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ILC TARGET WHEEL RIM FRAGMENT/GUARD PLATE IMPACT ANALYSIS

L. Hagler

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Lisle Hagler
Mechanical Engineer
Lawrence Livermore National Laboratory

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Introduction

A positron source component is needed for the International Linear Collider Project. The leading design concept for this source is a rotating titanium alloy wheel whose spokes rotate through an intense localized magnetic field. The system is composed of an electric motor, flexible motor/drive-shaft coupling, stainless steel drive-shaft, two Plumber's Block tapered roller bearings, a titanium alloy target wheel, and electromagnet. Surrounding the target wheel and magnet is a steel frame with steel guarding plates intended to contain shrapnel in case of catastrophic wheel failure. Figure 1 is a layout of this system (guard plates not shown for clarity).

This report documents the FEA analyses that were performed at LLNL to help determine, on a preliminary basis, the required guard plate thickness for three potential plate steels.

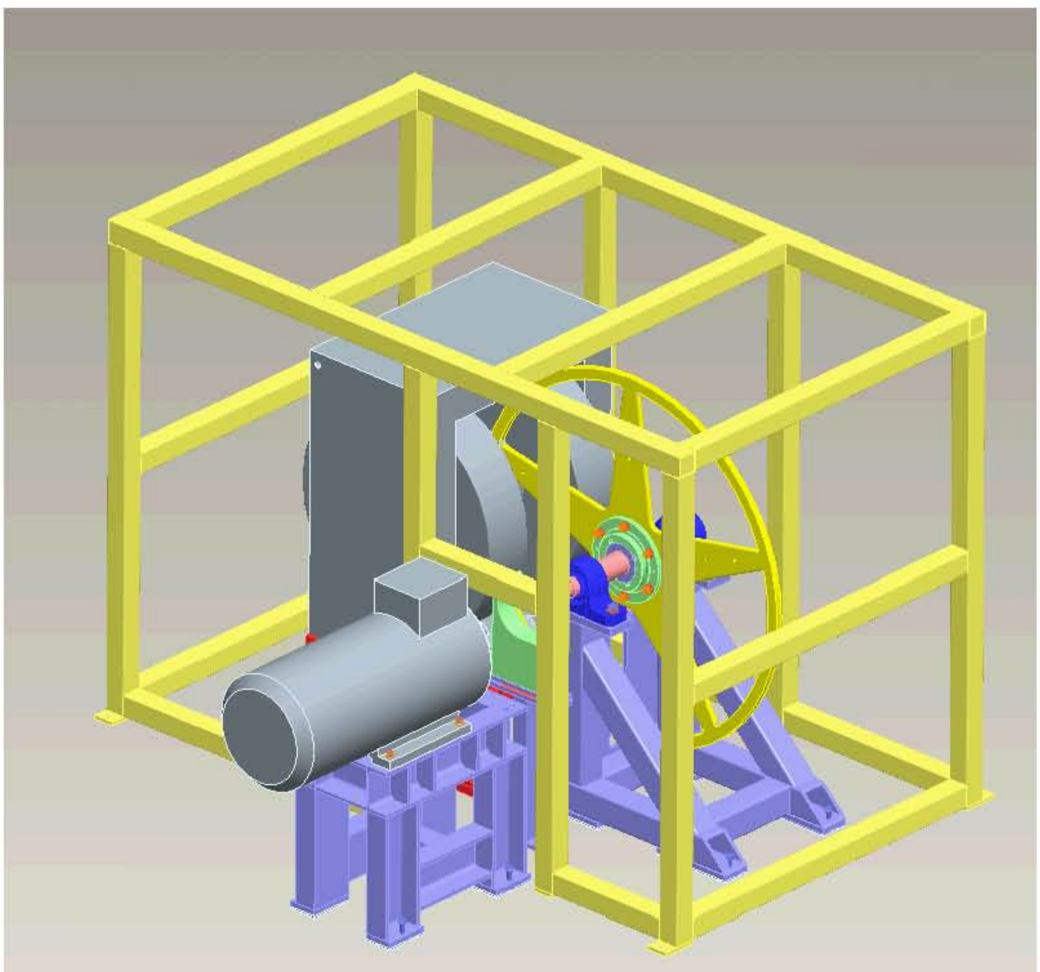


Figure 1. Target Wheel System

Target Wheel Catastrophic Failure

Figure 2 shows the high stress locations on the target wheel during operation at maximum RPM. These points also correspond to the likely failure locations on the wheel for the improbable event [1] of wheel structural failure. Structural failure at these locations will result in rim fragments whose size, mass, and velocity are given Table I.

