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TEARING RESISTANCE OF A THIN SHELL AGAINST PROJECTILE PENETRATION -- MATERIAL PROPERTY EFFECTS

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Abstract

This report presents results from a series of finite element analyses performed to study material effects on the tearing resistance of a thin shell subjected to projectile penetration. These analyses simulated a round, slender projectile impacting the top center of a metallic cylindrical shell at high speed. We varied eight selected shell material properties systematically using an L18 matrix (design of experiment technique). From the results, we determined effects of the eight properties on the minimum projectile velocity required to penetrate the shell. The material properties examined here included: yield strength, hardening and recovery characteristics, heat coefficient, initial porosity, and damage exponent (a void growth parameter). The DYNA2D finite element code along with the Sandia plasticity/damage model for ductile metals were used in the analyses.

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1. Introduction

This paper presents results from a series of finite element analyses performed to study effects of material properties on the resistance of thin shells against projectile penetration. Results obtained here can be used to design more penetration resistant components.

The series of analyses simulated a long, slender rod impacting the top center of a thin cylindrical shell. The rod represented a high velocity projectile such as a bullet. We used the DYNA2D finite element code (Ref. 1) and the Sandia plasticity/damage model for ductile metals (Ref. 2) to simulate the impact and to predict tearing in the shell's wall. We used one finite element mesh, but changed the shell's material properties throughout the series. From the finite element results, we calculated material property effects on the minimum projectile velocity required to penetrate the shell.

For effectiveness, we used the design of experiment technique to develop an analysis matrix. An L18 matrix (Ref. 3) was selected to investigate the main effects of eight shell's material properties. We assumed interactions between the selected properties were negligible.

It is important that readers be familiar with the Sandia plasticity/damage model since the selected material properties are used in the model. This study was a hypothetical material study; material properties defined as "trial materials" in the L18 matrix were selected regardless of whether these trial materials can be produced. We did not conduct any verification experiment because of this hypothetical nature. This analysis series can also be viewed as a penetration sensitivity study of the Sandia damage model. A short description of the model is included in Appendix A.

Besides projectile penetration, many other extreme mechanical loads are possible in an abnormal environment. The work summarized in this report is a part of the Advanced Barrier Project, an ongoing effort to study material and geometry effects on tearing resistance of thin shell structures under various mechanical loads. Component housing designers can use the knowledge obtained from this project to make trade-off decisions in optimizing their designs. Safety assessors can apply this knowledge in assessing the response of existing and future components to extreme mechanical loads.

In the following sections, we first describe the geometry, the material properties, the analysis matrix, and the finite element modeling method. We then present the results, a discussion, and conclusions.

2. Analyses

2.1 Geometry

Figure 1 shows the geometry selected for all analyses in this study. This simple geometry allowed for 2D modeling. The shell was cylindrical. It had an 8.0 in diameter and a 0.0625 in wall thickness. The shell edge was fixed. The penetrator was 4.0 in long and had a 1.0 in diameter. The penetrator's smooth ends had a 0.0625 in edge radius.

2.2 Material

The penetrator represented a high strength steel projectile. We modeled it as an elastic material with a $30 \cdot 10^6$ psi Young's modulus and a Poisson's ratio of 0.3. Penetrator deformation was assumed to be negligible.

The Sandia plasticity/damage model was used for the shell material's constitutive model. Eight material properties were varied throughout the analysis matrix. We kept all other material properties required by the Sandia model constant (see Appendix A). Table 1 lists these constant material values. These values came from existing data for 304L stainless steel.

Figure 1. Geometry selected for this study.

Table 1. Constant material values (based on SS304L).

E	30.0*10 ⁶ psi
Poisson's ratio	0.30
initial temperature	293 K
density	7.35*10 ⁻⁴ lbs*s ² /in
c2	0. K
c4	4.68*10 ² K
c5	7.04*10 ⁻⁶ s ⁻¹
c6	0. K
c7	5.72*10 ⁻⁴ (psi) ⁻¹
c8	1.23 K
c9	8.7*10 ⁴ psi
c10	0. K
c11	0. (psi*s) ⁻¹
c12	0. K
c14	7.01 K
c16	0. K
c18	6.79*10 ³ K

Note: base units in lbs, in, s, K.

