FACTORS OF SAFETY AND RELIABILITY

Present Guidelines & Future Aspects

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ABSTRACT

Derivation of Guidelines for Factors of Safety based on structural reliability is briefly described. Specific underlying assumptions (e.g. material scatter, linear behaviour) are highlighted. Extension of the approach to Fatigue and Fracture is outlined, as well as future extension to the Partial Factors of Safety approach.

1. INTRODUCTION

The conventional understanding of a safe structural design is a structure designed such that "the strength exceeds the stress with a sufficient margin". Various factors of safety (FoS) have traditionally been applied to increase calculated loads or decrease predicted strength. The traditional definition of these factors is based on generally unclear assumptions, resulting in an unknown conservatism or optimism. Such an approach is of course not well suited for extrapolation to new applications, e.g. new materials, new loads, or new man rated spacecraft requirements.

In order to rationalize the approach to the FoS a preliminary study was performed [1.1] [1.2] in which the FoS's were defined such as to reach a specified structural reliability target for typical unmanned and manned spacecrafts. This study integrated design and testing aspects on the basis of the stress-strength theory and of statistical data on loads and materials. The outcome was a set of FoS in terms of load types, component construction types and spacecraft model philosophy.

A complementary study [1.3] was performed to assess the impact of some statistical assumptions made and consider other aspects such as load classes, redundancy, fatigue, fracture analyses, etc... The objective of the present paper is to give a brief overview of the resulting draft ESA Factors of Safety Guidelines addressing all FoS's required for basic structural component design and introduce the approach outlined in the field of fatigue and fracture aspects.

The above described methodology uses the well known stress-strength method to define FoS's. A more advanced method such as the Partial Safety Factor (PSF) concept, sometimes called the Level I procedure in structural reliability engineering, capable of reflecting the importance of the scatter of the various parameters defining stress and strength respectively is presently under investigation for future extension of the work.

2. THE FACTOR OF SAFETY GUIDELINES

2.1 Basic Principles & Definitions

In traditional design a "distance" is maintained between the material allowable stress and the "maximum" expected load by using the so called FoS. Empirical rules are used to define the FoS such as for example to use the material ultimate to yield ratio. So called material allowables are usually statistically defined, the load definition is more "fuzzy" and the relationship to any probability of failure is totally unknown.

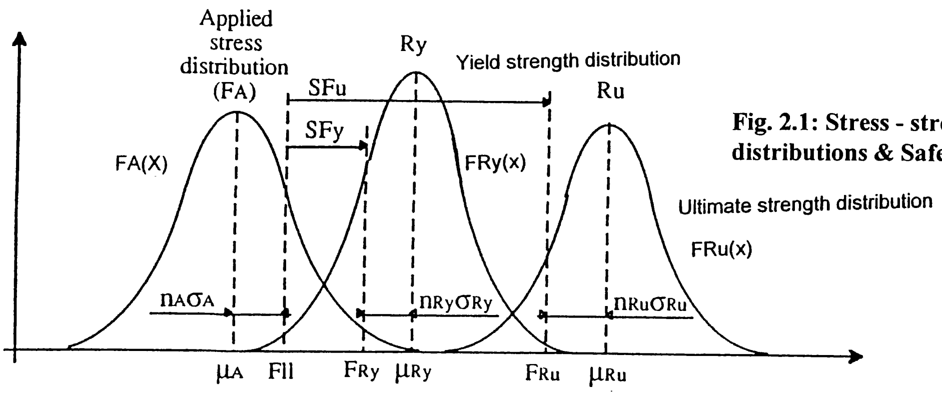

Fig. 2.1: Stress - strength distributions & Safety Factors

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If, instead of using only single deterministic values, the distributions of the resistance and the load are respectively considered, the probability of failure pf can be defined :

$$p_f = \int_0^{\infty} F_R(x) f_A(x) dx$$

where $F_R(x)$ the cumulative distribution function (CDF) of the strength R, and $f_A(x)$ is the probability density function (PDF) of the applied stress A.

Consider load originating applied stress distribution and material strength yield and ultimate distributions as shown in Fig. 2.1 (where μA, μRy, μRu are the mean values of the applied stress, the yield stress and the ultimate stress, σA, σRy, σRu are the standard deviations, nA, nRy, nRu are multipliers of the standard deviations and Fru and Fry are the allowable ultimate and yield strengths of the material) following factors SF, FOS and the safety margin MS can be defined respectively:

$$SFy = \frac{Fry}{Fl} = FOSy(1 + MSy)$$

$$SFu = \frac{Fru}{Fl} = FOSu(1 + MSu)$$

SF is called the Safety Factor, and reflects an actual relationship of the allowable strength to the applied stress.
FOS is the Factor of Safety, i.e. the minimum value of SF required. This factor is specified in the Guidelines.
MS is the Margin of Safety. It has to be positive.

