Experimental Evaluation of As-Processed Propellant Grains

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Grain structural integrity evaluations are generally based upon mechanical properties data obtained from tests of specimens removed from carton samples of propellant. During the past several years, Aerojet has performed numerous sample excisions and motor dissections to verify grain structural capabilities. These studies demonstrate that the standard carton samples often provide incomplete and/or misleading information about bulk and local properties in the actual propellant grain, as well as properties of other materials such as the liner/insulation. The reasons for the observed discrepancies have not been completely elucidated, but it is clear that motor processing methods, as well as material interactions in the assembled motor, are significant factors. In this paper, examples of recent motor studies demonstrate the importance of experimental evaluation of the as-built propellant grain as a key element in the overall structural assessment.

Introduction

It is common practice in grain structural integrity analyses to assume that the material characteristics for the as-processed propellant-liner-insulation system in a given motor are adequately represented by design specifications and the results of tests conducted using samples prepared under laboratory conditions. After considerable experience in excising samples from grains and in dissecting and testing motors, it has become clear that significant deviations from the assumed behavior can be induced by the manufacturing process and amplified by aging. Failure to account properly for these deviations can lead to serious errors in calculated safety margins and perhaps result in costly structural problems.

The purpose of this paper is to increase awareness of these potential problems among structural integrity engineers. Several examples will illustrate the broad range of unexpected behaviors that might be encountered and their impact upon the grain structural evaluation. Factors discussed include carton-motor bias, gradients in propellant and bond properties, orientation effects, liner properties variations, and combined effects. Although some of the data illustrated may not be directly usable in structural analyses, the results suggest phenomena that are likely to show similar effects upon the related response and failure properties required to perform an analysis.

Discussion

Carton-Motor Bias

A bias has been found to exist between properties of propellant from dissected motors and corresponding data from laboratory samples. Comparisons between test results from the two sources indicate that although the magnitude of these differences may vary among systems, the direction of the differences is relatively consistent.

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The bias between motor and carton is such that data from laboratory samples will tend to overestimate strain capability and underestimate modulus. Comparisons based on propellant strength are less consistent than those based on other properties. These tendencies are illustrated in Table 1, where ratios for uniaxial tensile properties (motor-to-carton) for propellants used in six different motors are listed.

It is reasonable to expect that relaxation moduli will show a bias similar to that measured for uniaxial tensile moduli. This is verified by a comparison based on relaxation moduli measured at temperatures of 0, 40, and 77°F that indicates a motor/carton ratio >1.3 (Fig. 1).

Since predicted bond stresses are directly related to relaxation moduli, motor-carton bias will lead to the calculation of stress requirements that are too low and therefore margins of safety that are too high. In the case of the ballistic motor for which data are provided in Fig. 1, the magnitudes of the error would be approximately 30%, thereby converting an apparently "safe" margin of +25% to a potentially dangerous −4%.

Gradients in Propellant Properties

Significant variations in material properties may exist in the as-built motor as functions of distance from bore and bond interfaces. It is believed that these gradients are due largely to 1) particle orientation and segregation related to flow patterns and 2) migration of mobile species from the propellant into the liner/insulation during and after cure.

Migration effects can be simulated in laboratory samples, but flow patterns relative to various cast techniques are best determined from testing the dissected propellant grain. Generally, propellant adjacent to a bond interface will be harder (higher strength and modulus, lower elongation) than propellant in the midweb area. Moduli at the bond interface compared to those at the midweb may differ by a factor of 2 or more.

Differences in plasticizer and catalyst levels between propellant and liner will influence the gradient in properties that may become more severe with aging. An example of the gradients in strain capability in an air launch motor containing a relatively thick liner is shown in Fig. 2. The extreme temperature sensitivity of the profile is a good indication that the effect is related to local plasticizer loss.

Propellant adjacent to a bore surface may be affected by materials used to facilitate core release, as well as by volatiles that may be released from core or fin materials (e.g., nylon) during motor cure. Depending on the reaction (if any) among core, release agent, and propellant, properties at the bore surface may be harder or softer than in the bulk of the grain.