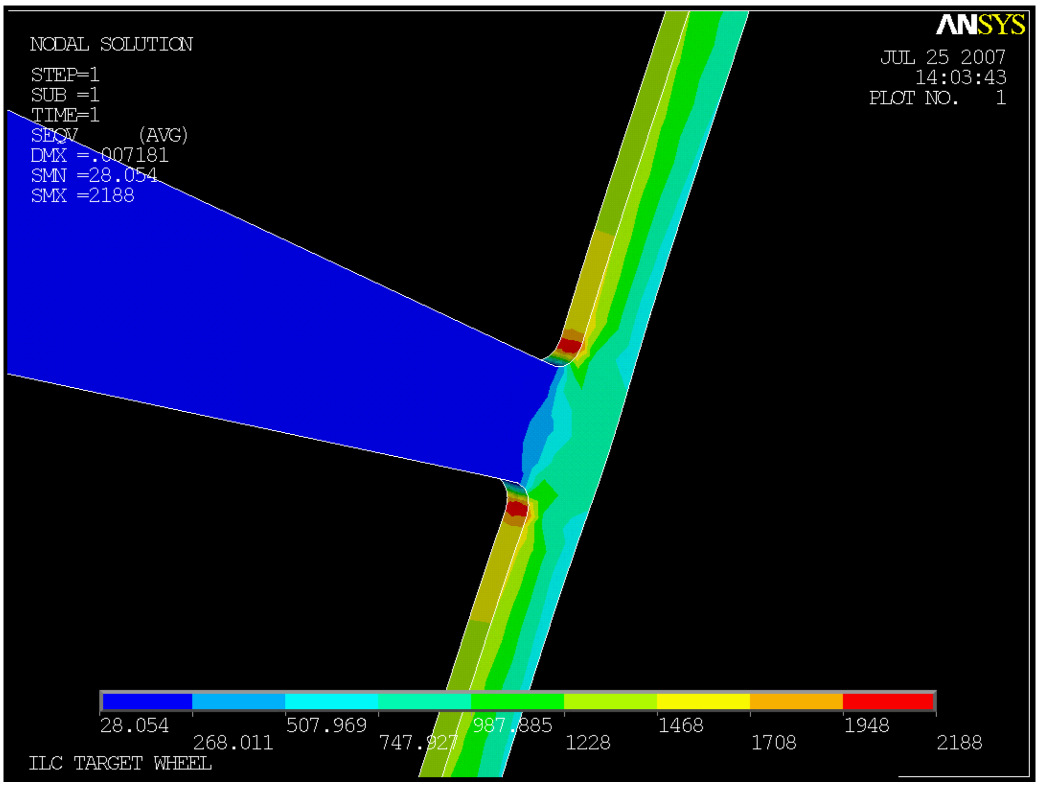


Figure 2. Target Wheel Operational Stresses

Table I. Target Wheel Rim Fragment Characteristics

Parameter	**Parameter Value**
Rim Fragment Dimensions	24.00 in. x 1.18 in. x 0.63 in (609.6mm x 30.0mm x 16.0mm)
Rim Fragment Mass	7.44 x 10^{-3} lbf*s^2/in. (1.3 kg)
Rim Fragment Velocity	4000.3 in/s (101.6 m/s)
Rim Fragment Material	Ti_6Al_4V

Rim Fragment/Guard Plate Impact

The half-symmetry finite element model consists of 60,000 3-D continuum elements and the explicit dynamic finite element code DYNA3D [2] was used to analyze the impacts. The model is shown in Figure 3. The mesh density was chosen such that localized stresses/strains in both components could be adequately resolved with special attention to resolving the bending in the guard plate. The stress/strain behavior of all materials was assumed to be elastic-plastic isotropic power-law hardening (DYNA3D material model #18).