Knowing the distributions, the factors SFy and SFu can be selected optimally assuming null margins of safety so as to satisfy a component target probability of failure pf in relationship to global system reliability allocations and project programmatic/verification approaches.

2.2 *Establishment of the Guidelines FOS's*

For the study, the following basic approach was taken. For a set of spacecrafts, the mechanical dimensioning files were screened to identify the various load types, the items with lowest margins of safety and their relevant failure modes, materials and construction types. Also identified was the number of such critical items of each type in the surveyed spacecrafts in relationship to the spacecraft types and masses. Based on this information and assuming all related load and material distributions are known, the stress-strength approach can be used in combination with FoS's to compute component reliabilities. From these, assuming independence and the serial approach, the spacecraft system mechanical reliability was evaluated and compared to the reliability target (Fig. 2.2).

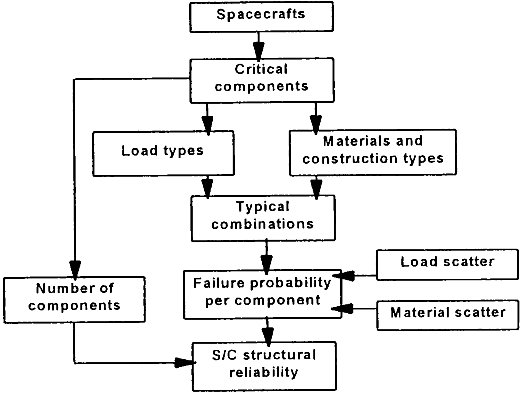
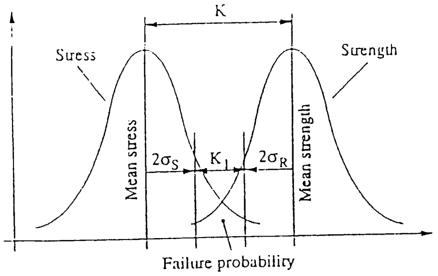


Fig. 2.2: Derivation of the Structural Reliability

To apply this methodology an extensive survey and scatter analysis of materials has been performed using test data from the aerospace field. A similar survey has been performed regarding loads using flight data whenever possible but also by assessing scatter of analytically defined loadings. Loads (index I) and materials (index j) classes have been defined for each couple (combined index ij) for which a central factor of safety

$$K_{1ij} = \frac{\mu R_i - nR_i * \sigma R_i}{\mu A_j - nA_j * \sigma A_j}$$

(ratio of fractiles) has been defined to comply with the target component probability of failure of 10^{-6} An example of such combination is shown in Fig. 2.3. This target was derived from the fact that about 1000 critical items could be identified for typical 2200 kg mass spacecrafts and that, from analysis of successful program, it appeared that the level of spacecraft global mechanical reliability had to be put at 0.999. More details can be found in Tables 2.2.1 to 2.2.3.



	Metallic Material (σ/μ = 8 %)	Metallic Material: Yield Strength when R/Yield = 1.2 (σ/μ = 15 %)	Buckling Strength of Conical or Cylindrical Metallic Shells (σ/μ = 14 %)	Carbon Fiber Composites (σ/μ = 10 %)	Junction by Screw, Rivet Welding (σ/μ = 8 %)	Bonding Structural Insert (Axial Loading), (σ/μ = 12 %)	Honeycomb: Tension (σ/μ = 16 %)	Honeycomb: Shear, Compression (σ/μ = 10 %)	Honeycomb: Face Wrinkling (σ/μ = 8 %)	Equipment Insert (in Honeycomb Axial Loading), (σ/μ = 16 %)
Launch Vehicle Thrust (σ/μ = 5 %)	1.29	2.24	1.98	1.42	1.29	1.64	2.60	1.42	1.29	2.60
Launch Vehicle Other Static Loads (σ/μ = 30 %)	1.45	1.98	1.82	1.51	1.45	1.62	2.21	1.51	1.45	2.21
Transient Loads (σ/μ = 50 %)	1.59	2.00	1.87	1.62	1.59	1.71	2.19	1.62	1.59	2.19
Thermal Loads (correlated) (σ/μ = 7.5 %)	1.29	2.17	1.93	1.41	1.29	1.61	2.51	1.41	1.29	2.51
Deployment Shock (σ/μ = 10 %)	1.29	2.11	1.89	1.41	1.29	1.58	2.45	1.41	1.29	2.45
Thruster Loads (σ/μ = 2 %)	1.31	2.34	2.07	1.48	1.31	1.71	2.73	1.48	1.31	2.73
Acoustic Loads (σ/μ = 40 %)	1.53	1.98	1.84	1.57	1.53	1.67	2.19	1.57	1.53	2.19
Vibration Loads - Thermal Loads (uncorrelated) (σ/μ = 20 %)	1.37	2.01	1.82	1.45	1.37	1.59	2.28	1.45	1.37	2.28