Failure to recognize and account for the differences in properties between bore or bondline and bulk propellant can lead to significant errors in estimating grain structural requirements and/or capabilities.

Orientation Effects

Mechanical Properties

It has long been known that properties of most propellants tend to be anisotropic—probably due to particle orientation during cast. Although some measure of this effect may be determined from laboratory samples (horizontal vs vertical orientation), it is best evaluated with specimens from a dissected motor.

The effect of specimen orientation on uniaxial tensile properties measured at 77°F, 0.74 min^{-1}, under 600 psig superimposed pressure was determined for propellant from two or three areas each from four large ballistic motors. Specimens were prepared representing radial, axial, and hoop orientations. Results of these tests indicate differences up to approximately 20% between orientations. These data, normalized to values measured in the hoop direction, are summarized in Table 2.

In this case, the largest difference among orientations was for values of modulus with a difference of 18% between values for hoop and radial specimens. Little difference was evident between hoop and axial orientation, however. In general, radially oriented speciments were lower in strength and modulus and higher in strain capability than specimens oriented in the other two directions.

These values are, no doubt, dependent on many variables, including motor configuration and specimen location, as well as shape and size distribution of solids. These data do, however, illustrate another factor that must be considered in attempting to evaluate a full-scale motor based on data from laboratory samples.

Burn Rate

Burning rates of propellant strands prepared from full-scale motors also show a difference with specimen orientation, as well as a gradient with respect to location within the motor.

An illustration of burning rate profiles for propellant from a large strategic motor is shown in Fig. 3. The profiles from axially and radially oriented specimens are reversed from one another with respect to location of maximum and minimum values. It is interesting to note that a profile of uniaxial tensile properties of propellant from the same general location in the motor showed a profile in moduli of axially oriented specimens very similar to that measured for burning rate in the same orientation (Fig. 4).

Table 1 Uniaxial tensile properties—comparison between motor and carton samples

Motor type	Propellant type	Ratios in uniaxial tensile properties[a] (motor/carton)			
		σ_m	ϵ_m	ϵ_b	E_0
Tactical ground launch	Polyurethane	0.98	0.69	0.78	1.50
Tactical ship launch	CTPB	1.16	0.77	0.72	1.50
Strategic upper stage	Polyurethane	0.90	0.59	0.71	1.79
Strategic upper stage	CTPB	1.19	0.86	0.86	1.20
Strategic upper stage	PEG/FEFO	1.17	0.60	0.61	2.15
Strategic upper stage	HTPB	0.97	0.76	0.87	1.21
	Average	1.06	0.71	0.78	1.56

[a]Measured at 77°F, 0.74 min^{-1}, σ_m: nominal maximum stress; ϵ_m; strain at nominal maximum stress ϵ_b: strain at break, E_0 initial tangent modulus.

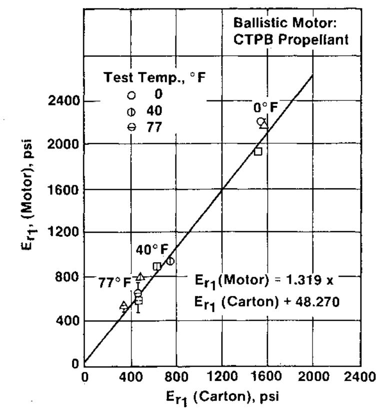

Fig. 1 Stress relaxation properties—comparison between carton and motor samples.

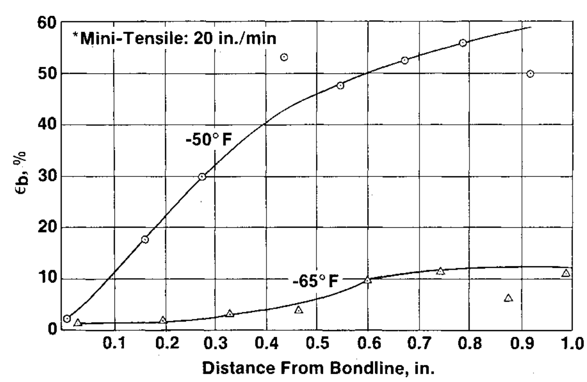

Fig. 2 Propellant elongation profiles adjacent to an insuliner.