The relevant material properties for the model are listed in Table II. The rim fragment is titanium alloy, while the three steels are two mild low-carbon steels and 304 stainless. The strength and hardening coefficients for mild steel 2 weren't available, so they were assumed to be those of mild steel 1 since both materials are very similar. The titanium alloy material parameters were derived from curve-fitting to experimental data [3], while mild steel 1 and 304 stainless material parameters are from an already existing table. The curve-fit calculation and material parameter table are in the attached Appendix

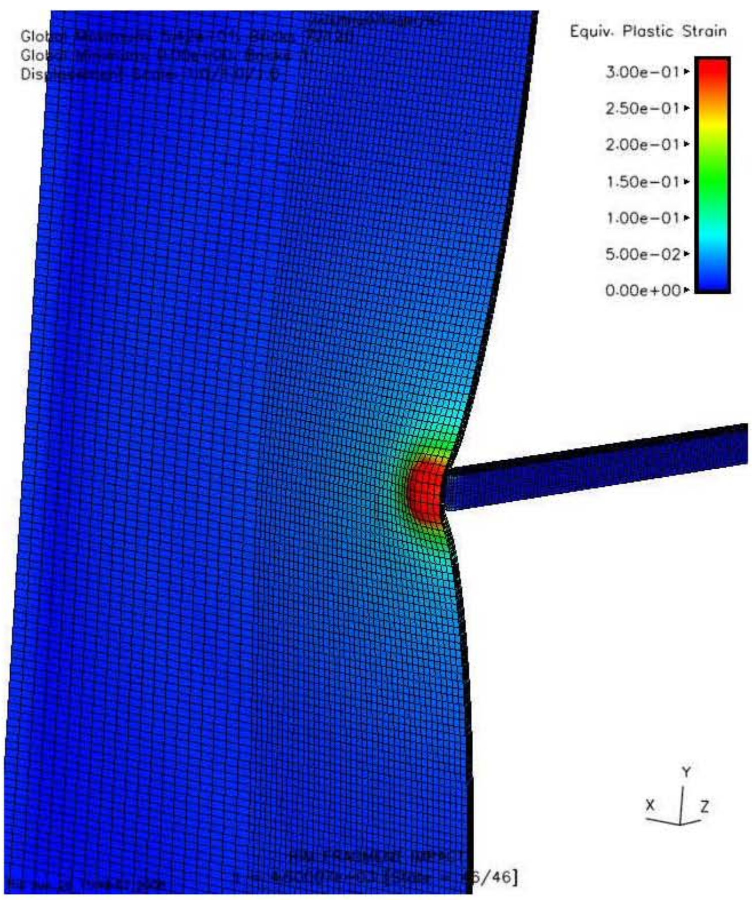


Figure 3. Rim Fragment/Guard Plate Impact: FEA Mesh

Table II. Target Wheel and Guard Plate Material Parameters

Material	**Yield Strength (σ_y)**	**Strength Coefficient**	**Hardening Parameter**	**Elongation-At-Failure**
Ti_6Al_4V	128 ksi (882.5 MPa)	176.9 ksi (1.22 GPa)	0.0774	15%
Mild steel 1: SA-350 LF3	37.5 ksi (258.6 MPa)	129.27 ksi (891.3 MPa)	0.262364	30%
Mild steel 2: Grade S275	37.5 ksi (258.6 MPa)	129.27 ksi (891.3 MPa)	0.262364	24%
304 Stainless Steel	30.0 ksi (206.8 MPa)	145.3 ksi (1.0 GPa)	0.300105	>36%

The FEA model does not explicitly include a material failure mechanism. This means that the model would continue to allow material to carry load beyond its ultimate strain. Consequently a conservative pass/fail criterion was necessarily adopted. Namely, no more than 20% of the guard plate "through thickness" will have achieved at or near ultimate strain when the kinetic energy of the impacting rim fragment reaches zero. This ensures the validity of the FEA results, in that little or none of the guard plate material in the model will carry load after it would have, in fact, failed. Also, all three plate steels considered are very ductile and any material failure is by ductile tearing not crack propagation, i.e. the critical stress for crack propagation is far above the yield strengths of the three steels.

Figure 4 shows the result of the impact of the fragment with the guard plate consisting of mild steel 1 and having the original 3mm thickness specification. It can be seen that the entire "through thickness" of the plate in the impact region exceeds the failure strain (true) of the material (26.2%). This means the material will fail and the original specification is inadequate.

Next, the three types of steel were analyzed and the minimum guard plate thickness for each type was determined using the pass/fail criterion described above. The results are shown in Figures 5-7 and tabulated in Table III.

