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Structural Analysis Procedure for a Case Bonded Solid Rocket Propellant Grain

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During the service life, a case-bonded solid propellant rocket grain is subjected to many stress-inducing environments. The viscoelastic nature of the propellant causes a strong load-rate and temperature dependence of mechanical properties. Besides a natural decrease of physical propellant parameters in unloaded conditions, called chemical aging, there is also a mechanical properties degradation, reffered to as cumulative damage. Temperature variations are found to be the main reason for the propellant strain and stress capacity decreasing during the storage.

Various mathematical models for a structural solid propellant grain integrity analysis have been made, but they are not of the same validity as the more common models for elastic analysis. They have to be followed by appropriate three-dimensional tests. Unfortunately, it is almost impossible to make reproductive failure tests that would verify the quality of the analysis. In the case of an antihail rocket propellant grain, the repeated appearance of cracks in the star pointed grain channel has given a useful statistical sample for mathematical model verification and further analysis.

Key words: **rocket motor, propellant grain, solid rocket propellant, structural analysis, mechanical characteristics, temperature influence, service life.**

Nomenclature

A_D , A_S , A_P	- Temperature amplitude, daily, seasonal, noise
A, B, C, D	- Constants
a_T	- Time-temperature shift factor
$D(t)$, ΔD	- Time-dependent cumulative damage, damage increment
$d(t)$	- Time dependent damage fraction
E , E_e , E_{rel}	- Modulus variable, equilibrium, relaxation
$E(\omega)$	- Dynamic modulus
$E^{'}(\omega)$, $E^{''}(\omega)$	- Storage modulus, Loss modulus
M, N	- Cumulative damage law parameters
P, P_f	- Probability, Probability of failure
R, R_i	- Reliability, Daily reliability
$R,$	- Strain rate
T , T_0	- Temperature, Reference temperature
T_G, T_S, T_D	- Temperature, annual mean, seasonal, daily
T_P	- Temperature noise
t , Δt_i , Δt_{fi}	- Time, time exposed to the i-th load level, time to failure on the i-th level
ε , ε_0 , ε_m	- Strain, Initial strain, Strain at maximum stress (Ultimate strain), respectively
ξ	- Reduced time
$\eta(t)$	- Propellant aging factor
η_E , η_σ , η_ε	- Aging factor for modulus, stress, strain
ν	- Safety factor
σ , σ_m	- Stress, Strength (Ultimate stress),
$\sigma_{r,\theta}$	- Stress components, radial, tangential
$\varepsilon_{r,\theta}$	- Strain components, radial, tangential
σ_{m0} , $\sigma_m(t)$	- Initial strength, Time-dependent strength
ω_D , ω_S	- Circular frequency, daily, seasonal

Introduction

THE solid propellant grain structural integrity analysis is a branch of technics that arised at the end of the 1950s, with appearance of case bonded rocket motor grains. It coordinates information between several technical disciplines, such as the study of the propellant grain structural properties, its response to loads, theory of viscoelasticity, aging, cumulative damage, load and failure analysis, statistics, probability and reliability.

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Our research in the structural analysis began at the end of the 1970s, during the design of the sustainer for the air to earth rocket „Grom“, using case bonded HTPB propellant grain [1]. After the rocket had been finished, the activities were continued with the decreased intensity. An important rocket propellant service life research in co-operation of the Military Academy and the Military Technical Institute was done in the same period. Good results were achieved in the field of propellant mechanical characterization [2], and an elementary procedure for an analysis was made [3].

Solid propellant is a viscoelastic material composed as a mixture of three quarters of oxidizer particles embedded in the remaining one quarter rubber fuel matrix. The fuel content is sufficiently large to cause the mixture to possess significant time- and temperature-dependent properties.

The structural analysis is based on a detailed material characterization which is more complex than an elastic one.

Stress and strain values in a viscoelastic body are time-dependent and a satisfactory stress-strain time relation is needed. There is an important difference between models for structural analysis of viscoelastic and more common elastic media, but analysts are trying, more or less, to modify and use known models for the elasticity analysis.

A physical model for the analysis may be of different degree of sophistication. It depends on the analyst's knowledge as well as on the project importance, support and resources. Analysts always aim at confirming the analysis quality by three-dimensional tests that simulate the grain failure. However, it is almost impossible to make reproductive failure tests that would verify the quality of the analysis, or it is very expensive to do it. At the beginning of our research in the field of the structural solid propellant grain analysis, some methods of three-dimensional testing were defined [4].

Structural problems with the appearance of cracks in star-perforated, antihail rocket case bonded grains, caught our new attention in this field. Composite HTPB grains were cured into stiff sandwich tube structures made by rolling a paper ribon over cilindical models.

Only three months after the antihail grains production, the cracks in the star-perforated channels appeared, due to thermal stresses. One half of the grain series failed. During the next two months the cracks have appeared on the additional 30 % of grains.

An useful statistical sample was made for the physical model verification and for further analysis.

Preliminary Analysis

The antihail rocket grain with a star-perforated channel is cured into a thin stiff case that inhibit the outer cylindrical surface from burning (Fig.1).

Internal ballistic calculations have shown that the five pointed star-perforated grain was quite enough to give the requested thrust program. A selected propellant composition was very close to some former compositions, so there was no need to make a complete propellant mechanical characterization. There is a standard procedure after the propellant is cured, and only the tensile tests at +20°C and 50 mm/min were done.

The standard test results were used for a preliminary grain margin of safety estimation, and the results were acceptable. The advantage of the solution was a relatively small price of the grain production, because the existing tools for the star channel forming were used.

The first results of the motor firing tests were good.