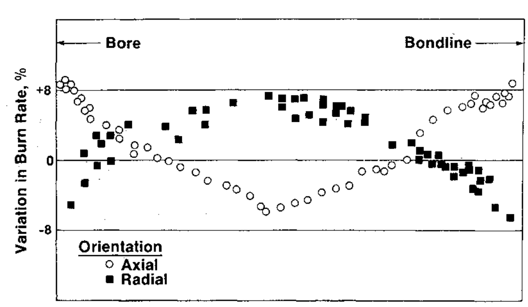

Fig. 3 Effect of location and orientation on burning rate for a large strategic motor.

Table 2 Effect of specimen orientation upon mechanical properties

Property	Orientation[a]		
	Hoop	Axial	Radial
Nominal max stress	1.00	1.00	0.92
Strain at nominal max stress	1.00	1.01	1.06
Strain at break	1.00	1.03	1.04
Initial tangent modulus	1.00	0.91	0.82

[a]Properties normalized with respect to values measured in hoop orientation.

The variation in both burning rate and modulus curves is believed to be due to particle orientation. The alignment of particles that causes reinforcement in a mechanical sense will also provide a faster burn rate.

Effect of Web Thickness

Propellant properties also may vary as a function of web thickness. Both bore and bond surfaces are subject to gradients in properties due to migration and diffusion effects (plasticizer, catalysts, curative, oxygen). In areas where web thickness is small, effects of proximity to surface and bondline may combine with other effects (flow orientation, etc.) to produce properties significantly different from those of bulk propellant.

The decrease in strain capability in a thin web area could easily lead to cracking in the fin slots during firing. The relationship between web thickness and strain capability measured with specimens obtained from a large ballistic motor is shown in Fig. 5.

Variation in Bond Strength

Dissection of full-scale motors is also useful in determining variations in bond strength that might not be anticipated based on data from laboratory samples. Measurements of bond tensile strength as a function of axial location in an aged composite case strategic motor indicated relationships between bond strength and the thickness of case and insulation (Fig. 6). Degradation of bond strength was related to diffusion of moisture through the case and varied with the thickness (and barrier effect) of case and insulation at a given location. The susceptibility to variation with aging was therefore inherent in the motor at the time of manufacture.

Liner Properties Variations

One area that is often overlooked in structural evaluations involves the properties of the as-processed liner. It is common practice to characterize liner mechanical, physical, and bonding properties using samples prepared in the laboratory under conditions that can differ markedly from those in the production situation. The results can, therefore, be quite misleading.

In one motor development investigation involving apparent grain cracking upon ignition at low temperature, it was found through dissection of several motors that the liner, which was quite thick, contained significant porosity. In the original stress analysis it was assumed, based upon laboratory evaluation, that the liner in the motor was void-free, i.e., incompressible. The effect of the porosity observed would be a reduction in the thermal strain in the grain, due to a volume increase occurring in the liner. The incremental strain produced by rapid pressurization is thus increased due to the combination of the rapid recovery of the reduced thermal strain increment and the additional strain resulting from compression of the liner voids.

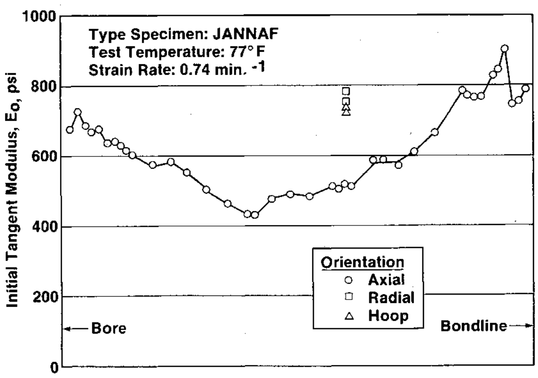

Fig. 4 Effect of location and orientation on initial tangent modulus.