2.3 Analysis matrix, selected factors and their levels.

The eight material properties selected for this study were: two yield strength parameters (Y and V), hardening (H), static and dynamic recovery (R_s and R_d), initial porosity, damage exponent, and heat generation coefficient. A copy of the model theory with definitions for these properties (Ref. 4) is included in Appendix A. Appendix B shows effects on the inelastic characteristics of the model for five of these selected parameters.

We planned the analysis matrix using the design of experiment technique. This technique effectively changed levels of several properties simultaneously throughout the matrix. An L18 Taguchi matrix was selected to investigate main effects of 8 factors, one factor at two levels, and seven factors at three levels. Each factor was used for each of the eight selected properties. We assumed that interaction effects were secondary to main effects. The simplicity of this screening study justified this assumption. Table 2 shows the L18 matrix, which defined required combinations of levels for the selected eight material properties for each of the 18 trial runs.

The Sandia plasticity/damage model allows for temperature dependency through material parameter definitions. Of those selected parameters in this study, R_s , Y, V, H, and R_d were temperature dependent. Their definition has the form:

$$c_i(c_j/\theta)$$

where c_i and c_j are input parameters and θ is the temperature. In this study, we did not examine temperature effects. The level of each selected parameter was adjusted by changing the c_i terms; the c_j terms were kept constant. Thus, only parameters c_1 , c_3 , c_{13} , c_{15} and c_{17} were used to change levels of yield Y, yield V, dynamic recovery Rd, hardening H, and static recovery Rs respectively (See Appendix A).

Table 2. L18 matrix and trial run results.

Trial Run	Rs	Y	V	H	Rd	n	p	Ho	Failure vel. (in/s).
1	A	A	A	A	A	A	A	A	3000
2	A	A	B	B	B	B	B	B	2300
3	A	A	C	C	C	C	C	C	3300
4	A	B	A	A	B	B	C	C	1400
5	A	B	B	B	C	C	A	A	4000
6	A	B	C	C	A	A	B	B	2200
7	A	C	A	B	A	C	B	C	3900
8	A	C	B	C	B	A	C	A	3400
9	A	C	C	A	C	B	A	B	1600
10	B	A	A	C	C	B	B	A	3100
11	B	A	B	A	A	C	C	B	2400
12	B	A	C	B	B	A	A	C	3600
13	B	B	A	B	C	A	C	B	2000
14	B	B	B	C	A	B	A	C	2800
15	B	B	C	A	B	C	B	A	2000
16	B	C	A	C	B	C	A	B	2000
17	B	C	B	A	C	A	B	C	2200
18	B	C	C	B	A	B	C	A	4200

We chose levels for each selected material property by deviating from existing data for SS304L. The magnitude of the deviations were based on what we thought were achievable. Table 3 shows the eight selected factors and their c_i levels.

2.4 Finite element modeling

The finite element code DYNA2D was used for this study. We included slide lines on the penetrator and the shell outer surface to model the material interface. The penetrator was the master surface, and the shell was the slave surface. Figure 2 shows the finite element mesh used in all analyses.

The penetrator was given an initial velocity to start each analysis. We ran each analysis until the penetrator either had penetrated through the shell or had rebounded off the shell.

Table 3. Selected factors and their c_i levels.

Factor	Level A	Level B	Level C
Static recovery, R_s (psi*s) ⁻¹	$4.77*10^{-7}$	$4.29*10^{-6}$	none
Yield, Y (psi)	$6.97*10^3$	$3.49*10^4$	$2.09*10^4$
Yield, V (psi)	$8.93*10^2$	$4.47*10^3$	$2.68*10^3$
Hardening, H (psi)	$5.50*10^4$	$4.95*10^5$	$2.75*10^5$
Dynamic recovery, R_d (psi) ⁻¹	$1.50*10^{-4}$	$1.35*10^{-3}$	$7.50*10^{-4}$
Damage exponent, n	$4.70*10^0$	$7.05*10^0$	$5.88*10^0$
Initial porosity, p	$1.00*10^{-4}$	$1.00*10^{-3}$	$5.50*10^{-4}$
Heat coefficient, H_o (K/psi)	$0.00*10^0$	$3.00*10^{-3}$	$1.50*10^{-3}$

