MINIMIZING RAIL DEFLECTIONS IN AN EM RAILGUN

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ABSTRACT

Electromagnetic (EM) railguns have yet to be fielded due to several technical issues that need to be worked out in the near future. One of the problems is the high electromagnetic repulsive force that pushes the rails apart and causes the armature to lose contact with them. In laboratory guns, rail deflections can be minimized by building a massive containment structure. For tactical launchers, however, there is a need to keep the containment structure as light as possible, and therefore laboratory type approaches cannot be used. This paper will look at two proposed designs for use as tactical launchers. The first design has an oval shaped cross section with thick insulators and has been studied many times in the past. The second design utilizes geometric considerations and high modulus composite fibers. In this approach, the sides of the containment are kept as flat as possible so that the fibers are highly loaded in tension as the rails attempt to separate. By using ultra high modulus fibers, a thin and light weight structure can be fabricated. This paper will describe these two approaches by analyzing their best and worst case scenarios. The best case is perfect bonding between all the parts. In that case, both the insulator and the wrap contribute to holding the rail in place. The worst case is with theoretically frictionless surfaces, where the insulator does essentially nothing in minimizing the rail deflection. By comparing the best and worst case for each of these designs, a better understanding of how to minimize rail deflections using geometric considerations can be achieved.

1. INTRODUCTION

Electromagnetic railguns are of interest to the military due to their ability to achieve muzzle velocities above two kilometers per second and the absence of propellant [McFarland et al., 2003]. Velocities above 2 km/s are important because they increase the projectile’s kinetic energy and are above what is currently possible with conventional powder guns. The lack of propellant allows for more stowed rounds and decreases the chances of sympathetic detonation.

Though electromagnetic (EM) railguns have these advantages over conventional guns they have yet to be fielded due to several technical issues that need to be worked out. The problem of interest for us in this paper is the high electromagnetic repulsive force pushing the rails apart and causing the armature to lose contact with them. In laboratory guns, rail deflections can be minimized by building a massive containment structure. For tactical launchers, however, there is a need to keep the containment structure as light as possible, and therefore laboratory type approaches cannot be used. We will look at two proposed designs for use as tactical launchers. The first design has an oval shaped cross section with thick insulators and has been studied many times in the past [Lehman et al., 2005; Tzeng, 2005; Werst et al., 2005; Hahne et al., 1995; Laughlin et al., 1993]. The second design utilizes geometric considerations and high modulus composite fibers. In this approach, the sides of the containment are kept as flat as possible so that the fibers are highly loaded in tension as the rails attempt to separate. By using ultra high modulus fibers, a thin and light weight structure can be fabricated. This paper will describe these two approaches by analyzing their best and worst case scenarios. The best case is perfect bonding between all the parts. In that case, both the insulator and the wrap contribute to holding the rail in place. The worst case is with theoretically frictionless surfaces, where the insulator does essentially nothing in minimizing the rail deflection. By comparing the best and worst case for each of these designs, a better understanding of how to minimize rail deflections using geometric considerations can be achieved.

2. DESIGN DESCRIPTIONS

The first design has a cross section shaped similar to a flattened oval with thick insulators and a composite wrap. This was used by previous programs [Freeman, 2004] and presents a low risk option for building a tactical EM railgun launcher. The rails and insulators are both fairly large. In this paper, this design will be referred to as the oval design. It is shown in Figure 1.

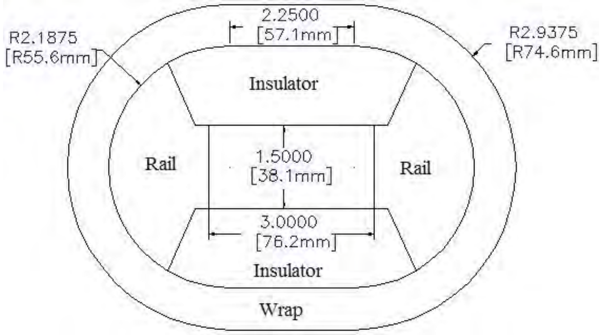

Fig. 1. Oval design

The second design is a newer design that has not been used in the past. This paper will refer to it as the flat design because the sides of the cross section are flat. The design is based on the fact that loading in a railgun is primarily in one direction. Therefore, the resistance to that loading should be in line with the direction of the loading and as close to where it is applied as possible. In this design, the sides of the wrap are very close to the bore, achieving this condition and making a very stiff cross section. The problem with this design is that it cannot resist loading in other directions very well. Plasma pressure would be very difficult for this design to handle should it be present, whereas the oval design can handle plasma pressures much more efficiently. The flat design is shown in Figure 2.