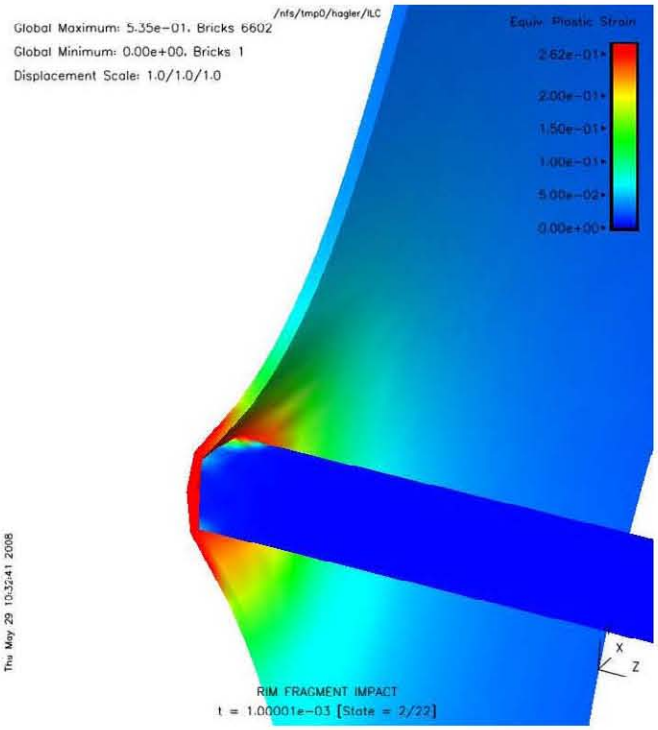


Figure 4. Rim Fragment Impacting 3mm Thick Mild Steel 1 Plate

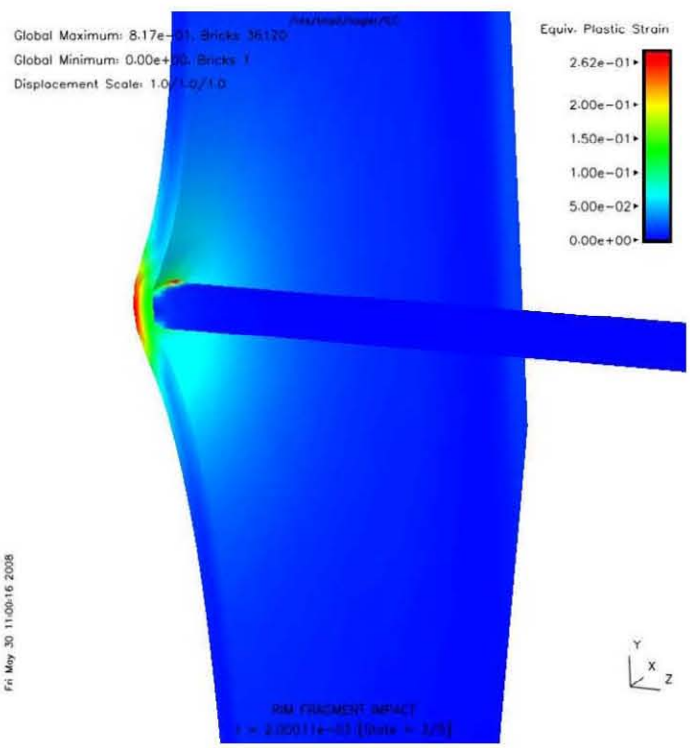


Figure 5. Rim Fragment Impacting 10mm Thick Mild Steel 1 Plate

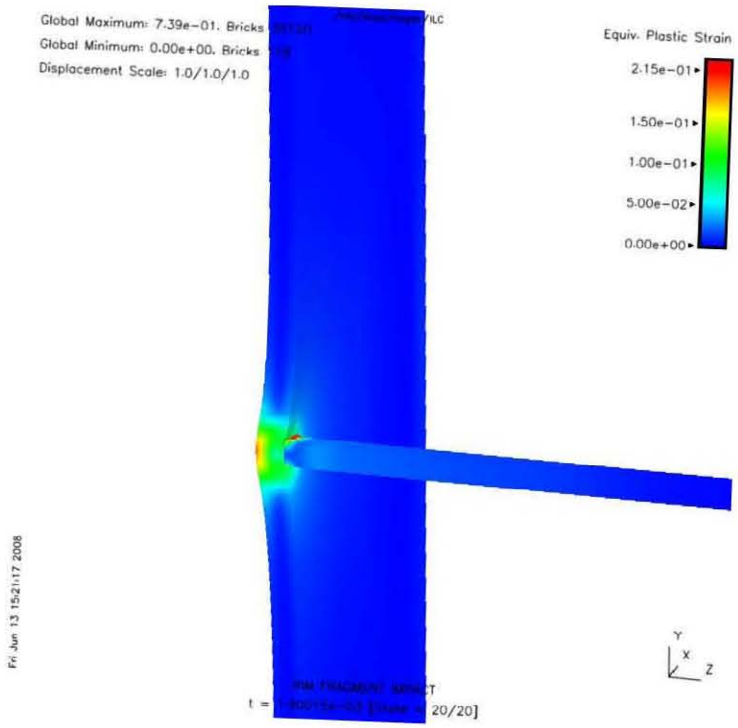


Figure 6. Rim Fragment Impacting 20mm Thick Mild Steel 2 Plate

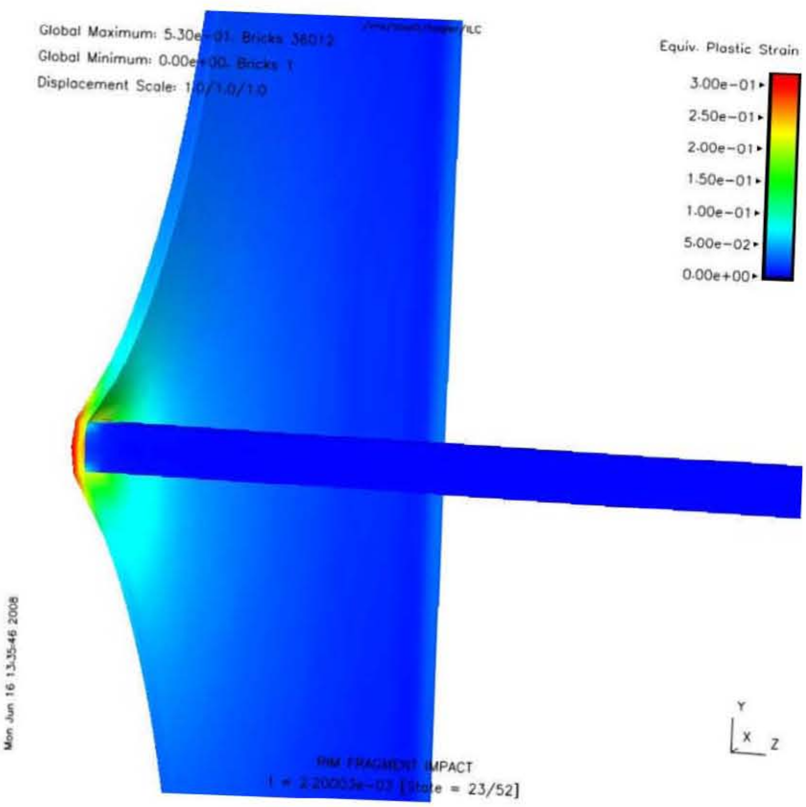


Figure 7. Rim Fragment Impacting 5mm Thick 304 Stainless Steel Plate

Table III. Minimum Guard Plate Thickness

Guard Material	Minimum Required Thickness
Mild steel 1: SA-350 LF3	10mm
Mild steel 2: S275	20mm
304 Stainless Steel	5mm

Conclusions

All three types of steel considered will work. The required thickness of the guard plate for each steel type varies from 5mm (304 stainless) to 20mm (Grade S275). The 304 stainless and the Grade S275 steels appear to be the most readily available in the UK. So, assuming cost and weight constraints to be on equal footing, if the price of Grade S275 steel is equal to or greater than 25% of the price of 304 stainless, on per unit weight basis, then I recommend that 304 stainless steel be the material of choice.