Note: base units in lbs, in, s, K

Effects of material properties on the penetration resistance were measured in terms of failure velocity. We defined the failure velocity as the minimum initial velocity required for the penetrator to penetrate the shell. This minimum velocity was required for each trial run of the L18 matrix. Since each analysis ended as a failure (penetrated) or a no failure (rebounded), we had to iterate an analysis several times to determine the failure velocity for each trial run. On the average, each trial run took about five iterations to determine a failure velocity that had a 100 in/s uncertainty.

The Sandia plasticity/damage model tracks a damage coefficient to predict void growth. Voids grow to degrade material properties and increase the damage coefficient. Complete failure in a finite element (tearing) is predicted when this damage coefficient reaches a critical value (.99). Penetration of the shell occurred when there existed a continuous path of failed elements through the shell's thickness. Figure 3 shows a deformed shell, and Figure 4 shows a penetrated shell.

3. Results

The last column in Table 2 shows the failure velocity for each of the 18 trial runs. The average failure velocity for these 18 runs was 2740 in/s.

Table 4 shows the average failure velocity for each level of each factor. For any level of any factor, the value in Table 4 was obtained by taking the average of failure velocities of all the runs that had that particular factor set at that particular level. For example, the average failure velocity of level B of factor H was determined by taking the average of runs 2,5,7,12,13, and 18.

Table 5 shows the relative importance for each factor level. This table shows relative effects of material properties on the shell's tearing resistance. We obtained the results in this table by subtracting the average failure velocity, 2740 in/s, from respective values of Table 4.

Figure 2. *Finite element mesh used in all analyses.*

Figure 3. A deformed but not penetrated shell.

Figure 4. A penetrated shell.

Table 4. Average failure velocity of the factors and their levels (in/s).

Level	Rs	Y	V	H	Rd	n	p	Ho
A	2789	2950	2567	2100	3083	2733	2833	3283
B	2700	2400	2850	3333	2450	2567	2617	2083
C		2883	2817	2800	2700	2933	2783	2867

Table 5. Relative effects of the factors and their levels (in/s).

Level	Rs	Y	V	H	Rd	n	p	Ho
A	44	206	-178	-644	339	-11	89	539
B	-44	-344	106	589	-294	-178	-128	-661
C		139	72	56	-44	189	39	122

Figure 5 summarizes major results of this study. The bars in this plot show effects of selected material properties on the shell's tearing resistance as measured by the failure velocity. The length of the bar between two levels of a factor shows the change in failure velocity from changing the level of that factor. An increase in failure velocity means higher tearing resistance for the shell.

From Figure 5, we see H and H_O had the largest effects. Effect of Y and R_d was about one half of the effect of H and H_O. R_s showed almost no effect and V, n and p showed relatively little effects.

Figure 6 shows plots of failure velocities versus selected levels for each examined factor. For three level factors, these plots also show the degree of linearity of their responses. In all factors, level A was the lowest level, level B was the highest level, and level C was in the middle. The nonlinearities in some factors (Y, V, n) suggest interactions between the factors.

Results of the L18 matrix can be used to form a model to predict failure velocities for other combinations of selected material properties. To do this, one takes the average failure velocity (2740 in/s) and adds contributions (Table 5) of selected levels for each of the eight examined material properties. The following example illustrates this prediction capability.

According to the results (Table 5 or Figure 5), the combination that would produce the highest failure follows: R_s, Y, R_d, p and H_O at level A; V and H at level B; and only n at level C. The failure velocity (in/s) for this "strongest" combination is calculated from the L18 model as follow:

$$2740 + 44 + 206 + 106 + 589 + 339 + 189 + 89 + 539 = 5417$$

Figure 5. Effects of selected properties on shell's penetration resistance.

Figure 6. Failure velocity at different levels for each selected property.