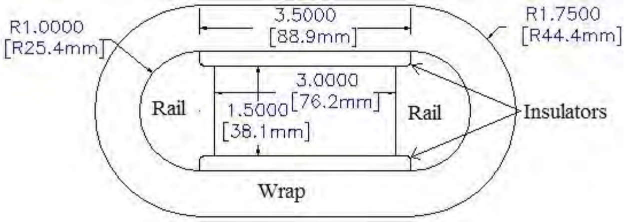

Fig. 2. Flat design

These two designs provide a good basis for studying how the shape of the railgun's cross section affects its stiffness. For this study, we analyzed the designs using properties of materials commonly used in laboratory railguns along with wrap materials that would be used for the tactical launcher. The rail material is copper, while the insulator material is G-10. For the wrap, the primary material of interest is the intermediate modulus carbon fiber IM7, though we will also look at the ultra high modulus fiber Dialead K63712. We also varied the thickness of the wrap to understand its effect on rail displacement.

3. ANALYSIS

The analysis began with building two-dimensional static finite element analysis (FEA) models of the designs using Abaqus. A quarter model was used with symmetry boundary conditions and plane stress elements, due to the fact that a railgun could freely expand in the axial direction during operation. The composite wrap was modeled using smeared properties and a cylindrical material orientation for the circular parts of the wrap. A picture of the mesh of the flat design with the applied rail pressure is shown in Figure 3.

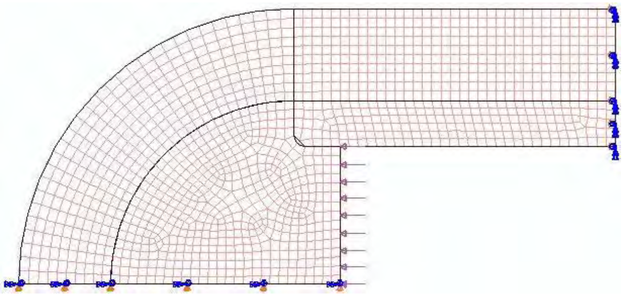

Fig. 3. FEA mesh, loads, and boundary conditions

The material orientations and material properties are given in Figure 4 and Table 1 below. Since the rail is isotropic, no material orientations are given. For the composites materials, smeared properties were used to simplify the analysis. With composites, each layer has its own material orientation and therefore its own properties. Smeared properties combine the properties of each layer into one group so they do not have to be modeled individually. The properties apply to the whole composite part rather than to each individual layer.

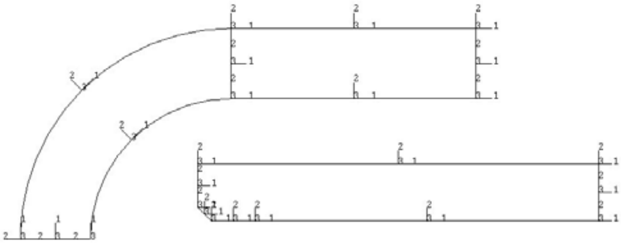

Fig. 4. Material orientations for the wrap and insulator

Table 1. Material properties

	G-10	**IM7**
E1 (GPa)	26.2	137.9
E2 (GPa)	10	5.49
E3 (GPa)	26.2	75.84
Nu12	0.237	0.03
Nu13	0.1	0.03
Nu23	0.237	0.03
G12 (GPa)	2.76	2.83
G13 (GPa)	2.76	5.65
G23 (GPa)	2.76	2.83

	Copper
E (GPa)	115
Nu	0.33

The pressure load was applied to the bore face of the rail at 68.9, 137.9, 206.8, 275.8, 344.7, and 413.7 MPa (10, 20, 30, 40, 50, and 60 ksi) to gain an understanding of what happened at different rail pressures. The result that is the most important to look at in these models is the deflection of the rails, or the distance they moved apart under load. This is measured in percentage of the rail separation so that it can be compared across multiple bore sizes.