Failure probability = $10^{-6} \rightarrow K_1 = \frac{\text{Minimum guaranted strength } (2\sigma \text{ value})}{\text{Limit Load } (2\sigma \text{ value})}$; ($1.29 < K_1 < 2.73$).

Fig. 2.3: Typical Central Factors of Safety

To enable practical application of the method, the aspects related to verification by test have to be considered in relationship to the hardware and testing philosophies on one side and the number of classes has to be reduced on the other side .

- Regarding test verification aspects, firstly the significance of the structural qualification test was addressed in the light of the requirement that this test shall prove a minimum structural reliability by detecting potential design problems. The assumption is made that the mean strength is not the predicted value but a lower value and that the strength distribution is invariant and its coefficient of variation is unchanged (Fig. 2.4).

As a result of this the so called qualification factors K_Q ratio of the qualification loads to the limit loads was defined.

Secondly, different possible combinations of hardware philosophy (qualification models, qualification model with no-yield during qualification test - to enable hardware re-use, or proto-flight model approach) and testing philosophy (system level test, subsystem level test) in relation with the risk of failure during qualification testing have been considered. The hardware philosophy triggers the accepted test risk (QM : 10%, PFM: 1%) whereas the testing philosophy triggers the type and number of tests performed during

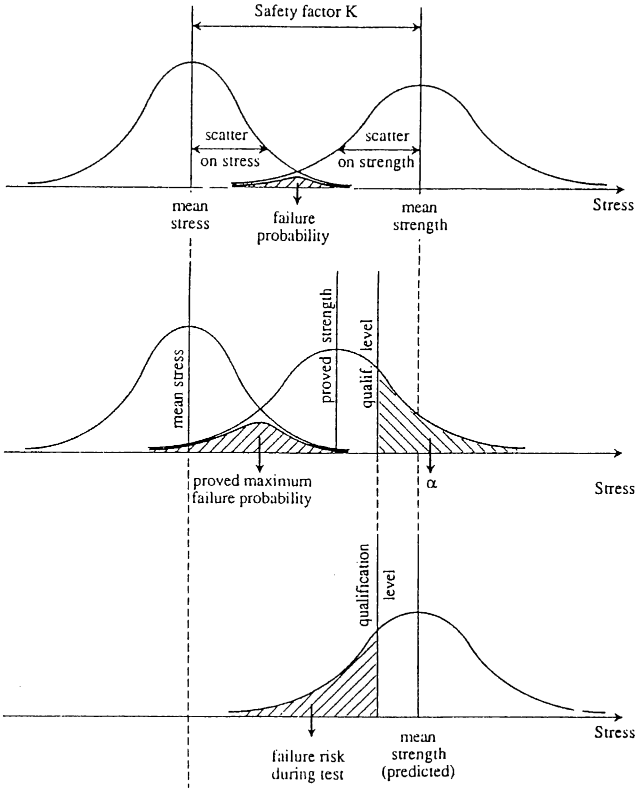


Fig. 2.4: Accounting for Test Aspects

TABLE 2.2.1 : STRUCTURAL MATERIAL SCATTER

MATERIAL	STRENGTH CHARACTERISTIC	Coefficient of Variation CV = σ/m
Metallic	rupture yield if Fru/Fry < 1.2 yield if Fru/Fry > 1.2	8% 8% 15%
	buckling (combined loading)	14%
Carbon fibre composites	rupture	10% * (17%)
Screw, rivet, welding	rupture	8%
Bonding: - adhesive film - compound adhesive	adhesive strength	12% * (16%)
Metal/metal bonding		8% * (13%)
Honeycomb	tension shear, compression face wrinkling	16% 10% 8%
Structural inserts (full potted inserts) in sandwich panel	axial loading in-plane loading	12% σ/m of the skin
Equipment inserts (partially potted inserts) in sandwich panel	axial loading in-plane loading	16% σ/m of the skin
Mirror vitreous silica (HERASIL) vitroceramic (ZERODUR)	static strength	10% to 30% depending on the surface treatment
INVAR superior Hammer hardened	ultimate stress yield stress	3.4% 2.3%
INVAR superior Tempered	ultimate stress yield stress	8.7% 20%
Fibrous Thermal Protection (e.g. AQ60)	in-plane tension In-plane compression normal tension normal compression	12% to 24% (depending on temperature) 15% to 20% (depending on temperature) 2% to 13% (depending on temperature) 5% (no temperature test)