To evaluate the significance of these effects, an analysis was conducted in which the incremental bore strains produced by pressurization of the motor at low temperature were calculated as functions of liner thickness and void content. The results, illustrated in Fig. 7, showed that the actual strain could exceed the predicted value by as much as a factor of 3, based on the real liner properties.

It was subsequently concluded that liner porosity was a significant contributor to the motor problem. As a result, the chamber lining method was changed and the void problem eliminated.

Combined Effects

An excellent example of how several of the phenomena discussed previously can combine to set the stage for a motor malfunction was provided by experience with a ground-launched tactical motor containing concentric booster and sustainer grains, and a sprayed-in liner/insulation. Although the original grain stress analysis indicated adequate safety margins, several motor firings exhibited ballistic anomalies that suggested the occurrence of sustainer cracking and/or sustainer-liner separation in the forward end of the motor (principal design features in this region, as well as locations of maximum stress and strain, are indicated in Fig. 8).

As part of the subsequent investigation, several motors were dissected and the resulting samples subjected to physical and chemical testing. The results revealed significant differences in properties between those assumed in the original analysis and those actually observed. These included the following:

1) The liner puddle, which had been assumed to be incompressible (i.e., void-free), actually had a void content of up to 15%.

2) Bulk properties of the sustainer in the motor exhibited higher moduli and lower elongations than corresponding carton data (Table 3).

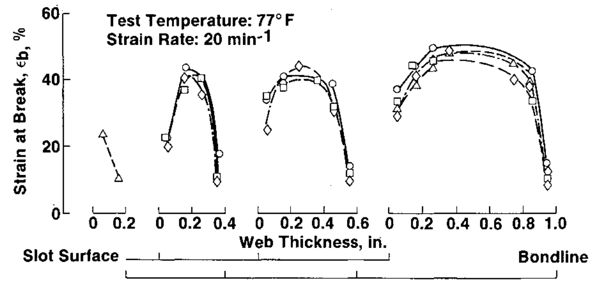

Fig. 5 Maximum strain capability in slot web decreases with web thickness.

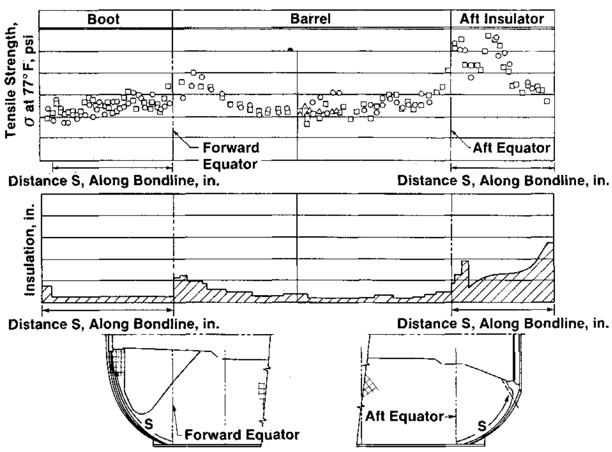

Fig. 6 Relationship between bond strength and insulation thickness.

Table 3 Comparison of initial carton and dissected motor data for sustainer propellant

	Initial (carton)				Motor			
Temp, °F	σ_m,[a] psi	ϵ_m,[b] %	ϵ_b,[c] %	E_0,[d] psi	σ_m,[a] psi	ϵ_m,[b] %	ϵ_b,[c] %	E_0,[d] psi
−40	367	72	78	3044	337	53	65	5067
77	140	36	45	755	135	22	30	1103
140	81	21	25	633	86	15	21	870

[a]Maximum nominal stress. [b]Elongation at maximum nominal stress. [c]Elongation at break. [d]Initial tangent modulus.

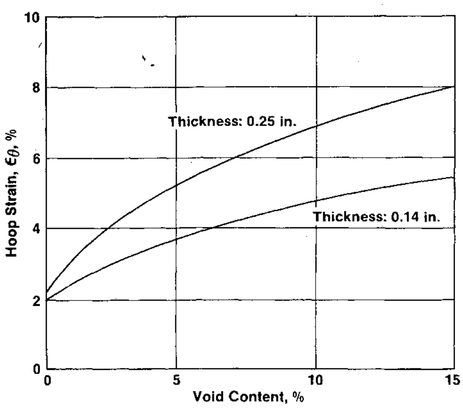

Fig. 7 Effect of liner thickness and void content upon maximum propellant hoop strain for pressurization at −65°F.