For the first set of models, we ran each design with an IM7 wrap at three different thicknesses and frictionless contact surfaces to simulate the components being in contact but not bonded together. In this case, the wrap holds all the parts together by itself while containing the electromagnetic forces applied to the rails. It is basically a worst case condition as the components are free to separate as the rails deflect. A contour plot of the Von Mises stresses in one of the models and the rail expansion results for the different designs with different wrap thicknesses are shown below in Figures 4 and 5. Rail expansion is the maximum percentage that the 3” rail to rail separation distance increased under load. It is measured at the midpoint of the bore surface of the rail. So, if the rail to rail distance increased by 0.03”, the rail expansion would be 1%.

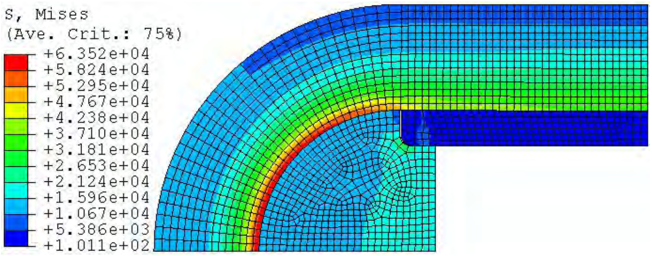

Fig. 4. Von mises contour plot of flat design with 20 ksi rail pressure (stresses are psi)

This plot clearly shows that the flat design outperforms the oval design under proper railgun loading conditions with frictionless contacts. It is also much lighter than the oval design, weighing less than half that of the oval design, and will therefore prove to be a much better fit for any gun system. The only way that the oval design can come close to the flat design’s performance is if it is prestressed. Prestressing greatly improves the oval design’s performance, however details of how to obtain this prestress are beyond the scope of this paper. The flat design would have problems under fault conditions or if transition from sliding to plasma contact occurs as both conditions can result in large plasma pressures being generated. This would cause the performance of the flat design to degrade but again this is beyond the scope of this paper so it will not be covered.

Another important piece of information we get from this plot is the effect of changing the thickness of the