We ran a confirmation finite element analysis for this best combination to verify the L18 results. The minimum initial velocity needed for penetration was 5700 in/s (to the nearest 100 in/s). A 5% difference between the prediction from the L18 model and the finite element analysis supported the design of experiment results.

4. Discussions

The ranges selected for levels of the examined factors played a large role in the outcome of this study. For example, if the range of the dynamic recovery (R_d) was twice as large, its effect would likely double. If this is true, its effect would be equal to that of the hardening (H) and the heat generation (H_0 , see Figure 5), the two most important properties according to the obtained results. Therefore, the relative results with respect to the selected ranges for the various properties are more useful than the absolute results. Although levels of examined properties were hypothetical, we chose realistic numbers to bound the property effects.

The selected simple geometry allowed for the use of inexpensive two-dimensional (2D) analyses. This study focused on material and not geometry effects. We assumed that the selected geometry, which lacked geometry effects of a 3D event, had little influence on the results. We believe the material results obtained here are true in general, and not restricted to 2D events.

Without laboratory verification, the validity of these results rest entirely on the validity of the Sandia plasticity/damage model. The model has compared well with similar penetration studies (Ref.5), which considered the same type of thin shell penetration. This model has also done well in many other impact studies that involved thin shells and extreme loads (high velocity projectile, pressure loads from explosions, etc.; see Ref. 2)

A firing set housing is packed with electronic and mechanical components. For simplification, we did not examine effects of internal components and partitions. We plan to examine these effects in future studies, which would involve 3D modeling.

5. Conclusion

We successfully quantified effects of eight selected material properties on the penetration resistance of the examined cylindrical shell. For the examined system (selected geometry and ranges of properties), the hardening (H) and the heat generation (H_0) parameters contributed most to the penetration resistance of the shell. The static recovery (R_s) parameter had no significant effect. Figure 5 summarizes the influences on the shell's penetration resistance of the eight examined properties.

Results obtained here can be used to improve or assess the penetration resistance of metallic housing structures. These screening results can also be used to plan for more detailed and more comprehensive material studies.

6. References

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Appendix A

Sandia plasticity/damage model for ductile metals.
Reproduced from pages 3,4, and 7 of Reference 4.

The Model

The model assumes the strain rate D can be decomposed into elastic and plastic parts

$$D = D^e + D^p \quad (1)$$

and that the elastic part obeys the linear relation:

$$\dot{\sigma} = (1 - \phi) (\lambda \text{tr}(D^e) I + 2\mu D^e) - \frac{\dot{\phi}}{(1 - \phi)} \sigma \quad (2)$$

where the Cauchy stress is convected with the elastic spin.

$$\dot{\sigma} = \dot{\sigma} - W^e \sigma + \sigma W^e \quad (3)$$

The model assumes a flow rule of the form

$$D^p = f(\theta) \sinh \left[\frac{\sqrt{\frac{3}{2}} |\xi| - k - Y(\theta)}{V(\theta) (1 - \phi)} \right] \frac{\xi}{|\xi|} \quad (4)$$

where $\xi = \sigma' - \frac{2}{3} \alpha$ and the internal variables, the backstress tensor α , the hardening scalar k , and the void scalar ϕ are given by the evolution rules:

$$\dot{\alpha} = h(\theta) D^p - [r_d(\theta) |D^p| + r_s(\theta)] \sqrt{\frac{2}{3}} |\alpha| \alpha \quad (5)$$

$$\dot{k} = H(\theta) |D^p| - [R_d(\theta) |D^p| + R_s(\theta)] k^2 \quad (6)$$

$$\dot{\phi} = \beta \left[\frac{1}{(1 - \phi)^n} - (1 - \phi) \right] |D^p| \quad (7)$$

The Model

$$\beta = \sinh \left[\frac{2(2n-1)p}{(2n+1)\bar{\sigma}} \right] \quad (8)$$

where $\bar{\sigma}$ is effective stress, p the mean stress, θ the temperature, h, H, r_s, r_d, R_s, R_d , are the temperature dependent plasticity parameters of the form $c_1 \exp(\pm \frac{c_2}{\theta})$, and n is the void growth parameter.