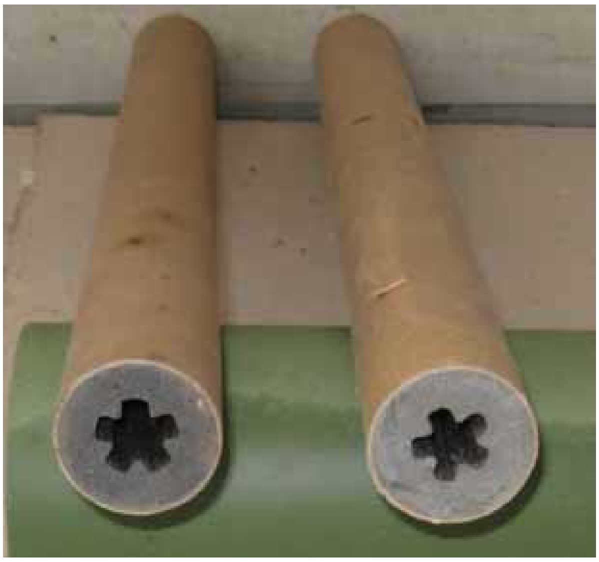

Figure 1. Antihail rocket propellant grain

Three months after two series of grains had been made, the crack appearance in the grain star channel was observed. The percent of failed grains was a clear argument that the preliminary analysis had not been good enough.

More Detailed Analysis

Propellant Mechanical Characterization

At first, an important amount of new propellant was made for a detailed uniaxial mechanical characterization. For that purpose, the same propellant composition was used as in the antihail grain. In the moment of the propellant production for a detailed structural analysis, the propellant grains with the cracks in the channel were two years old. This naturally aged propellant was used for the mechanical characterization in the period between two and three years after production.

The „Instron-1122“ tester and the „JANAF-C“ specimens were used for uniaxial tensile tests, conducted at twelve various temperatures and twelve constant crosshead speeds. This was necessary because there exists a strong temperature and time dependence of the propellant mechanical properties.

Master curves of ultimate stress, ultimate strain and relaxation modulus vs reduced time are shown in Figures. 2-4. The known method for data processing is used [5].

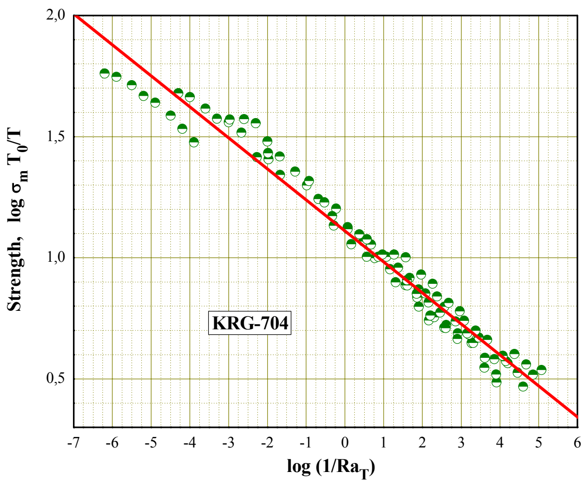

Figure 2. Ultimate stress master curve

It is important to make a difference between 'new' propellant, which is tested in the very early period after the propellant is cured, and the propellant after a certain period of storage. These first series of tests were done using the 'new' propellant.

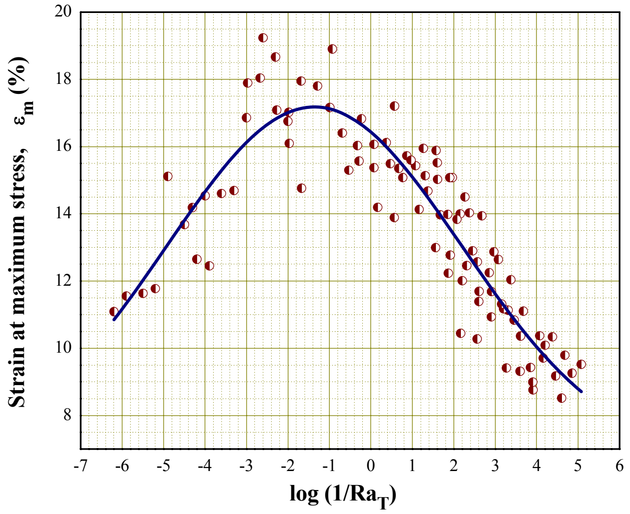

Figure 3. Ultimate strain master curve

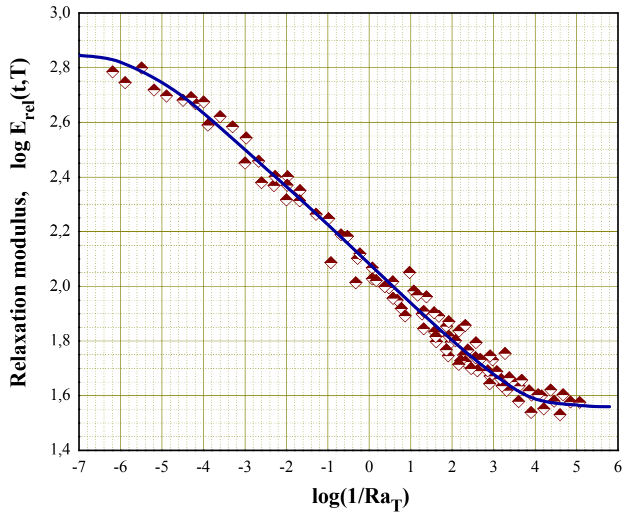

Figure 4. Relaxation modulus

During the initial period after the composite propellant is cured, there is an important change of its mechanical properties. Besides, certain differences between curing procedures may have a strong influence on the initial properties. It means that the choice of the time for the initial propellant characterization is of questionable validity.