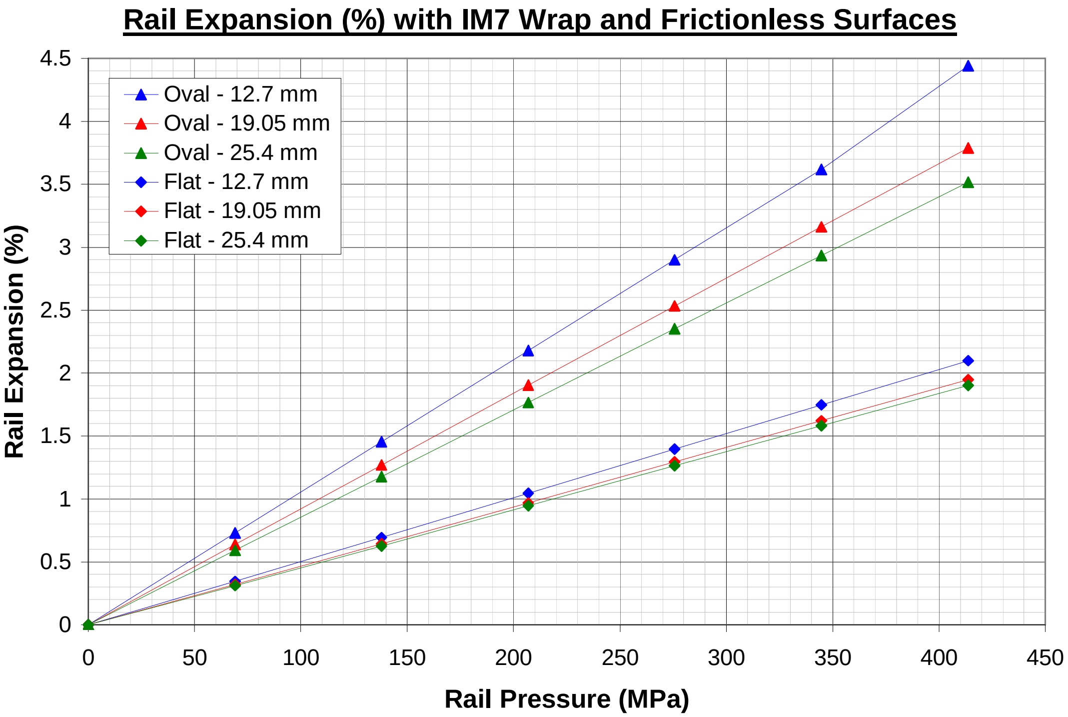

Fig. 5. Results with frictionless contacts

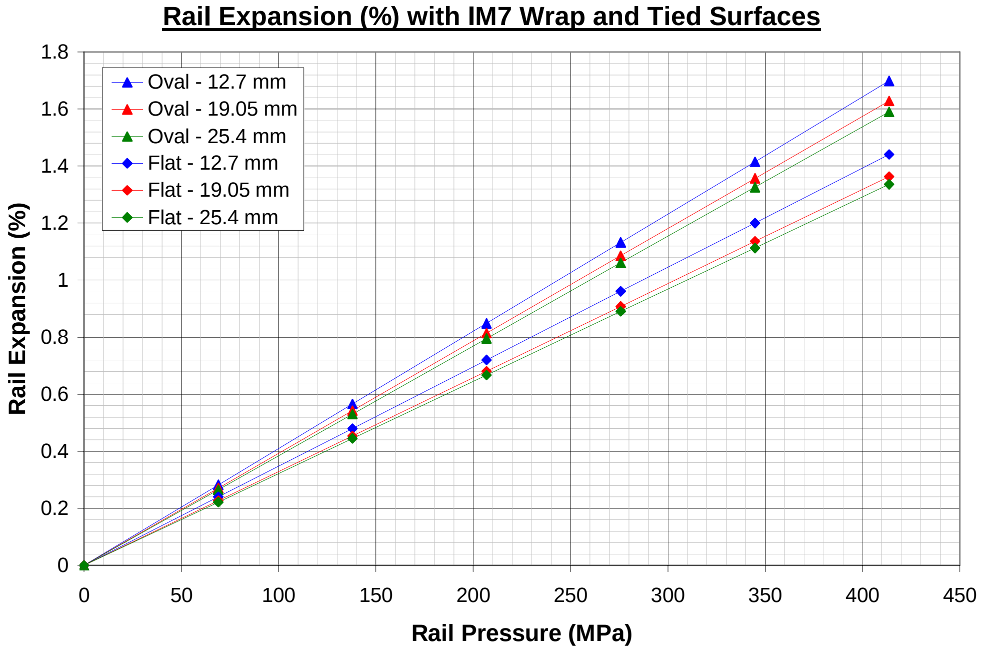

Fig. 6. Results with frictionless contacts

wrap. Thickening the wrap obviously helps reduce rail expansion, but as it gets thicker and thicker, the benefit is reduced while the weight continues to increase. This can be seen in that the 12.7 mm (½ in) and 19.05 mm (¾ in) results are farther apart than the 19.05 mm (¾ in) and 25.4 mm (1 in) results. This is true despite which design you are looking at. The low out of plane modulus is the cause of this problem. The load does not transfer well between layers of composite and the outside layers do not carry much load at all.

