discussed in the analysis sections.)

Fig. 6. Stress distribution on rail/sidewall interface. (Along Line A in Fig. 6 from inside to outside.)

the peak stress by 25% while maintaining the same total preload on the interface.

The final preload values on the components are shown in Fig. 7. A simple equilibrium balance approach can be used to determine the relationship between the bolt preloads and the rail/sidewall interface preload. These results, also shown in Fig. 7, indicate that a reasonable preload estimate can be made without an FEM analysis.

The preload stress state obtained from the FEM analysis was used as an initial condition for the firing loads analysis. The firing loads analyses for the HIMASS and LTS launchers are described in the next section.

Fig. 7. LTS preload distribution calculated by FEM (and by equilibrium balance). P is the bolt preload.

FIRING LOADS ANALYSIS OF LAUNCHERS - HIMASS AND LTS

The ultimate test of a launcher is the firing loads. The launcher must not deform so much that the projectile acceleration is altered. Also, if the launcher is to be reused with minimal repair, the launcher components must not be over-stressed.

There are two components of firing loads for arc-driven railguns: the plasma pressure and the magnetic rail force. The plasma pressure acts like an internal pressure on the bore components (the rails and the insulators). The magnetic rail force acts on the rails in such a way as to try to push them away from each other. These forces interact to load the launcher in a manner that is dependent upon projectile velocity and arc dynamics. The most severe loading conditions generally occur when the current is highest.

A two-dimensional plane strain FEM model was used for the dynamic firing loads analysis. The applied loads were the plasma pressure, magnetic rail force, and preload. The results from these analyses included the bore deformations, gaps, and component stresses. These quantities were determined for the most severe loading conditions.

The HIMASS II launcher (Figs. 1 and 3) was fired in October 1985. The bore pressure and rail force loads were estimated from rail current and projectile acceleration data obtained during the test. The maximum load conditions are shown in Fig. 8. The rail force is shown as an equivalent pressure on the rails. This load condition occurs in the control volume behind the projectile start location.

Figure 9 shows the rail and sidewall movements as a function of time. These movements depict the bore deformations. Note that the bore shape at any time was quite complex. The sidewall responds to the bore pressure, but not to the magnetic rail force. Because of rail inertia, the rail responds much more slowly to the plasma pressure than to the sidewall. Figure 10 shows the gap between the rail and the

Fig. 8. HIMASS II maximum loads for October 1985 test.

Fig. 9. Bore deformations in HIMASS II (October 1985 test maximum loads).

sidewall (Location D in Fig. 3). The small preload used in this design allowed the interface between the rail and sidewall to open quickly and to stay open for a relatively long time. The maximum opening was about 1/8 in. at 150 μ s.

Figure 11 shows the critical stresses for this firing load condition. The highest stress in the Kevlar is 300 kpsi at Location E in Fig. 3. The anticipated tensile failure stress is 200 kpsi for this 55% wrap of Kevlar 49. The largest compressive stress in the G-10 sidewall (Location F in Fig. 3) is 80 ksi during rebound when the rail/sidewall gap closes at approximately 450 μ s. Material failure is anticipated at compressive stresses of 50 to 60 kpsi in the G-10 sidewall. Some material failure is expected at both of these high-stress locations. As of this date, it has not been possible to inspect these parts to determine whether or not material failure occurred.

As of this time, the LTS Launcher has not been fired. The three load cases for the baseline design are shown in Fig. 12. Three separate load cases exist because there are three current peaks in this staged

Fig. 10. Rail/sidewall gap in HIMASS II (October 1985 test). (Location D in Fig. 3.)

Fig. 11. Critical stresses in HIMASS II (October 1985 test).

railgun. All three cases are considered because it is not obvious which is most severe without considering the interaction with a particular launcher geometry. The rail force loads are shown as equivalent pressures on the bore surface of the rails. The three current peaks occur at 1.2, 31, and 53 ft along the length of the launcher. The zero times shown in Fig. 12 for each load case correspond to 54, 1030, and 1600 μ s, respectively after railgun firing.

Figure 13 shows the rail displacements for the three load cases (Location B, Fig. 5). The peak for the third load case gives the largest rail displacements, but only the second load case causes a rail/sidewall separation. Figure 14 shows the separation for the second load case. Note that the separation never goes the full length of the interface. The model results indicate that the polycarbonate bore liner can seal the rail/sidewall gap, thus preventing arc products from getting into the gap. However, the polycarbonate may intrude into the gap. This could have the benefit of reducing the large rebound stresses in the G-10 sidewall. However, the polycarbonate intrusion could also prevent the bore from

Fig. 12. LTS baseline design loads (case L41).