It is an usual practice to make the first mechanical tensile tests one or two days after the cured propellant is put into the standard storage conditions. If it is required to make a complete characterization, with a lot of different test conditions, it is not possible to finish it in a short period. The storage time influence may be as strong as the crosshead speed or temperature influence. The intensity of the material properties change during the time is very strong and a special attention was directed to make an adequate correction [6].

The main task of the structural analysis is to evaluate the grain margin of safety comparing real stress (strain) values with ultimate values (strength or strain at maximum stress), using the recommended failure criteria. For example, the value of time dependent strength may represent propellant ultimate values needed for comparison.

The strength is a combination of the initial value, the aging factor and the cumulative damage [7]:

$$\sigma_m(t) = \sigma_{m0} \cdot \eta(t) \cdot [1 - D(t)] \tag{1}$$

The test results in fig.2 represent the first member in eq.1 the initial stress (σ_{m0}) versus reduced time ($\xi = 1/Ra_T$), which is a combination of time-temperature shift factor (a_T) and strain rate (R).

1. Ultimate stress (strength) is represented as a line in the log-log diagram:

$$\log\left(\sigma_m \cdot \frac{T_0}{T}\right) = C - D \cdot \log \xi \tag{2}$$

2. Strain at maximum stress, fig.3, is found to have the best representation using the Gaussian curve, similar to the normal distribution function:

$$\varepsilon_m(\%) = \varepsilon_0 + A \cdot e^{-2\cdot\left(\frac{\xi - \xi_0}{B}\right)^2} \tag{3}$$

3. Relaxation modulus, fig.4, is represented by the Wickert or generalized Maxwell model, in the series form:

$$E_{rel}(t) = E_e + \sum_{i=1}^{i=n} E_i \cdot e^{-\frac{t}{\tau_i}} \tag{4}$$

4. The relaxation modulus (eq. 4) is converted into the frequency dependent complex modulus representation [9], because it is convenient to be used for the cyclic termal loads calculation:

$$E'(\omega) = E_e + \sum \frac{E_i \omega^2 \tau_i^2 a_T^2}{1 + \omega^2 \tau_i^2 a_T^2} \tag{5}$$

$$E''(\omega) = \sum \frac{E_i \omega \tau_i a_T}{1 + \omega^2 \tau_i^2 a_T^2} \tag{6}$$

The complex part $\left(E''\right)$ of the dynamic modulus, named 'loss' modulus, is quite small and may be neglected [7].

Load Analysis

It was established that the thermal stress was the major reason for crack appearing in the antihail grain. It depends on the temperature difference that consists of four parts: annual mean, representing the difference between the stress free and seasonal mean temperature, seasonal and diurnal cyclic components, and thermal noise, as a random component, which may be expressed as a combination of a few cyclic components [8].

$$T(t) = T_G + T_S(t) + T_D(t) + T_P(t) \tag{7}$$

$$T_S(t) = A_S \cdot \sin(\omega_S \cdot t) \tag{8}$$

$$T_D(t) = A_D \cdot \sin(\omega_D \cdot t) \tag{9}$$

$$T_P(t) = \sum_{k=1}^{k=n} \frac{1}{n} \cdot A_P(t) \cdot (-1)^{k-1} \cdot \sin(\omega_k \cdot t) \tag{10}$$

The real annual temperature distribution in Belgrade in the period April 2007. - April 2008. is expressed in Fig.5. The mathematical model of temperature (Eq.7) is expressed in Fig.6 and is more conservative because it is made for the service life calculations. The component of the temperature noise is greater than in reality.

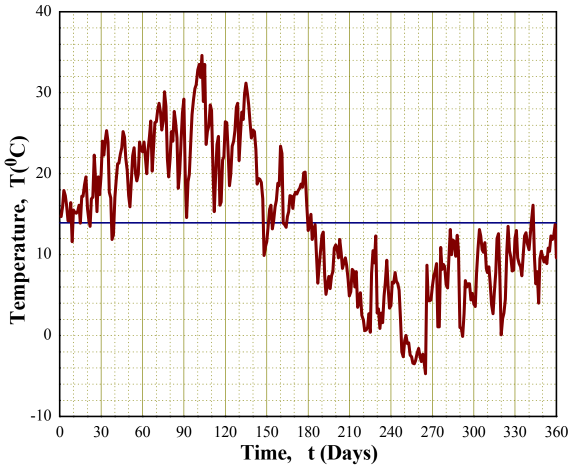

Figure 5. Real temperature annual distribution

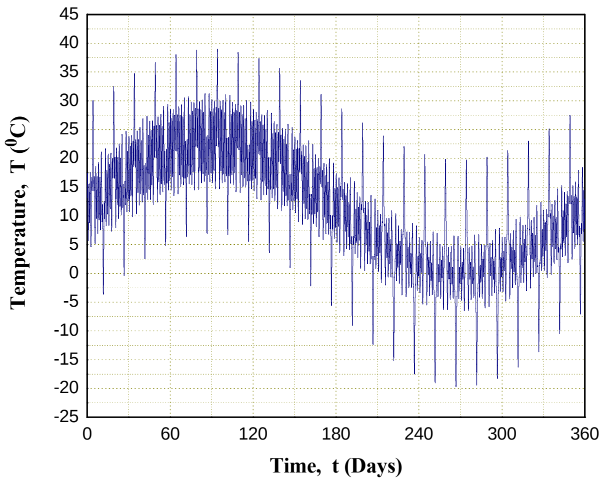

Figure 6. Mathematical model of temperature distribution

In the case of the antihail propellant grain the procedure [9] was used to calculate the time-dependent stress $\sigma(t)$. With the set of equations from the elastic analysis [8], a quazielastic procedure is reached for temperature stress and strain components calculations, replacing the elastic modulus with the complex modulus and neglecting its imaginary part (eq.6).

