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RELIABILITY ANALYSIS OF EXTERNAL TANK ATTACH RING (ETA)

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The work in this report is part of an overall study in the area of the evaluation of the performance of the shuttle. Besides the main engines and the Orbiter, the main parts of a shuttle are the Solid Rocket Boosters, External Tank, and the External Tank Attachment Ring (ETA). The present study is restricted to ETA, but the concepts discussed are general in nature and can be applied to any structural component. The strengths of steel, the cross-sectional dimensions of the steel section and, thus, the strength of the model itself and the loads are all variable parameters. In other words, taking the entire structural element under consideration, the resistance and the applied load are random variables. Consequently, the traditionally used deterministic analysis (the so-called margin of safety approach) does not reveal the actual safety reserve in the structure, because it does not include the inherent variability in the material, geometric and load parameters. Such a variability can easily be included in the probabilistic analysis using probabilistic methods which are in use and have been continuously developed for about the last two decades. The objective of this research work is to use some of the existing probabilistic methods to calculate the reliability of ETA Ring at various critical sections for the limit state of stress. This is done both in terms of the traditional probability of failure (P_f) and reliability levels as well as the well known safety indices (β) which have become a commonly accepted measure of safety.

For any probabilistic analysis, a certain deterministic model is needed for which the limit state function can be formulated in terms of the general basic variables of resistance and load. The variability of the materials, cross-sectional properties and load can then be incorporated into the deterministic model which then forms the basis of the probabilistic model and the beta value can then be calculated. The details of the deterministic model and the corresponding deterministic analysis which was done by USBI (2) under contract for NASA and specifically for Marshall Space Flight Center forms a basis for the present probabilistic study.

If R is the resistance variable and S is the load variable, the limit state function g is then g=R-S=0 which divides the failure and the survival region. The corresponding safety index (β) which is the shortest distance from the origin to the failure surface can be defined as,

$$\beta = \frac{\bar{g}}{\sigma_g} \qquad [1]$$

β can also be considered as the measure of the number of standard deviations that the mean value of the limit state function is from the failure surface. If R and S are normal-normal or lognormal-lognormal, the following relations hold:

$$P_f = \Phi(-\beta) \qquad [2]$$

where Φ is the standard cumulative normal distribution function. If R and S are normal, β can be expressed as (1)

$$\beta = \frac{\bar{R}-\bar{S}}{\sqrt{\sigma_R^2+\sigma_S^2}} = \bar{g}/\sigma_g \qquad [3]$$

Knowing P_f from equation [2], which in turn uses β from equation [3], the reliability can be calculated. This would indicate that the higher the value of beta, the higher is the safety reserve in the structure with respect to that limit state. It should be noted that while there exists in the literature a closed form relation similar to equation [3] for R and S both being lognormal, numerical techniques have to be employed for other distributions.

In the present study, as the ETA Ring is complicated, there are no closed form expressions between the output variable of principal stress and the corresponding input variables. Hence, probabilistic study is quite complicated. The deterministic procedure used for the calculation of stresses is the well known finite element method (FEM). The corresponding probabilistic study which will use Monte Carlo techniques, will involve FEM in conjunction with the properties of the probability distributions of all variables involved in the calculation of stresses at critical points. This procedure has been successfully applied before (5) and the details are given in the extended report (4). In the study of ETA Ring the limit state g is defined as

$$g = (\sigma_u)_{ALL} - (\sigma_P)_{ACT} \qquad [4]$$

corresponding to $P_f = P((\sigma_u)_{ALL} < (\sigma_P)_{ACT})$. $(\sigma_P)_{ACT}$ stands for actual principal stress and $(\sigma_u)_{ALL}$ is the ultimate allowable stress of the material. In here, both $(\sigma_u)_{ALL}$ and $(\sigma_P)_{ACT}$ are considered as random variables. Using the procedure described in detail in reference 4, P_f, R and β values are calculated for all the critical elements at all critical sections. The critical sections identified were the tunnel splice plate and H-fitting lugs (2). In addition to this a probabilistic margin of safety (PMS) is calculated which is defined as (3)

$$PMS=\frac{(\overline{\sigma}_u)_{ALL}-(\sigma_P)_{max}}{s_{\sigma_u}} \quad [5]$$

$$(\sigma_P)_{max}=\overline{\sigma}_P+\beta s_{\sigma_P} \quad [6]$$

where, a bar over a variable indicates the mean value and s indicates standard deviation of the variable used as a subscript for s. This is done for ready comparison with the corresponding deterministic value of margin of safety calculated in reference 2.

Based on this extensive study discussed in detail(4), it has been found that the probabilistic margin of safety is consistently higher than the deterministic margin of safety indicating higher safety reserve. It has also been found that the reliability of all the critical elements is quite high indicating a good quality control of the work done at NASA.

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