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STRUCTURAL ASSESSMENT OF SOLID PROPELLANTS UNDER THERMAL LOADING CONDITIONS FOR VARIOUS CLIMATE CONDITIONS

Tuğrul AKSOY[1] and Tarık OLĞAR[2] and Sibel ARAL[3]
ROKETSAN Inc.
Ankara, Turkey

ABSTRACT

In this study, a probabilistic approach is developed for the structural assessment of propellants of solid rocket motors, which are exposed to random thermal loading during their service life. Critical stress and strain values are obtained via finite element analysis (FEA) under thermal loading. In order to relate these values to the input variables, a design of experiment (DOE) study is carried out and response surface models (RSM) are extracted. Limit state functions are defined for bore cracking failure condition by using RSM results. By using mean value-first order second-moment (MVFOSM) method, structural reliabilities based on the limit state functions are calculated for an anticipated duration. Reliability calculations are repeated for the climate conditions of three locations in Turkey. Damage and aging effects of the propellant are also taken into account.

INTRODUCTION

Rocket motors containing solid propellants are designed to be stored in various geographic locations and storage conditions. Hence, they are required to withstand to various climate conditions and preserve their structural integrities against these conditions. For that purpose, thermomechanical analyses are carried out in order to obtain the stress-strain distributions of the propellants under random thermal loading environments and predict the structural failure condition.

Previously, many researchers studied on the structural assessment of the solid propellants exposed to uncontrolled thermal loading environments. Some of them performed deterministic approach [Zhou et al., 2015; Chu and Chou, 2003; Tunç and Özüpek, 2019]. for the estimation of margin of safety levels whereas some others developed probabilistic approaches by taking into account the statistical distributions of thermal loading inputs and material properties [Heller et al., 1979; Heller and Singh, 1983; Akpan et al., 2003]. Since the climate conditions which the rocket motors are to be stored have significant variances and material properties of the propellants (i.e. long-term modulus (E_∞), coefficient of thermal expansion (CTE)) have remarkable uncertainties, probabilistic approaches became more important in the last decades.

As a first step in this study, finite element analysis (FEA) of the propellant is performed under an arbitrary thermal loading condition and structurally critical location is detected. This location is found to be the transition from the cylindrical to fin region. For this location, maximum equivalent stresses and strains are computed and margin of safety values are calculated. As a result of these calculations, margin of safety for the strain capacity is found as much lower

[1] Specialist Engineer at Structural Analysis and Test Department, Email: tugrul.aksoy@roketsan.com.tr
[2] Leader Engineer at Structural Analysis and Test Department, Email: tolgar@roketsan.com.tr
[3] Leader Engineer at Structural Analysis and Test Department, Email: satlar@roketsan.com.tr

with respect to stress capacity. Therefore, the structural reliabilities are calculated based on the limit state functions considering the strain capacity.

METHOD

Initial Analysis for the Estimation of Failure Criterion

FEA studies are carried out on ABAQUS© finite element software. An initial thermomechanical analysis is performed by applying a thermal loading as shown in Figure 1. As a result, the equivalent stress-strain distributions are obtained as demonstrated in Figure 2 and the critical location is found as the transition from the cylindrical to fin region. In order to determine which failure criterion to be used in the reliability analysis, margin of safety values are calculated for the critical location by considering stress-strain capacities via following expression [Fitzgerald and Hufferd, 1971]:

$$MS_{\sigma} = \frac{\sigma_{cap}}{\sigma_{eqv}} - 1;\ MS_{\varepsilon} = \frac{\varepsilon_{cap}}{\varepsilon_{eqv}} - 1 \quad (1)$$

With these calculations, margin of safety for the stress capacity (MS_{σ}) is computed as 5,75 while for the strain capacity (MS_{ε}) computed as 1,58. Since the margin of safety is found as lower for the strain capacity, structural reliability calculations will be based on the strain criterion.