Propellant Aging

The second member $\eta(t)$ in Eq.1 is a factor that represents chemical propellant aging. When the results of an analysis disagree with the cracks appearing in the very early period of storage, it seems that this factor may be one of the main causes.

It is supposed that during real time the propellant master curves are translatory moved along the time axes. Therefore, it was enough to make periodical tensile tests only under standard conditions. The measured values of the initial modulus, tensile strength and strain at maximum stress for a three-year period are shown in Figures 7-9.

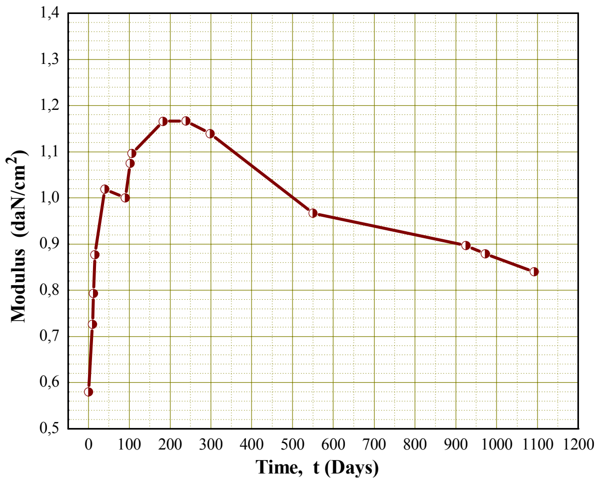

Figure 7. Propellant initial modulus vs time

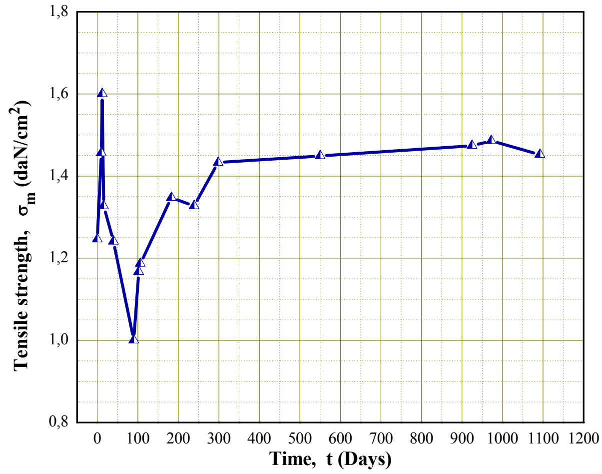

Figure 8. Propellant tensile strength vs time

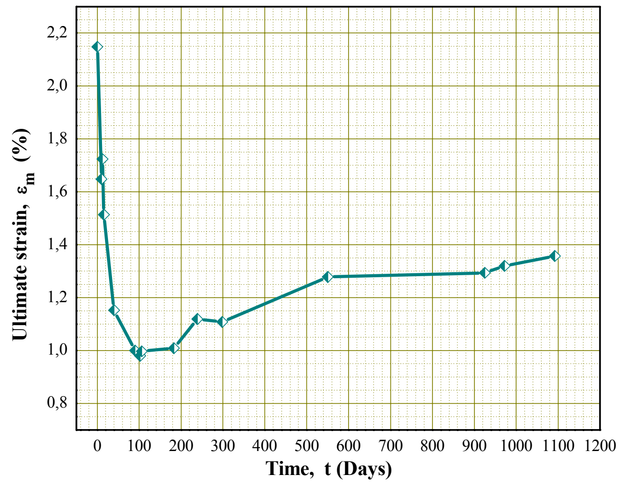

Figure 9. Propellant ultimate strain vs time

It can be seen that all of the three characteristic propellant mechanical properties are changed during two different phases. In the first phase, there is a strong initial modulus increase (Fig.7) and an ultimate strain decrease (Fig.9). The change of tensile strength (Fig.8) is not so clear in this phase as the first two changes in the properties, but it may be described in the similar manner. All three propellant properties may be expressed using exponential functions in the first phase as well as in the second one:

$$\eta_i = A + B \cdot e^{-\frac{t}{C}} \tag{11}$$

$$\eta_E = \frac{E(t)}{E_0}; \qquad \eta_\sigma = \frac{\sigma_m(t)}{\sigma_{m0}}; \qquad \eta_\varepsilon = \frac{\varepsilon_m(t)}{\varepsilon_{m0}} \tag{12}$$

The aging law for all three propellant properties is evaluated for a period of 3 years [8]. For example, the modulus time-distribution from Fig.7 is divided into two phases, as in Figures 10 and 11.

It can be seen that a very good regression is reached. The statistical variations are evaluated in details [8], and they are used later, in a more detailed analysis.

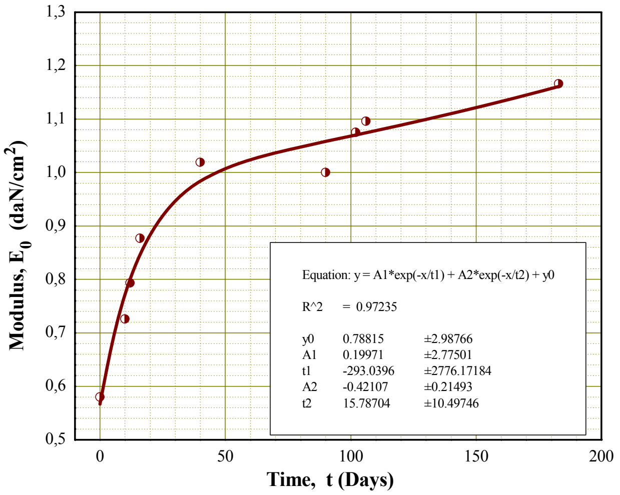

Figure 10. Modulus vs time (1st phase)