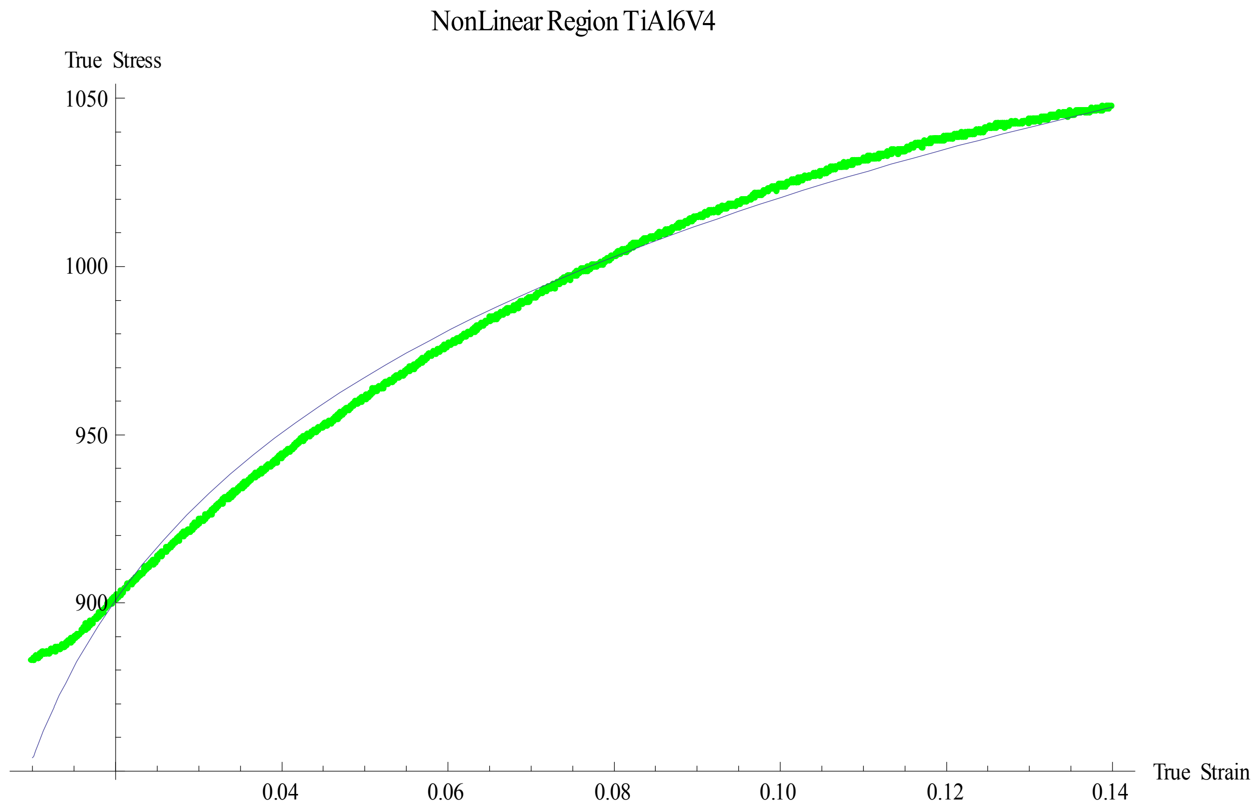
The objective of the analyses presented in this report is to establish minimum plate thicknesses for three types of commonly available steels. The criteria used to determine these minimum thicknesses are based on engineering judgment with the intended purpose of protecting valuable equipment (essentially a factor-of-safety of one). However, for personnel protection purposes, additional protective measures, such as sand-bagging, or increasing the minimum plate thickness with an appropriate factor-of-safety should be considered.

References

1. Hagler, L.B., ILC Target Wheel Structural Analysis, Internal Report, December, 2007.
2. Lin, J.I. et. al., DYNA3D User's Manual, UCRL-MA-107254, January, 2005.
3. Sun Woo, Anne, Personal Communication, April, 2008.

APPENDIX

Titanium Alloy Power-Law Hardening Curve Fit



Strength Coefficient = 1219.55 MPa
Hardening Coefficient = 0.0774074

Material and Power-Law Hardening Parameters for Low-Carbon Mild Steel and 304 Stainless Steel

Assumptions:
(1) All material (except bolts) can be modeled using DYNA3D material model #18
(2) All materials have temperature about 75F

Components	Specification	Density lb/in^3	Young's modulus psi	Poisson's ratio	SIGY psi	K psi	n
Guard Plate							
	SA-350 LF3 carbon st.	0.283	2.76E+07	0.3	37500	129270.7	0.262364
Rim Fragment							
	Stainless steel Type 304	0.29	2.81E+07	0.3	30000	145300.8	0.300105