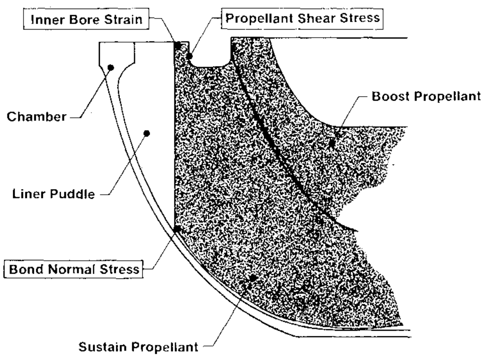

Fig. 8 Boost/sustain motor—locations of critical stresses and strains.

3) Sustainer propellant immediately adjacent to the liner puddle was found to be significantly harder than the bulk, i.e., higher modulus and lower elongation (Fig. 9). This was found to be caused by migration of plasticizer from the propellant to the liner and filtration of binder and fine filler particles from the sustainer into the surface pores on the liner puddle (Fig. 10).

4) The binder filtration also contributed to reduction of the propellant-liner bond strength relative to that expected, based on tests of samples prepared in the laboratory.

Consideration of the above changes in material properties had a dramatic effect on the structural margins of the grain.

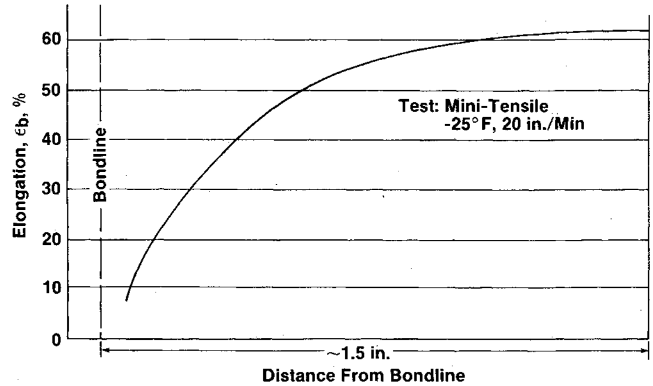

Fig. 9 Elongation gradients in sustainer adjacent to liner.

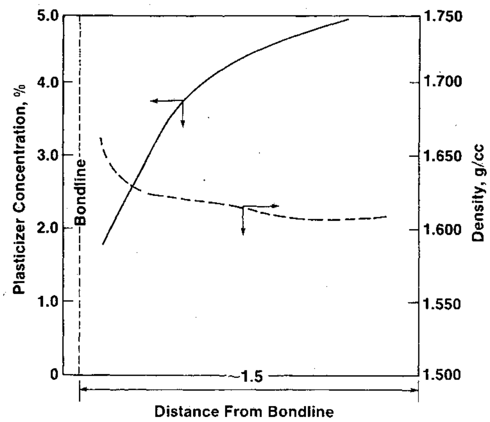

Fig. 10 Plasticizer and density gradients in sustainer adjacent to liner.

When all changes were considered, the minimum margin of safety (defined as allowable divided by requirement minus 1) for grain cracking due to operation at low temperature was −0.73, as compared to the original design value of +0.88. This comparison clearly illustrates the sensitivity of the analysis to these local phenomena occurring in the motor and emphasizes the importance of experimental evaluation of the full-scale propellant grain as a key element in the overall approach to structural integrity assessment.

Conclusions

The examples presented in the paper clearly illustrate that various factors associated with the manufacture and processing of solid rocket motors, as well as interactions between the various materials involved, can produce deviations from the assumed behaviors that could be structurally critical. To assure maximum possible accuracy for the grain structural integrity evaluation, it is crucial that some experimental evaluation of the full-scale propellant grain—in the form of excised samples, or preferably full motor dissection—be conducted during the initial motor qualification, and certainly should be included as an integral part of any motor aging and surveillance program.