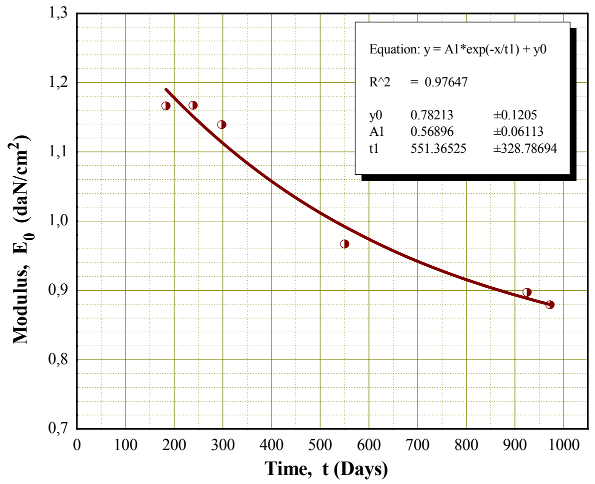

Figure 11. Modulus vs time (2nd phase)

It is said earlier that the translatory motion of the master curves during the real time axes was supposed. This presumption is equal to the statement that the aging law does not depend on test conditions.

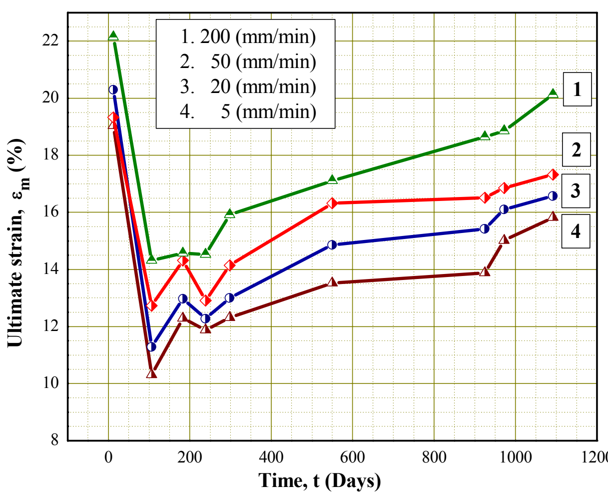

Figure 12. Periodical ultimate-strain results for different crosshead-speeds

The results of the uniaxial periodical tensile tests at a standard temperature of +20°C are shown in Fig.12, for the values of ultimate strain. Four different crosshead speeds were used. For the other two properties, a similar relation between the different crosshead-speed results was seen. The intuition says that the basic statement is correct.

The results of the initial mechanical property tests and periodical tests during the three-year period are enough to get the strength distribution defined in the first part of eq.1, connected with the chemical aging in unloaded conditions.

$$\sigma_m(t) = \sigma_{m0} \cdot \eta(t) \tag{13}$$

The real practice shows that the last member in eq.1, which represents the cumulative damage is not so important and it seems that it can be neglected in the beginning of the motor storage life. Heller [7] and Zibdeh [10] in their works consider some examples where the cumulative damage in the grain is of the order of 10^{-3} during the period of ten years.

For that reason, in the first step of the antihail grain structural analysis, the one-year period after production was considered, with the cumulative damage neglected.

On the basis of the represented results, a „quasielastic" analysis has been done, only for the temperature load acting on the propellant grain, trying to compare the results with the appearance of cracks in the grain channel. This term „quasielastic" is used to underline the differences related to an elastic as well as to a viscoelastic one. Viskoelasticity is included through the time and temperature dependence of the three main propellant properties (modulus, strength and ultimate strain). Furthermore, instead of the modulus of elasticity in the elastic analysis, an effective modulus in a quasielastic analysis is used, equal to the dynamic modulus.

The results of the damage fraction vs the time distribution $d = f(t)$ are shown in Fig.13, during a period of one year. There is a difference between the „cumulative damage" and the „damage fraction". The last represents the relation between real load and a material ultimate property.

$$d(t) = \frac{\sigma(t)}{\sigma_m(t)} \tag{14}$$

From the classic point of view, „damage fraction" is equal to the safety factor inversion $d = 1/\nu$. It represents the occupied amount of material capacity. One of very important questions is always to choose valid failure criteria. Sometimes, for viscoelastic media, it is better to compare stresses than strains and vice versa.

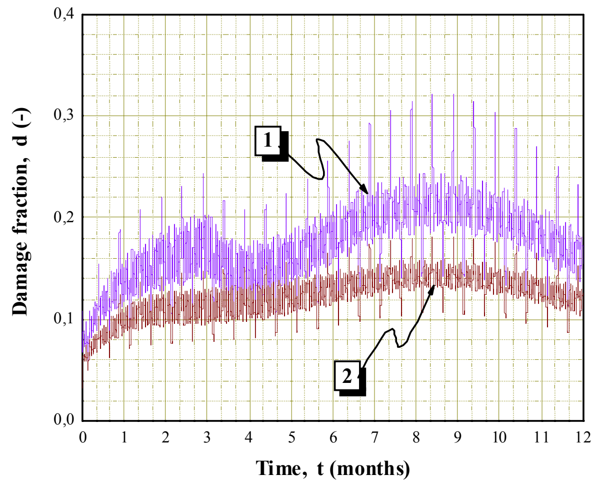

Figure 13. Damage fraction vs time distribution

Fig.13 shows the difference between stress (1) and strain (2) damage fractions in the critical point of the antihail grain, the star channel root.