* values applicable only if the characteristic is checked on a batch acceptance basis. If not use ( ) values.

the verification process. The accepted risk of failure during test is given by the probability of failure during test when the strength distribution is nominal, as illustrated by Fig. 2.4. As a result the so called test correction factors Ktest were defined. Finally, a set of material dependent factors Kadd is defined such that the following relationship holds:

$$Ko \times Ktest \times Kadd = K1$$

i.e. to ensure simultaneous control of structural reliability and of testing risk aspects.

Regarding materials and load classes, the following project adapted simplified categories have been considered:

- conventional materials: materials with sufficient statistical data and with scatter ≤ 10%.
- inserts, bonding: this category of materials exhibits scatter from 12% to 16%.
- unconventional materials: materials with high scatter (≥ 16%), caused by geometry shape, manufacturing process.
- yield failure mode: the scatter of yield strength is 8% for metallic materials when the ratio ultimate/yield strength < 1.2 and 15% when the ration ultimate/yield strength > 1.2.
- buckling failure mode: in the global buckling ultimate condition, the geometric effects are derived dominant over the material scatter. The

TABLE 2.2.2: LOAD SCATTER

TYPE OF LOADS	CV = σ/m	Origin of the results
Launch vehicle thrust	5%	STS (ascent), ARIANE
Launch vehicle other quasi-static loads: - thrust axis sinus POGO oscillation - stages cut-off - wind shear and gust - landing (STS)	30%	Analysis of data from STS, DELTA, ARIANE
Transient loads	60%	ARIANE 4 flight dynamic loads analysis
Thermal loads correlated temperatures uncorrelated temperatures	 7.5% 20%	Thermal test results
Deployment shocks: - solar arrays - antennas	10%	Test results of AEROSPATIALE mechanisms using a regulation
Thruster loads - apogee motor burn - attitude control thrusters pulses	2%	Calibration of attitude control thrusters or apogee motor before launch
Acoustic loads	30%	ARIANE 4 flight data, STS data
Vibration loads	20%	Analysis of damping factors measured during satellite tests
Re-entry		no data available
Preload with gauge without gauge	 5% 15%	Test results

scatter of this failure mode is shown to be 14% under combined loading.

Where not explicitly mentioned, the considered material failure mode is ultimate rupture.

Details of the derivation of the various factors can be found in references [2.1] and [2.2].

2.3 Example of FoS for Project Use

For the purpose of illustrating the application of the Guidelines, we will consider a classical automatic spacecraft project (less than 1000 critical items) for which the most usual "QM with no-yield exceedance" philosophy is applied (risk 10%). Limit loads are supposed to be defined at 99% probability (as for ARIANE 5) and materials allowables are taken as A-values. The relationship of loads and FoS's is therefore are follows:

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         Kq                        |-->Yield loads
Limit ----->Design loads-----  |
loads              |               |----->Ultimate loads
          Qualification loads
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Considering standard scatter of materials according to Table 2.2.1, it is shown that the fulfilment of the reliability targets requires factor of safety shown in Table 2.3.1. with a qualification factor of 1.4 ensuring a reliability proved by qualification at 90% probability and 95% confidence level. Making the assumption that the metallic materials have scatters reduced to 5% for ultimate and 8% for yield, Table 2.3.1 shows the corresponding factors which request a qualification factor of 1.25 only. However following points have to be considered:

- The reliability proven by qualification has now decreased to 40%. To compensate a throughout test-prediction correlation is needed;
- The restriction of the scatter has to be duly validated.