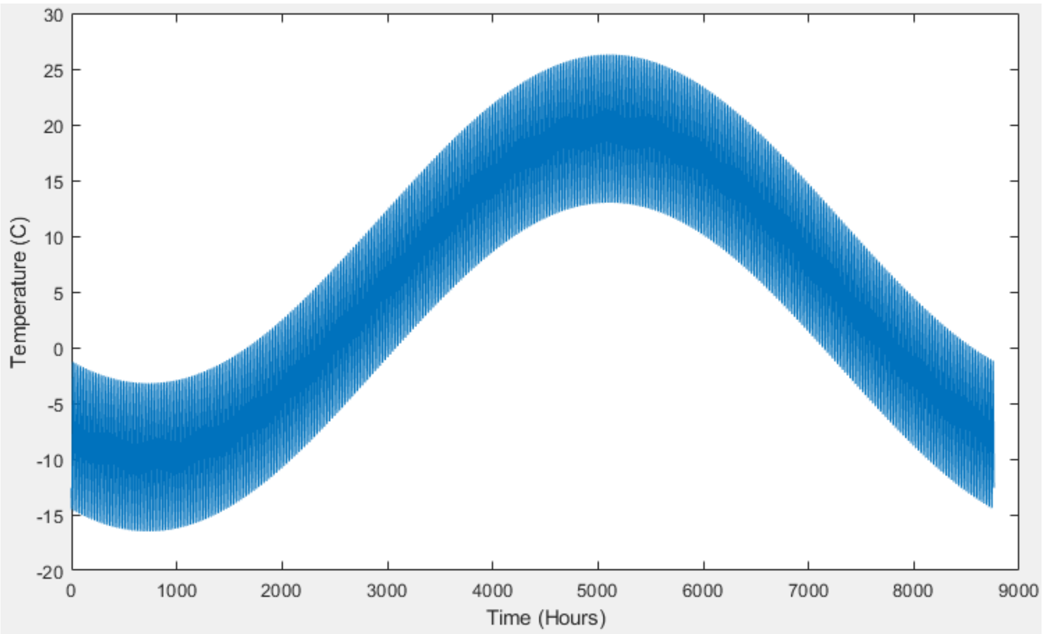

Figure 1: Arbitrary thermal loading

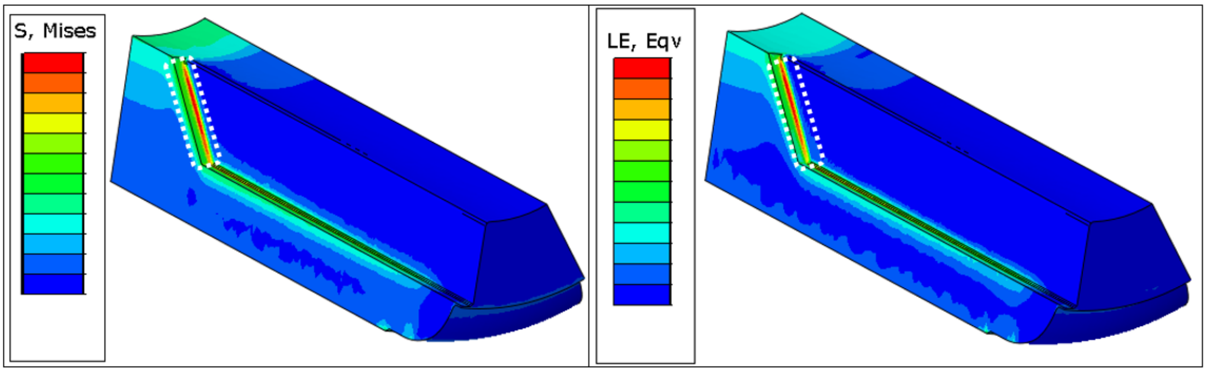

Figure 2: Critical region for the equivalent stress and strain distributions

Design of Experiment (DOE) Study

In order to construct a correlation between the input variables (thermal loading variables and propellant material properties) and outputs (equivalent strain), a RSM is extracted by performing a DOE study. Outputs are computed via FEA's.