The second analysis consisted of running the same models, only this time incorporating no slip contact surfaces between the parts. In Abaqus, this is done by creating "Tied" constraints between the surfaces that tie the nodes from contacting surfaces so that they cannot move relative to each other. These models demonstrate what happens when the parts are perfectly bonded

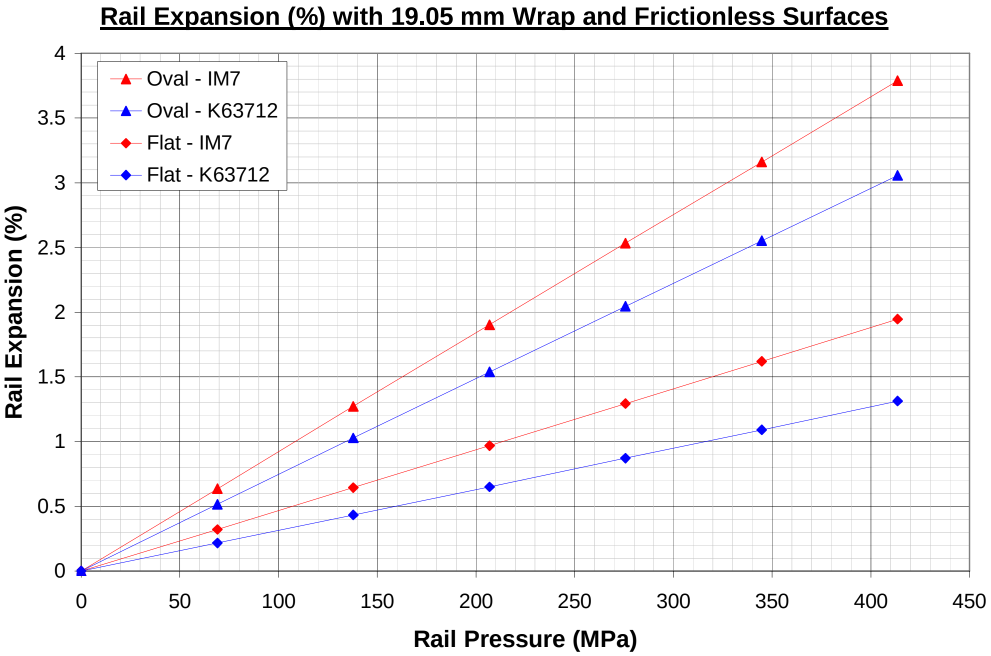

Fig. 7. Wrap material comparison with frictionless surfaces

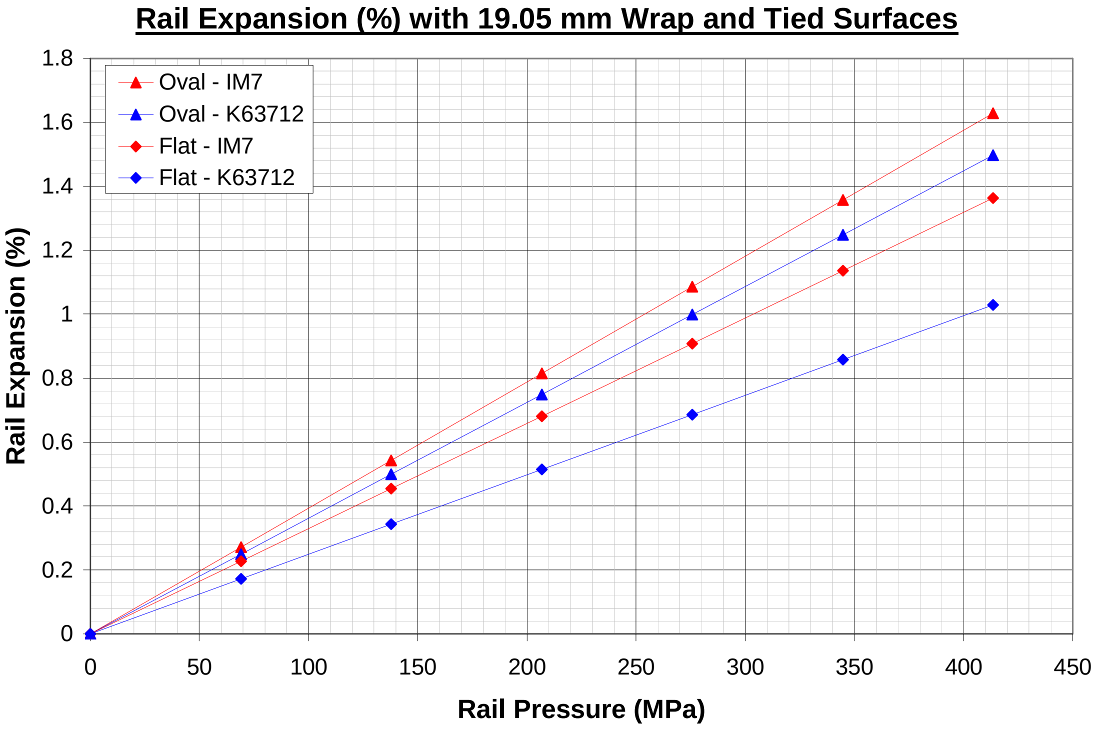

Fig. 8. Wrap material comparison with tied surfaces

together and the bonds do not break. It is a best case condition. The results for the case are shown in Figure 6.

Again it can be seen that the flat design outperforms the oval design under all loading conditions. The oval design only outperforms the flat design if it has a prestress and the flat design does not. This shows that prestressing the gun tube can have a greater effect on the stiffness of the cross section than the geometry itself if the conditions are right.

Up to this point we have only looked at using an intermediate modulus carbon fiber (IM7) for the overwrap. As mentioned earlier, the flat design was developed to take advantage of the ultra-high modulus carbon fibers available. To see what advantage can be gained by utilizing these fibers we will now replace IM7 with Dialead K63712. K63712 has a modulus of 634 GPa (92 Msi) compared to 290 GPa (42 Msi) for IM7. Rather than rerun all of the different wrap thicknesses we have chosen 19.05 mm (¾ in) for the wrap thickness. The results are shown in Figure 7 and 8.

As can be seen from Figure 8, the flat design is again superior to the oval design. Utilizing this ultra-high modulus fiber allows us to achieve smaller rail deflections using the same wrap thickness and thereby same weight. Alternatively we could use a thinner overwrap to achieve the same deflections as IM7 and thereby decrease the launcher weight. Another benefit of the flat design is that it has a much lower mass per unit length of tube as compared to the oval design. The oval design has a mass of 75.59 kg per meter of the tube. The flat design has a mass of 35.43 kg per meter length of tube. Its mass is less than half that of the oval design. Even if the flat design were not superior in terms of rail expansion, it would be worth considering simply for the weight savings.

CONCLUSION