TABLE 2.2.3: CLASSICAL SATELLITE (1000 CRITICAL ITEMS)

PART COUNT OF CRITICAL ELEMENTS WRT STRENGTH SCATTER AND LOAD CASES (QUALIFICATION TESTS)

	STRENGTH SCATTER			
	CV = 8% Metallic Honeycomb face wrinkling	CV = 10% Carbon fibre Honeycomb (shear, compression)	CV = 12% Bonding Structural inserts	CV = 14% Buckling of metallic shells
STATIC TEST				
structure	10	10	5	1
others (payload)	50	15	7	
VIBRATION TEST				
solar array	80	10	10	
antennas	40	5	5	
propulsion	10	2		
others (payload)	100	30	15	
structure	7	7	4	
interfaces between subsystems to be tested at system level	25	5	3	
system	260	60	40	
ACOUSTIC TEST				
antenna	4	1	1	
solar array	4	1	1	
others	10	3	2	
system	20	5	5	
THERMAL TEST				
structure	2	2	1	
others	20	6	3	
DEPLOYMENT TEST				
solar array	200	25	25	
antennas	100	15	15	
ORBITAL LOADS				
solar array	30	4	4	
antennas	20	2	2	
PRESSURE, INITIAL TENSION				
propulsion	30	8		
solar array	32	4	4	
antennas	16	2	2	
others (payload)	20	6	3	

The factors of Table 2.3.1 are very similar to those used in spacecraft design practice and thus confirm the approach while clarifying the underlying conditions to be fulfilled.

2.4 *Specific Aspects*

Various other aspects are considered in the FoS Guidelines which will not be addressed in details here, such as load combination rules (pressure, thermal...), pre-loaded structures, geometric tolerances, structural redundancy, specific aspects related to glass-like materials (life-time, static fracture analysis, proof test level), design of composite parts without full scale test, design with no-test option, etc...

Possible bias introduced in the estimated structural reliability by non-linearities even when the limit load Fll operates in the linear domain (i.e. $FoS \geq Fru/FRy$) are highlighted. These bias can result from non-linearities in material stress-strain behaviour (softening materials give conservative estimates, see Fig. 2.5, hardening materials give non-conservative ones) or from non-linearities in the applied load-resultant stress relationship (see fig. 2.6) since indeed it must always be kept in mind that reliability is defined on the basis of stress-distribution, not of load distribution.

From the above cases it is obvious that a proper

QM model with no yield exceedance requirement	standard scatter Qualification factor = 1.4			Reduced scatter Qualifications status = 1.25		
	FOS's wrt qualification loads FOS's wrt limit loads			FOS's wrt qualification loads FOS's wrt limit loads		
	yield/ functional	ultimate	buckling	yield / functional	ultimate	buckling
Conventional materials Metallic	1.25 1.75	1.4 1.9	1.3 1.85	1.05 1.3	1.15 1.45	1.4 1.75
Conventional materials Non metallic	1.05 1.45	1.15 1.6	1.3 1.85	1.0 1.25	1.1 1.4	1.4 1.75
Unconventional materials	1.7 2.35	1.85 2.6	1.3 1.85	1.8 2.25	2.0 2.5	1.4 1.75
Inserts/bonding	1.7 2.35	1.85 2.6		1.8 2.25	2.0 2.5	

Table 2.3.1 - Factors of Safety for Classical Automatic Spacecraft

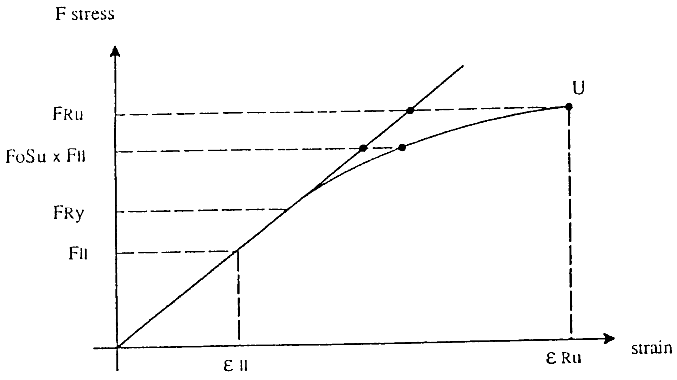

Fig. 2.5: Reliability bias: non-linear material

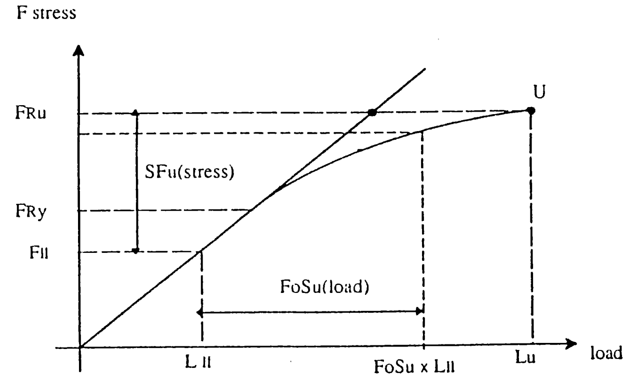

Fig. 2.6: Reliability bias: non-linear load - stress

evaluation of the structural reliability requires in such cases special procedures which enable to follow the actual loading path when the applied load Fll increases and that in no case one should proceed in dividing the allowable by a factor : the material allowable information shall always remain an untouched reference value.