Fig. 14. LTS rail/sidewall gap (baseline load case).

Fig. 13. LTS rail deflections (baseline load case).

Fig. 15. LTS sidewall compressive stresses (baseline load case).

returning to the desired round shape after firing. The large compressive stress in the G-10 sidewall on rebound (see the second load case in Fig. 15 at 75 μs) is considered the most likely failure area in this design. The anticipated failure stress for the G-10 sidewall is 50 to 60 ksi in compression.

LIMITATIONS OF ANALYSIS APPROACH

The computer programs used for the FEM analysis were NIKE and DYNA [1,2]. These continuum modeling programs have some very advanced features including the latest material models and slide line interfaces. The slide line algorithms are not ideal in that they allow some penetration and offer some resistance to sliding and separation. These errors are considered small in terms of the overall response of the structure.

The material models available today throughout the FEM community are quite good for modeling isotropic ductile materials with a well-defined yield criterion. However, there are no appropriate models for predicting material performance near failure for

nonisotropic, nonlinear, and brittle materials. The lack of suitable material models leaves an area for potential errors in this analysis approach.

The STRAPP program, written by Francisco Guerra at the Los Alamos National Laboratory, is used to post-process and analyze the results from the FEM programs. This program uses the Gauss point stress and strain information to determine nodal point values by interpolation and/or extrapolation. The results thus achieved are no better than the appropriateness of the interpolation scheme at that location in the FEM mesh. A fine mesh in the region of interest is required to obtain good results.

The LARGE program [3] is used to compute the loading functions on the launcher. These calculations use some assumptions concerning the current distribution, arc ablation, arc drag, and the computation of arc length that have not yet been confirmed by experiment. Changes in the arc length or current distribution in the arc can readily change the load functions. A comparison of LTS firing load cases 2

and 3 emphasizes that small changes in the load functions can have large effects in the structural response of a launcher.

The bore pressure and rail force are generally assumed to interact in the fashion shown in Fig. 12. This is a reasonable assumption when the projectile is at high velocity. In this case, the load pulse arrives at a given launcher location in an orderly manner, with the rail force rising as the bore pressure decays.

At lower projectile velocities, the interaction between bore pressure and rail force is not so clear. For HIMASS, the projectile started at rest with a control volume or sealed volume behind the projectile where the arc first formed. When the current peaked, the projectile had barely moved. In this case, the bore pressure and rail force were considered to rise together over the entire control volume as shown in Fig. 8.

The analyses presented here all use two-dimensional plane strain FEM models. The launchers and the fiber-winding load and bolt preload are geometrically two dimensional. However, the firing loads are three dimensional as the projectile and current move down the length of the launcher. The longitudinal bending stiffness of the launcher then interacts with the loading in a way that cannot be predicted with a two-dimensional model. Some preliminary work has been done with the HIMASS and LTS launchers to predict the longitudinal bending effects on bore deformations. The large steel and copper beam structures in the HIMASS launcher (Fig. 1) had a large bending stiffness effect while the bending stiffness of the LTS rail (Fig. 2) was negligible.

BENEFITS OF STRUCTURAL ANALYSIS

The primary benefits of structural analysis are as a design tool. For these two launchers, several design benefits have been derived from these analyses.

HIMASS II was successful in that the inner layers did not collapse during winding. This launcher performed well in the October 1985 shot, and has been refurbished for another firing this spring.

The polycarbonate locator blocks in the LTS launcher (Fig. 2) were discovered to be important in preload transfer. If they were too stiff, they would prevent a large portion of the bolt preload from reaching the rail/sidewall interface as desired. Chamfering the G-10 sidewall was found to be beneficial in allowing higher preload on the rail/sidewall interface. The anvil movement and rail movement under preload were characterized and the structural effects of two different rail geometries were evaluated.

CONCLUSIONS

The structural design of launchers for railgun systems is a very difficult problem. The analysis approach presented here is consistent in complexity and accuracy with the data and computational tools available. These methods have proven to be a beneficial design tool in the HIMASS and LTS launcher designs. At this time, experimental benchmark measurements are necessary to evaluate this approach and to point the direction toward improvements in the analysis approach that will prove to be beneficial in launcher design.

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