Input

To describe a material in PRONTO3D using the damage model, the material definition section needs to define the following;

Youngs modulus	
Poissons ratio	
Initial Temperature	
Thermal expansion	coefficient of thermal expansion
Damage constant	"n" in the equations
Initial damage	initial value of ϕ
Heat coefficient	$\frac{0.9}{\rho C_v}$ heat due to plastic work
c1, c2	$V = c1 \exp(-c2/\theta)$
c3, c4	$Y = c3 \exp(c4/\theta)$
c5, c6	$f = c5 \exp(-c6/\theta)$
c7, c8	$r_d = c7 \exp(-c8/\theta)$
c9, c10	$h = c9 \exp(c10/\theta)$
c11, c12	$r_s = c11 \exp(-c12/\theta)$
c13, c14	$R_d = c13 \exp(-c14/\theta)$
c15, c16	$H = c15 \exp(c16/\theta)$
c17, c18	$R_s = c17 \exp(-c18/\theta)$

It should be noted that for now the thermal expansion term is not used. Also the initial damage term must be non-zero for any damage to develop.

Appendix B

Effects of c_1 , c_3 , c_{13} , c_{15} and c_{17} on the inelastic characteristics of the Sandia plasticity/damage model.

Plots presented here were generated using the Bfit program (Reference 6).

Changing C1 while holding other parameters constant Unit system: lbf, inch, second, Kelvin.

c1 = variable	c7 =0.000572	c13 =0.00075
c2 =0	c8 =1.23	c14 =7.01
c3 =2.09e+04	c9 =8.7e+04	c15 =2.75e+05
c4 =468	c10 =0	c16 =0
c5 =7.04e-06	c11 =0	c17 =2.38e-06
c6 =0	c12 =0	c18 =6790

Parameter C1 (psi), rate = 0.01 s-1

a 893.
 b 2681.
 c 4470.

Changing C3 while holding other parameters constant Unit system: lbf, inch, second, Kelvin.

c1 =4470	c7 =0.000572	c13 =0.00075
c2 =0	c8 =1.23	c14 =7.01
c3 = variable	c9 =8.7e+04	c15 =2.75e+05
c4 =468	c10 =0	c16 =0
c5 =7.04e-06	c11 =0	c17 =2.38e-06
c6 =0	c12 =0	c18 =6790

Parameter C3 (psi), rate = 0.01 s-1

a 6970.
b 20,935.
c 34,900.

Changing C13 while holding other parameters constant Unit system: lbf, inch, second, Kelvin.

c1 =4470	c7 =0.000572	c13 = variable
c2 =0	c8 =1.23	c14 =7.01
c3 =3.49e+04	c9 =8.7e+04	c15 =2.75e+05
c4 =468	c10 =0	c16 =0
c5 =7.04e-06	c11 =0	c17 =2.38e-06
c6 =0	c12 =0	c18 =6790

Parameter C13 (psi)⁻¹, rate = 0.01 s⁻¹

a	.00015
b	.00075
c	.00135

Changing C15 while holding other parameters constant Unit system: lbf, inch, second, Kelvin.

c1 =4470	c7 =0.000572	c13 =0.00135
c2 =0	c8 =1.23	c14 =7.01
c3 =3.49e+04	c9 =8.7e+04	c15 = variable
c4 =468	c10 =0	c16 =0
c5 =7.04e-06	c11 =0	c17 =2.38e-06
c6 =0	c12 =0	c18 =6790

Parameter C15 (psi), rate = 0.01 s-1

a 55,000.
b 275,000.
c 495,000.

Changing C17 while holding other parameters constant

Unit system: lbf, inch, second, Kelvin.

c1 =4470	c7 =0.000572	c13 =0.00135
c2 =0	c8 =1.23	c14 =7.01
c3 =3.49e+04	c9 =8.7e+04	c15 =4.95e+05
c4 =468	c10 =0	c16 =0
c5 =7.04e-06	c11 =0	c17 = variable
c6 =0	c12 =0	c18 =6790

Parameter C17 (psi*s)⁻¹, rate = 0.01 s⁻¹

a 4.77e-07.

b 4.29e-06.

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