For specific materials, load types, or in case of non-linear behaviour, the following methodology is proposed:

- use of Factors of Safety as generally required and defined in the Guidelines;
- verification of the reliability using statistical methods (Montecarlo simulations, ...);
- where necessary adaptation of the Factors of Safety to restore the target reliabilities.

The advantage of the above approach is that where needed factors can be tailored to specific conditions.

As a result, the Guidelines provide a set of rules to enable modifications of FoS on the basis of statistical aspects with the aim to keep a constant component or/and spacecraft structural reliability. This enables flexibility as required by new designs or materials, but avoids "anarchy" and/or non-justified selection of FoS's.

3.DESIGN AND VERIFICATION REQUIREMENTS

Achievement of the desired structural reliability does not only depends on the usage of adequate Factors of Safety. It also requires application of a minimum of good engineering practice and checking of the completeness of the performed verification (analysis/test) activities. Therefore the Guidelines contains a set of Verification, Design and Stress Analysis requirements.

3.1 Verification requirements

Structural verification is based on analysis and test at component, subsystem and system levels.

- Regarding analysis, the check of its completeness starts at system level. The following approach is recommended:

- functional analysis;
- specification of reliability requirements;
- design load analysis;
- functional failure mode and criticality analysis enabling to allocate subsystem reliability requirements depending on failures criticalities;
- verification plan set-up, including hardware and testing philosophies aspects.

As a result of the above steps, the inputs for the structural design (e.g. target reliabilities, scatter of loads...) are available and the adequacy of standard Factors of Safety and test factors can be evaluated.

This completeness has to be checked further down at component level/subsystem using the above inputs by:

- assessing the failure mode analysis;
- assessing the stress modelling;
- checking adequacy of the material/load scatter assumptions, and where necessary adapting the FoS's or/and identify relevant material characterization tests needed;
- assessing not only the margins of safety, but the actual theoretical reliability against the target reliability allocation.

The latter aspect is felt very important since it enables to spot components/subsystems having low reliability although exhibiting possibly acceptable margins of safety (e.g. parts made of material with large scatter).

Where necessary, a verification plan including partial development/qualification tests shall be prepared at component/subsystem level to support the analyses where the system verification plan does not provide adequate/timely impact.

- Regarding testing aspects, completeness consist in the fact that adequate tests must have been defined to verify all critically loaded/stressed areas and cover all environmental conditions (from ground / manufacturing to orbital) and that, as far as possible, test outcomes have been correlated successfully to test prediction analyses.

It has been shown in section 2.3 that when considering low qualification factors (e.g. 1.25) much more emphasis has to be put on the correlation aspects since such low factors reduce significantly the proven reliability. This has to be supported by sufficient test measurements.

The above remarks apply to development, qualification or mathematical model identification tests although the objectives of these are different.

Regarding the test loads, it is clear that they have to bound adequately the relevant statistical loads by using where relevant an appropriate factor. This factor is not to be confused with the factors of safety and is not included in them.

- Lastly, completeness shall be assessable via the available structural verification documentation. This one should be detailed enough to allow a mechanical engineer not involved in the project to understand the analysis. In particular, all the results coming from the mission analysis and the dimensioning cases determination should be explained. All the assumptions made in the calculation files have to be justified. In particular it shall contain a standardized margin of safety summary which includes the previously described achieved theoretical reliabilities and therefore enables quick identification of the weak links of the design.

3.2 Design and Stress Analysis Requirements

- The detailed design of a structure shall be performed together or following a failure mode analysis as outlined in the previous section such as to make sure all potential failure scenarii and their consequences have been identified.

- The values taken into account in the analysis shall be for the modulus : mean value, for the strength: allowable value, for the thickness : minimum value (e.g. buckling analyses) or mean value. The choices of A or B value for allowable values depends on structural aspects (primary non-redundant/redundant, secondary structure), on mission aspects (requirements at system level) or on the available tests results. In any case the factors of safety have to be determined in coherence with these values on the basis of the FOS Guidelines.