Although neither of the two criteria is strongly valid, there is a big chance that the grain is structurally reliable. The maximum value of the damage fraction is about 0.32, and it corresponds to the maximum temperature noise. Indeed, the safety factor seems to be greater than 3.

Finally, the results of the more detailed analysis were opposite to the real crack occurence. The clear conclusion of the analysis was that the unexpected reason for the grain failure had been the third member in eq.1, cumulative damage, that has not been considered yet.

Cumulative Damage

Cumulative damage Law for Propellants

Stresses induced by different loads result in grain damage even though in the very early period of storage it is not detectable. Every new load causes additional damage untill failure finally occurs. For a grain analysis, the linear damage law is proposed [11] .

The damage $D(t)$ defined in eq.1 may be represented by a sum of damage fractions, the relations between times exposed to the i-th load level (Δt_i) and the times to failure on the i-th level (Δt_{fi}).

$$D(t) = \sum_{i=1}^{i=n} \frac{\Delta t_i}{\Delta t_{fi}} \tag{15}$$

For propellants, formulation (15) is based on the time to failure under constant stress [12]. In accordance with this, for the antihail HTPB composite propellant, a large number of constant load tests were organized.

Failure times (Δt_{fi}) have been measured for different loads. To describe the relationship between the applied stress (σ) and the reduced time to failure ($\xi = t_f / a_T$), a power function is used :

$$(t_f)_i / a_T = M \cdot \sigma_i^{-N} \tag{16}$$

The test results are shown in Fig.14. It is evident that the failure time is a statistical variable, loaded by a rather significant amount of dispersion. For a further analysis, the statistical variations of the parameter (M) are evaluated.

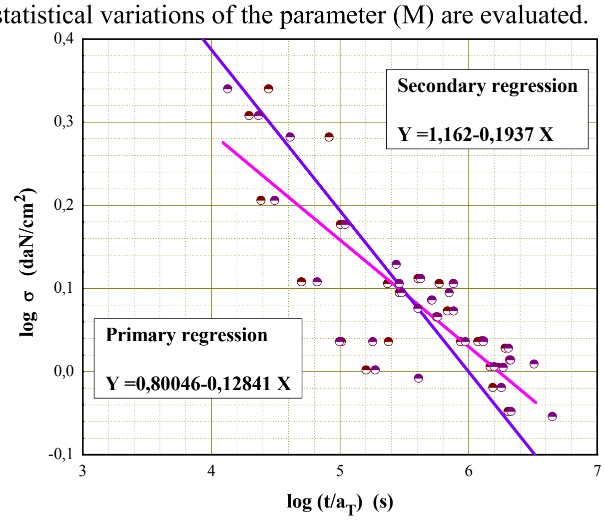

Figure 14. Stress vs Reduced time to failure

The linear regression line is represented in the form:

$$\log\sigma = m + n \cdot \log\left(\frac{t_f}{a_T}\right) \tag{17}$$

The more convenient form for the cumulative damage law is the inverse of eq.17:

$$\frac{t_L}{a_T} = M \cdot \sigma^{-N} = 1,239 \cdot 10^6 \cdot \sigma^{-6,21} \tag{18}$$

The law is estimated on the basis of a large number of long duration tests.

Cumulative Damage Analysis

In accordance with eq.15 a damage increment (ΔD) becomes:

$$\Delta D(t) = \frac{\Delta t_i}{\Delta t_{fi}} = \frac{\Delta t_i \cdot \sigma_i^N}{M \cdot a_{Ti}} \tag{19}$$

The stress components $\sigma_i = \sigma(t)$ in the grain channel are evaluated using the „quasielastic“ analysis for equal 10 min segments of (Δt) spent between (t) and ($t + \Delta t$). A numerical integration was done:

$$\Delta D = \frac{(t_{i+1} - t_i) \cdot [0,5 \cdot (\sigma_{i+1} + \sigma_i)]^N}{0,5 \cdot (a_{T(i+1)} + a_{T(i)}) \cdot M} \; ; \; D = \sum \Delta D \tag{20}$$

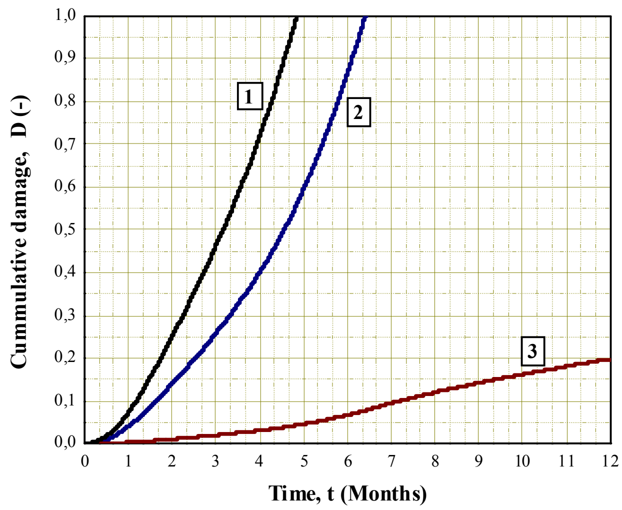

Figure 15. Cumulative damage analysis

Three different cases were analysed (Fig.16). The real damage (D) for the antihail grain (1), with a natron paper sandwich case, reaches the critical value (1.0) five months after production. The situation (2) is related to a steel case. The full damage is reached after 6 months. When the case is made of an invented material with the modulus of elasticity equal to steel, but with the coefficient of thermal expansion three times smaller, the situation (3) is reached. The accumulated damage during the whole year is of the order of 0.2. It is clear that the coefficient of thermal expansion is a factor of major influence.

The structural analysis has shown that the cracks in the grain channel were caused by low propellant resistance to the cumulative damage.