Thermal loading is modelled as the combination of yearly and daily temperature cycles [Heller et al., 1979]:

$$T(t) = T_m + T_y \sin\left(\frac{2\pi}{8760}\right)(t - \theta_y) + T_d\left(\frac{2\pi}{24}\right)(t - \theta_d) \tag{2}$$

Where T_m, T_y and T_d denotes the mean temperature, yearly temperature amplitude and daily temperature amplitude, respectively. θ_y and θ_d are the yearly and daily temperature phases. In the DOE study, T_m, T_y and T_d values are taken as thermal loading variables. In addition, CTE and E_∞ material properties of the propellant are considered as input variables. Ranges of these variables are presented in Table 1.

Table 1: Ranges of the Input Variables for DOE Study

	Min. value	Max. value
Mean temperature (T_m)	1 °C	19 °C
Amplitude of yearly cycle (T_y)	3 °C	32 °C
Amplitude of daily cycle (T_d)	1 °C	8 °C
Coefficient of thermal expansion (CTE)	6,3E-5	1,2E-4
Long-term modulus (E_∞)	0,18 MPa	0,42 MPa

DOE study is carried out on ISIGHT engineering software and a schematic representation of this DOE study is demonstrated in Figure 3.

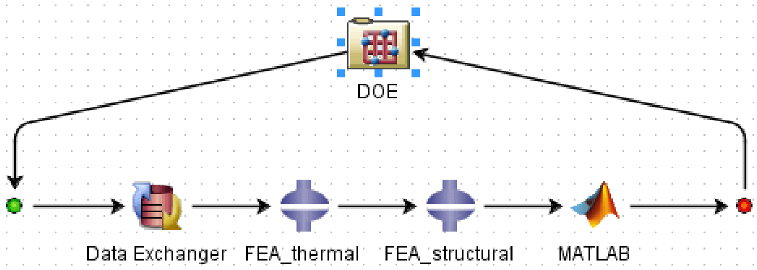

Figure 3: Scheme of the DOE study

As a result of the DOE study, equivalent strain output is correlated to the input variables by using Latin Hypercube method which allows many more points and combinations to be used for each input variable [Choi et al., 2007]. Totally 52 parameter set is used for this method. For the RSM technique, a second-order mathematical model is preferred as the following formula [Long and Narciso, 1999].

$$y = a_0 + \sum_{i=1}^{k} a_i X_i + \sum_{\substack{i=1,j=2 \\ i<j}}^{k} a_{ij} X_i X_j + \sum_{i=1}^{k} a_{ii} X_i^2 \tag{4}$$

where y is the output, x_i's are the inputs and a_i's are the RSM coefficients. In addition to the extraction of RSM coefficients, effects of input variables to the maximum strain output is determined at the end of DOE study as shown in Figure 4. According to this graph, CTE property of the propellant is the most effective input with %47,3 effect.

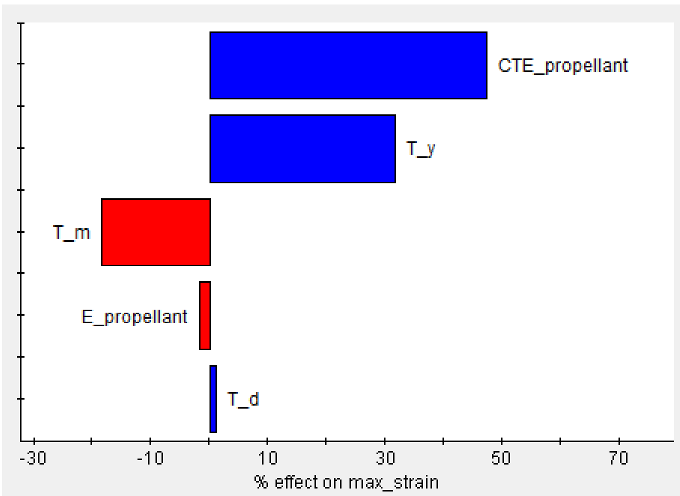

Figure 4: Standalone effects of the input variables on maximum strain value

Structural Degradation Mechanisms: Aging and Damage

In this study, Layton's model is used to account for the aging effect. According to this model, any mechanical property (S) at time t can be calculated as follows [Layton, 1973]:

$$S(t) = S_0 + k \log(t) \tag{5}$$

where S_0 is the mechanical property value at the end of cure and k is the rate of change of the mechanical property. k value can be calculated by means of Arrhenius equation as follows [Kivity, et al., 2005]:

$$k = Ae^{\left(-E_a/_{RT}\right)} \tag{6}$$

where A denotes the Arrhenius constant, R is the universal gas constant and E_a is the activation energy. Experiments show that the stress capacity and modulus of the propellant increases with aging whereas the strain capacity decreases. Therefore, the plus sign in equation (5) converts to minus for the strain capacity property. In this study, three locations of Turkey are taken into consideration for the structural reliability assessment. For these locations, temperature and aging factor variations with time for one year are demonstrated in Figure 5 and Figure 6. Seasonal temperature distributions for these locations are computed from the data adopted from Turkey Meteorology Head Office [Mgm, 2019]. By observing these graphs, it can be understood that the aging factors are increases with temperature as expected.

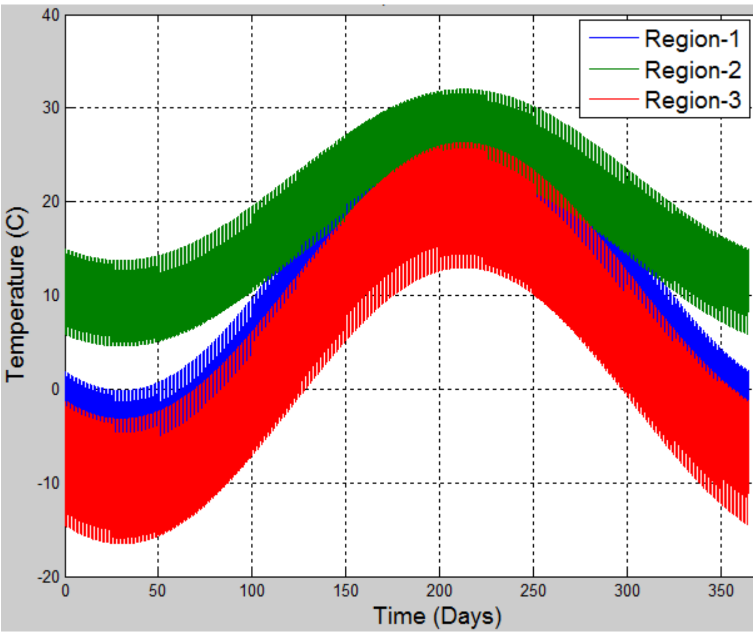

Figure 5: Seasonal temperature variations of selected three locations

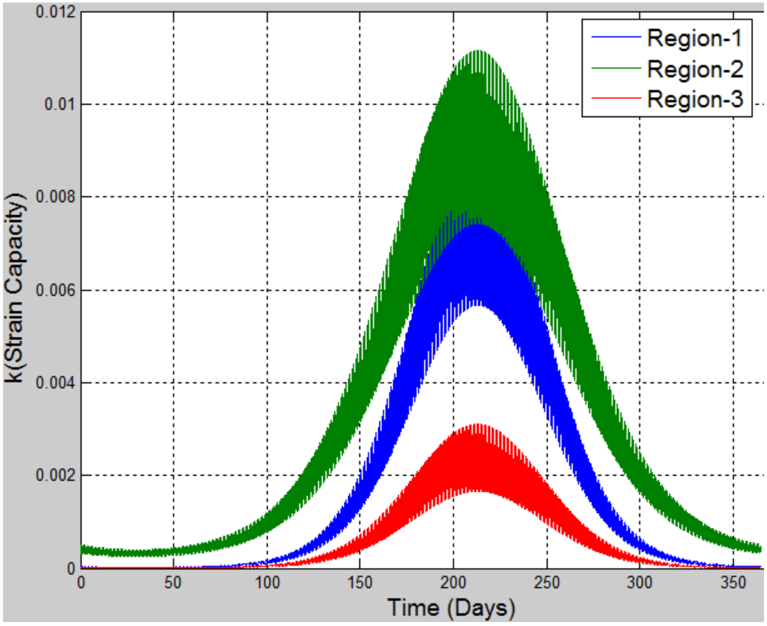

Figure 6: Seasonal variation of aging factors for selected locations

Fluctuating thermal loading causes mechanical damage to occur within propellant which deteriorates the structural capacity of propellant [Heller and Singh, 1983]:

$$S(t) = S_0(1 - D(t)) \tag{7}$$

where S_0 is the structural capacity of the propellant at zero time, S(t) is the capacity at any time t and D(t) is the time dependent damage factor. Damage factor for the propellants can be derived from the following expression [NASA, 1973; Bills et al., 1970]:

$$D(t) = \sum_{i=1}^{n} [\frac{\Delta t_i}{\alpha_T(T(t_i))} \left(\frac{\sigma_i}{N}\right)^{\beta}] \tag{8}$$

where N is the stress level causing to failure at unit time, Δt_i is the time duration of the propellant exposed to σ_i stress level and $\alpha_T(T(t_i))$ is the time-temperature shift factor calculated for the temperature at time t_i. Damage factors calculated under the thermal loading environment of three locations for 10 years duration are shown in Figure 7.

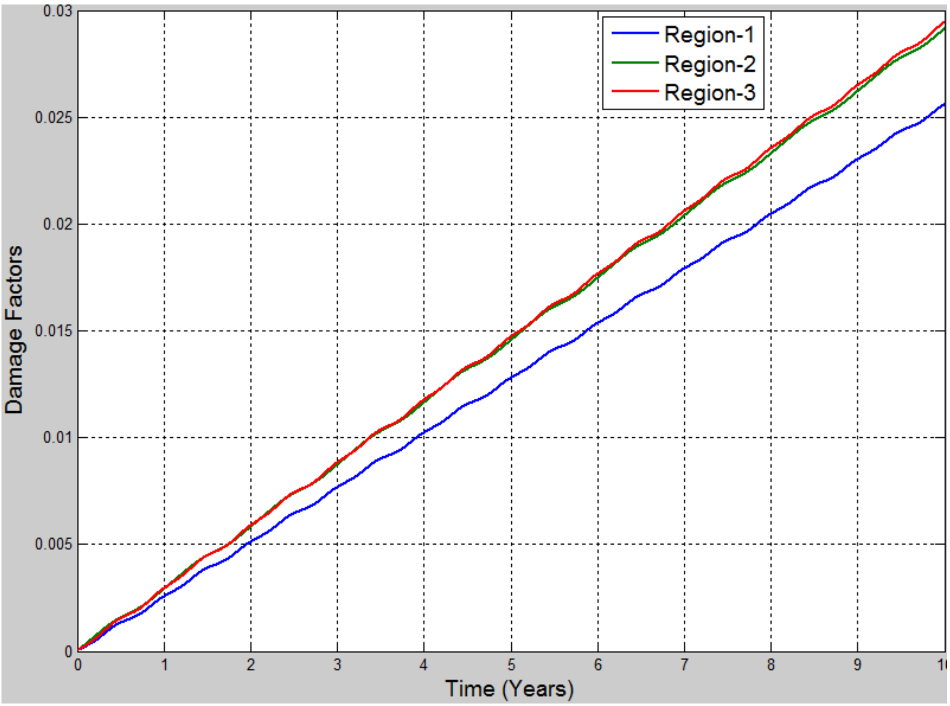

Figure 7: Damage factors for selected locations

Reliability Assessment

Reliability calculations are performed based on the limit state functions considering the strain capacity of the propellant. Limit state function is defined as [Akpan et al., 2003]:

$$g(x) = \varepsilon_{cap}(X) - \varepsilon_{eqv}(X) \tag{9}$$

where $\varepsilon_{cap}(X)$ and $\varepsilon_{eqv}(X)$ are the strain capacity and equivalent strain induced on the propellant, respectively. They are both functions of random variable X. Probability of failure is defined as the probability of the limit state function's being smaller than zero:

$$P_f = P\,[g(x) < 0] \tag{10}$$

According to MVFOSM, probability of failure depends on the reliability index:

$$\beta = {}^{\mu_g}/_{\sigma_g} \tag{11}$$

where μ_g, σ_g are the mean value and standard deviations of limit state function. Then the probability of failure is computed as the cumulative distribution of reliability index [Haldar and Mahadevan, 2000]:

$$P_f = \Phi\,(-\beta) \tag{12}$$

The hazard rate concept is introduced in order to calculate the progressive probability of failure [Ang and Tang, 1984]. This variable is simply defined as the probability of failure between time t and t + dt assuming that failure does not occur until time t:

$$\lambda(t) = \frac{P_f(t_i)}{1-\sum_{j=1}^{i-1} P_f(t_i-1)} \tag{13}$$

Then the progressive reliability can be formulated by using hazard rate as follows:

$$R(t) = e^{(-\int_0^t \lambda(\xi)d\xi)} \tag{14}$$

Progressive probability of failure can be related to progressive reliability as:

$$P_f(t) = 1 - R(t) \tag{15}$$

Progressive reliabilities are computed under three various climate condition locations of Turkey for 10 years duration. These reliabilities are plotted in Figure 8 as a function of time

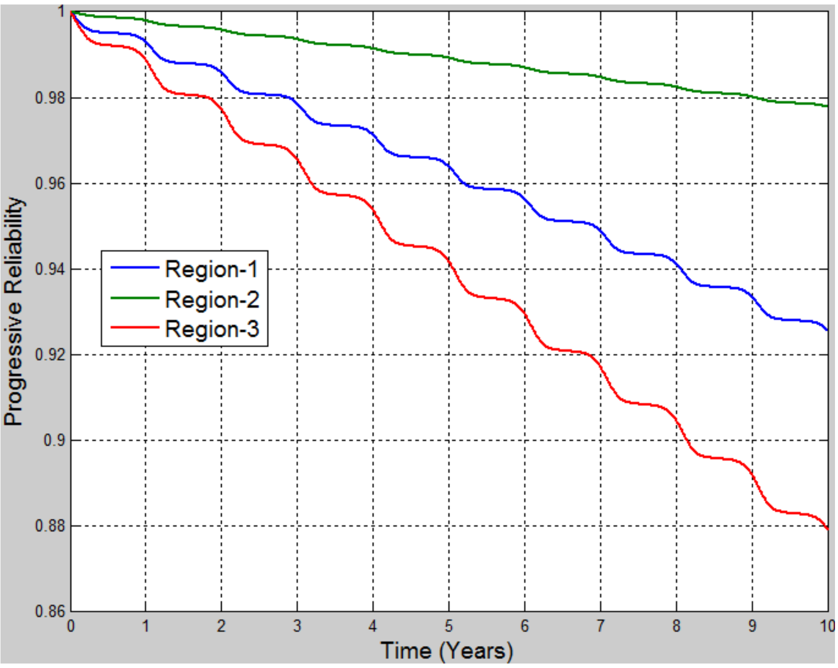

Figure 8: Progressive reliabilities computed for selected locations

RESULTS AND DISCUSSION

By observing the progressive reliability plots given in *Figure 8*, it can be said that the propellant located in the region-3 is more likely to fail since the progressive reliability values under this climate condition shows a rapid decrease with respect to other regions. This phenomenon can be explained with the case of the region-3 has colder climate condition than the other two regions. Because of this case, strains arisen within the propellant are higher than the propellants located in region-1 and region-2. Even though the aging factors are lower for the colder climate conditions (see Figure 6), this situation seems to be more effective on the reliability values.

CONCLUSIONS

In this study, structural assessment of a solid propellant exposed to thermal loading under three different climate conditions is performed. For that purpose, probabilistic approach is preferred and the reliabilities are computed for both three climate conditions. Finite element analyses are carried out in order to determine the critical stress-strain locations on the propellant and a DOE study is performed to construct a mathematical model between the input variables and critical stress-strain values. By using this model and considering the degradation mechanisms (aging and damage) of propellant, failure probabilities; thus the progressive reliabilities of propellant for both three climate conditions are calculated. As a result, the propellant exposed to climate conditions in region-3 is found as the riskiest for the structural failure because of the higher strain values computed due to the colder temperatures and high temperature differences. As a future work, experiments should be performed to verify this situation by monitoring the critical strains & stresses at the interior surfaces of the propellant and observing the structural failure cases under various climate conditions.

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