The issue of minimizing rail deflections in railguns under firing loads has been examined by looking at two different cross-sectional designs. The first design resembles a flattened oval and has large rails and insulators. This is the more traditional designed that has been previously studied [Lehman et al., 2005; Tzeng, 2005; Werst et al., 2005; Hahne et al., 1995; Laughlin et al., 1993] and normally requires prestress to minimize rail deflections. The other design is called the flat design because of its flat sides. This is a new design that relies on geometric considerations to minimize rail deflections. In this design very thin insulators are used to keep the sides as flat as possible and aligned with the loading direction. This way any rail deflection immediately loads the wrap in tension. This allows rail deflections to be directly minimized simply by increasing the tensile modulus of the wrap.

Finite element models of these two designs were created and subjected to possible firing loads. The models were run with all parts unbonded but in contact with each other and with all parts perfectly bonded to give upper and lower bounds for rail deflections. Additionally, different thicknesses of the wrap were modeled to assess the influence of wrap thickness on rail deflection. Finally, an ultra-high modulus carbon fiber was used instead of the intermediate modulus IM7 to show how this can improve the system's response.

In all cases the flat design showed that it was able to outperform the oval design. It is an inherently stiffer design so for the same wrap thickness it will produce smaller rail deflections. Since it has a smaller cross-sectional area keeping the wrap thickness the same will result in a lighter design. For a given rail deflection a thinner wrap can be used resulting in a substantially lighter gun than is possible with the oval design. If an ultra-high modulus fiber is used these benefits are increased.

The downside to the flat design though is that it is designed only for rail loading. It is not designed to handle loading on the insulator so any substantial plasma pressure will cause problems. Thus this design is best suited for systems where fault conditions and transition are minimized.

Even with this potential drawback the flat design has shown that it has some substantial benefits over a more traditional design. If the issues of transition and fault conditions can be overcome, this design becomes very practical and easy to implement. For these reasons more study of this design is warranted.

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