- The factors of Safety defined in the Guidelines cover statistical variability of loads and materials and should NOT be confused with common engineering practice design factors such as stress concentration factors, form factors, fitting factors, weld factors, buckling knock-down factor or other dimensioning method factors. These design factors shall be applied while designing mechanical parts to derive the actual local computed stress. The latter stress shall then be considered in the stress-strength method, i.e. shall be multiplied by the relevant Factor of Safety for the comparison with the appropriate material strength.

4. TIME VARIANT EFFECTS

4.1 General Remarks

As shown in the previous sections, traditional structural dimensioning of aerospace structures is performed on the quasi-static load assumption. Specific requirements related to life-time considerations are processed in a second step, e.g. by checking whether or not the structure or component meets the fracture control requirements [4.1]. Hence, it is quite natural to relate these requirements to the reliability goals. Consequently, in an extension of the determination of the safety factor concept as discussed above, these factors have to be verified to also meet the target failure probability at the end of the planned, i.e. design life. Principally, the life-time aspects can be dealt with in terms of fatigue (fail safe structures) and fracture analysis (safe life structures) respectively.

The current requirement, as stated in [4.1], is to prove that - for a specifically defined load spectrum - the structure or component can withstand safely four times its design life. No quantitative reliability measure, however, is attached to this requirement. The tools as suggested in [4.1] are of deterministic characteristics. As it is well known that generally both loading and material parameters show large scatter, i.e. statistical and probabilistic uncertainties, these uncertainties have to be taken into account. This allows on one hand to quantify the adequacy of this life-time factor w.r.t. the target failure probability of the component or structure, and on the other hand to identify the most significant sources, i.e. parameter uncertainties affecting the failure probability.
Note that the establishment of a quantitative statistical evaluation of the life-time factor requires a sufficient amount of data, which is currently not yet available. Hence the developed concepts yield, at this stage, a qualitative relation only.

4.2 Safety Factor Updated Based on Fracture Mechanics Approach

It is well known, that the most important feature of the fracture mechanics approach is that the damage process can be described by a physically observable parameter, i.e. the crack size itself. Thus, the failure probability can be directly defined by comparison of the actual crack length with an acceptable or critical crack length, i.e. the splitting in stress and strength components respectively is feasible, as well as the definition of a related FOS.

The evaluation of the probability of failure has been carried out by developing an update of the currently used code ESACRACK [4.2] which is based on linear fracture mechanics and uses the extended Forman equation to predict crack growth. The update uses Monte Carlo technique with variance reduction and contains the possibility of considering the statistical uncertainties of all the respective input variables [4.3]. It should be noted that the procedure also allows for a possible combination of brittle and ductile failure by utilizing the so-called Two-Criteria Approach and enables structural loading as well as resistance to be a function of a number of random variables. The failure probability of a structural component is calculated by the following multidimensional integral

$$p_f = \int_{g(X)<0} f_X(X)dX$$

where f_X (X) is the joint density of the variable involved and g(X) = 0 is the limit state function which separates the survival i.e. safe state from the failure state respectively.

4.3 Fatigue Approach

As no direct observable parameter of the deterioration process is given in the fatigue analysis, the splitting in a stress and strength components respectively - as in the case of the fracture mechanical approach - is not feasible. Only the probability distribution of the deterioration process is given in terms of the total damage D. Therefore, the time variance of the safety factor can only be included indirectly when applying fatigue analysis. Hence, the factor of safety for the life-time as specified to be in [4.1] is subject of investigation in this context.

The analysis is based on the software ESAFATIGUE [4.5] which has been extended to treat the statistical uncertainties involved [4.6] using Monte Carlo simulations with variance reduction. As a measure of the particular stage of a structure, the total damage D is evaluated by linear damage accumulation, i.e. the Palmgren-Miner rules. According to [4.1] the design is considered to be acceptable if it can be demonstrated that....... LIFE= 1/D > Factor on nominal life, i.e. should be ≥ 4.0. For the purpose of the statistical evaluation, the failure probability is defined by $p_f = P[D \geq 1.0]$ where D is evaluated for α times the nominal life and α selected such as to satisfy the target probability and compared to the above factor 4.

4.4 Application Examples

Utilizing the fracture mechanical approach and Al-7073-T73 data (Table 4.2) with a cyclic load, the central safety factor K_1 as defined in section 2.2 and its dependency wrt life is illustrated in Fig.5.1. Note that the target failure probability was selected to be 10^{-6}.