Further Analysis

The antihail propellant grain is only an example chosen to show a structural analysis procedure. For the physical model of a safety factor evaluation, the crack appearance in the grain channel is valuable. It is not easy, sometimes even not possible, to simulate a three dimensional failure to verify the quality of the model. A useful statistical sample was made for a further analysis.

A physical model is always of a questionable validity. If an analyst cannot make a failure simulation on a three-dimensional sample to verify his model, he has to believe, more or less, in the model quality, following some rules and former experience. One of the most important steps in a structural analysis is to have a useful failure criterion.

For the rocket propellant grains, there is not a unique rule whether it is better to compare stresses with propellant strength or real strains with ultimate strain. The grain is cast at a temperature that is higher than the ambient one, and a strain-free temperature is about 15 degrees over the casting temperature. It means that the difference between the ambient and strain-free conditions is always negative, and the largest components of stress and strain in the grain channel are tangential. In the bond, the critical value can be the radial stress. In the cases of other loads, the situation may be different.

Probabilistic Failure Criteria

It is recommended [12] for temperature and pressure loads to use the strain failure criteria in the grain channel and the stress criteria in the grain-case bond. However, usage of different criteria may result in the appearance of great differences in a final result of the analysis. Heller and Zibdeh [7],[10] recommend the probabilistic methodology for the rocket motor grain reliability evaluation.

This methodology may combine different criteria. For example, probability of a grain failure may be the union of three events:

1. The propellant strength is lower than the tangential stress in the grain channell:

$$P_{f1} = P\left(\sigma_{m\theta} \le \sigma_\theta\right) \tag{21}$$

2. The propellant ultimate strain is lower than the tangential strain in the grain channel:

$$P_{f2} = P\left(\varepsilon_{m\theta} \le \varepsilon_\theta\right) \tag{22}$$

3. The propellant strength is lower than the radial interfacial stress in the grain-case bond:

$$P_{f3} = P\left(\sigma_{mr} \le \sigma_r\right) \tag{23}$$

The three induced events are independent and the probability of failure may be approximated by the sum of probabilities:

$$P_f = P_{f1} + P_{f2} + P_{f3} \tag{24}$$

The probability approach is based on statistical measures of all the material properties and real stresses. With this technique, all measurements are assumed to have normal distributions and each measurement is discussed in terms of the two factors that characterize a normal distribution - the mean and the standard deviation.

Propellant Grain Reliability

Equation (24) gives the probability of failure at any time. To calculate the values of the grain reliability it is necessary to get the probability values at the end of every temperature cycle. The value of reliability depends on the events contrary to the failure:

$$R_i = 1 - (P_f)_i \tag{25}$$

After (n) cycles, using the multiplication rule of probabilities, the reliability is equal to the probability of surviving all of them, and it is given as an n- fold production:

$$R_n = (1 - P_{f1}) \cdot (1 - P_{f2}) \cdot \ \dots \ \cdot (1 - P_{fn}) \tag{26}$$

$$R_n = \prod_{i=1}^{i=n} (1 - P_{fi}) \tag{27}$$

An example of the probability of failure (1) and the reliability (2) for an analysed and experimentally tested rocket propellant grain is shown in Fig. 9. The periodical excursions of the probability of failure are caused by temperature noise. The advantage of the smooth reliability curve as a criterion of failure is evident.

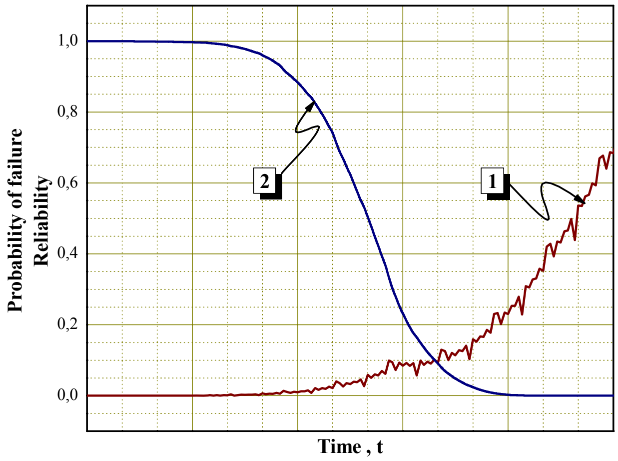

Figure 16. Reliability and Probability of grain failure

On the basis of reliability evaluation, the service life of the propellant grain may be easily estimated.

Discussion

The Antihail Grain Problem Solution

It is known that temperature stresses and strains in case bonded propellant grains are proportional to the difference between propellant and case coefficients of thermal expansion. The propellant coefficient is nearly ten times higher than the steel one, or the natron paper's. If a case material were selected to have a thermal coefficient similar to the propellant, it would result in low thermal stresses in the grain. It can be seen from Eq.20 that low stresses produce small damage increments.

The structural analysis indicated that the primary reason for the grain failure had been cumulative damage, and it was rather unexpected.

There were two possible ways of solving the antihail grain structural problem. At first, to change propellant composition, increasing the ultimate stress and, according to the new rule, increasing the resistance to damage. This solution is connected with some possible conflicting requirements of ballistic performance. The second one is to substitute the case material with a new one, strong enough, but thermally more closer to the propellant. This solution has been successfully chosen.

Recommendations for Preliminary Analysis

During the grain design, a limited set of mechanical properties for a new propellant composition is known. Usually, mechanical properties data of similar propellants is quite enough for preliminary calculations, before real uniaxial test results are ready for a further analysis.

For the cumulative damage law estimation, at least a few months is needed. For the sake of a preliminary service life estimation, a structural analyst may use a comparison between the cumulative damage law and ultimate stress, as in Fig.17. The results for two different propellants are shown. The antihail HTPB propellant is denoted as (1).