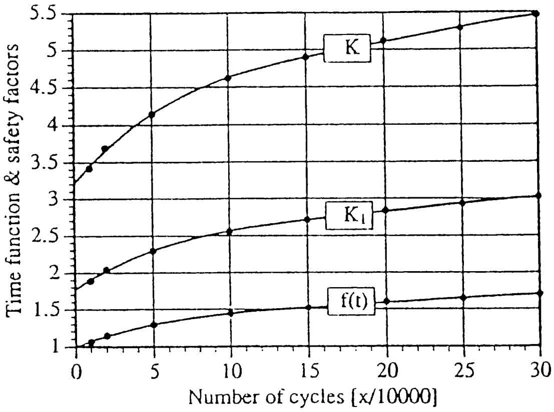

Fig. 5.1: Time dependency of FOS

For validation of the life-time factor of 4.0 both fatigue and fracture analysis can be utilized.Applying failure analysis for a particular set of material parameters as shown in Table 4.2, a particular load history and a target failure probability of $4.3.10^{-6}$ the life time factor α was estimated to be 3.8 which confirms the value suggested in [4.1]. To substantiate this result, of course, considerably more statistical information on the parameter - as listed in Tables 4.1 and 4.2, as well as on the load history is needed.

	Distribution type	Mean value	Coeff. var. (%)
a_0	Exponential	3.50 [mm]	20.0
S_y	Lognormal	427.50 [MPa]	5.0
K_{IC}	Rayleigh	903.40 [$MPamm^{0.5}$]	5.0
C	Lognormal	$1.07\ 10^{-13}$ [$MPa^{-3.643}mm$]	10.0
ΔK_0	Gamma	86.87 [Mpa $mm^{0.5}$]	5.0
f_{SIF}	Normal	1.00[ ]	5.0

Table 4.1: Uncertain parameters for fracture analysis [4.2]

	Distribution type	Mean value	Coeff. var. (%)
K_f	Lognormal	2.0 [-]	3.0
P	Normal	0.64 [-]]	5.0
K	Fixed	0.0 [MPa]	--
A	Normal	10.176 [-]	0.8
B	Rayleigh	2.69 [-log(MPa)]	0.8
C	Exponential	110.316 [MPa]	5.0
L	Uniform	68.948 [MPa]	10.0

Table 4.2: Uncertain parameters for fatigue analysis [4.5]

5.FUTURE DEVELOPMENTS: PARTIAL FACTORS OF SAFETY CONCEPT

The concept of safety factors, as described above, are based on the stress-strength consideration. The factors depend on particular material properties, loading configuration and structural type, however one unique factor is considered for each material - load condition (cf. Table 2.3.1). The so-called Partial Safety Factor concept (PSF) extends the above approach to reflect the importance of the scatter of the various individual parameters defining the stress and strength respectively. In a simplest case it can be described by

$$F_A / FOS_A \leq F_R \times FOS_R$$

As it refers to limit states - such as collapse, serviceability, etc. - it is independent of the respective material type of construction. The partial safety factors are derived such, that the designed structure meets the required target reliability. In [5.1] it is shown that the PSF concept can be extended such that the deterioration effects due to cyclic loading can be also taken into account (e.g. one PSF for each parameter of the Forman equation as listed in Table 4.1). These first results seem to be promising. However, there is no doubt that further investigations are still required before incorporating this concept into the Factors of Safety Guidelines.

6. CONCLUSIONS and OUTLOOK

The availability of a set of reference FoS's for all ESA spacecraft projects as well as a set of rules allowing for possible but controlled deviations was urgent to rationalize the structural design approach. The work presented in this paper reflect the current status of a contract in progress which produces a first "Draft Guidelines on structural Factors of Safety" based on reliability objectives. A time independent FoS set as well as methodologies to evaluate the adequacy of the life factors for fatigue and fracture aspects were shown.

The Guidelines will be presented to industry for critical review and constructive enhancement at the end of 1996. The intention is further to propose this draft as a starting point for the elaboration of an ECSS (European Cooperation for Space Standardization) level 3 standard.

While performing the work, the need got highlighted to collect additional data. As an example, statistical information on sensitive coefficients of the fatigue and fracture models are missing even for most common aerospace materials. There is scope here for future work.

Investigations have been performed regarding application of the PSF concept including deterioration effects to aerospace which allows a better separation of the load and resistance aspects. First results seem promising, but further investigations are necessary before its possible incorporation in the FoS Guidelines.

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