In the log-log stress vs reduced time diagram, the cumulative damage line (σ) is located approximately two decades of time related to the strength line (σ_m). A similar relation for two different propellants is seen. If it is used as a rule, for a preliminary analysis it is enough to have only information about propellant ultimate stress.

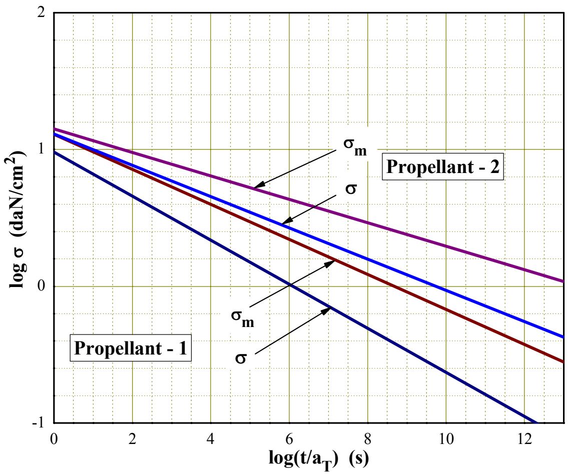

Figure 17. Comparison between ultimate stress (σ_m) and cumulative damage (σ)

Conclusion

A short review of a solid propellant case-bonded grain structural analysis is given in this paper. The real antihail rocket grain is considered. The appearance of cracks in the grain star channel is utilized as a sample for analytical model verification.

It is recognized that the temperature loads were of major intensity, because the grain failure had appeared before the motors were ignited. The mathematical model for the analysis is verified because the results of reliability and service life calculations coincided with the time of failure appearance on real grains.

The probabilistic failure criterion is recommended as a model that is better than a simple stress/strength or strain/ ultimate strain margin of safety evaluation.

During the HTPB composite propellant mechanical characterization and cumulative damage analysis, some potential rules were recognized. They can be used in the case of a new bonded grain design.

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Postupak strukturne analize vezanog pogonskog punjenja raketnog goriva

Tokom veka upotrebe, vezano pogonsko punjenje raketnog motora je izloženo uticaju raznih opterećenja. Viskoelastična priroda čvrstog raketnog goriva uslovljava izraženu zavisnost njegovih mehaničkih osobina od temperature i brzine opterećenja. Pored promene usled prirodnog starenja, mehaničke osobine goriva opadaju i usled akumulacije oštećenja. Tokom skladištenja, glavni uzrok slabljenja mehaničkih osobina goriva su varijacije temperature okoline.

Različiti matematički modeli postoje za strukturnu analizu pogonskih punjenja ali nisu pouzdani kao za elastična tela. Zbog toga je potrebna njihova provera u trodimenzionalnim testovima. Nažalost, teško je ostvariti opite koji dovode do loma, i služe za potvrdu kvaliteta proračuna. Kod protivgradne rakete, reproduktivna pojava prskotina u centralnom kanalu pogonskog punjenja sa oblikom zvezde dala je dobar statistički uzorak za proveru kvaliteta modela i dalju analizu.

Ključne reči: **raketni motor, pogonsko punjenje, čvrsto raketno gorivo, strukturna analiza, mehaničke karakteristike, uticaj temperature, vek trajanja.**

Процедуры структурного анализа скреплённого топливого заряда ракетного двигателя

В течение срока годности, скрепл топлив заряд ракетного двигателя зависит от влияния различных нагрузок. Вязкоупругий характер твёрдого ракетного топлива является причиной выраженной зависимости его механических свойств от температуры и скорости нагрузки. Помимо изменений из-за естественного старения, механические свойства топлива добавочно ослабляют и снижают и из-за накопления повреждений. Во время хранения в складах, основной причиной ослабления механических свойств топлива являются колебания температуры окружающей среды. Различные математические модели существуют для структурного анализа вождения заряд, но не столь надежны, как для упругих тел. Таким образом, они должны пройти проверку в трёхмерных тестах и контролях. К сожалению, очень трудно провести эксперименты, которые приводят к разрушению, и служат для подтверждения качества расчётов. У противоградовых ракет, репродуктивное явление трещин в центральном канале для топливого заряда топлива со звездой даёт хорошую статистическую выборку, чтобы проверить качество моделей и дальнейшего анализа.

Ключевые слова: **ракетный двигатель, метательный заряд ракеты, твёрдое ракетное топливо, структурный анализ, механические свойства, влияние температуры, срок службы.**

Un exemple de procédé pour l'analyse structurale du propergol solide chez le moteur à fusée

Pendant la durée d'emploi la charge propulsive d'un moteur à fusée est exposée à l'influence de différentes pressions. La grande élasticité du propergol solide conditionne la dépendance forte de ses caractéristiques mécaniques quant à la température et à la vitesse de la charge. Outre le changement causé par le vieillissement naturel, les caractéristiques mécaniques du propergol diminuent aussi à cause de l'accumulation de l'endommagement. Au cours du dépôt la cause principale de diminution des caractéristiques mécaniques du propergol sont les variations de la température ambiante. Les différents modèles mathématiques existent pour l'analyse structurale des propergols mais ces modèles sont fiables seulement pour les corps élastiques. Pour cette raison il est nécessaire de faire leur vérification par les tests à trois dimensions. Malheureusement il est difficile de faire les essais qui provoquent la défaillance. Chez la roquette contre grêle l'apparition reproductive des fractures dans le canal central en forme d'étoile a donné un bon échantillon statistique pour la vérification de la qualité du modèle et pour les futures analyses.

Mots clés: **moteur à fusée, charge propulsive, propergol solide, analyse structurale, caractéristiques mécaniques, influence de température, durée de vie.**