THE ROLE OF FRACTURE MECHANICS AND FATIGUE IN THE DESIGN OF ADVANCED AEROSPACE VEHICLES

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Abstract

Pressurized aerospace structures often contain small flaws or defects that are inherent in the material or introduced during fabrication. These defects, under the influence of operative environments, may grow to such an extent that explosive failures can take place. Noise induced vibrations can be quoted as one of the main causes of the defect growth, above all for the spacecrafts which will be carried into orbit through the Space-Shuttle.

For this kind of vehicles the interaction between noise induced vibrations and fracture mechanics must be deeply assessed if reliable design of such structures has to be performed.

To obtain adequate informations on such a problem a coordinate research effort is carried out in Italy among Universities and Industries under the sponsorship of the National Research Council.

The main objectives of such research are the following ones:

- Critical review of concept of reliability and safety as far as spacecraft structures are concerned.
- Theoretical and experimental method to assess the structural response to an acoustical environment.
- Defect growth evaluation under stress fluctuations due to acoustical excitation.
- Critical defect dimensions evaluation.

Foreword

With the development of Advanced Space Transportation Systems a new era for the Space-Age is being initiated for mankind.

Space activities have assumed the meaning of enterprises for the Systematic Exploration and Utilization of Space and have become occasions for "International Cooperation".

EUROPE is contributing to this advancement with the "SPACELAB" the Space Laboratory that will be used, over the next decades, for scientific and technological researches in conjunction with the United States of America developed SPACE SHUTTLE".

A large effort is being made in different Countries in Europe, now-a-day, to contribute with different activities to the advancement of this unique enterprise.

Under a contract awarded by the European Space Agency (E.S.A.), eleven outstanding Aerospace Companies, belonging to ten European Countries, joined in a Consortium lead by ERNO VFW-FOKKER, are performing the design, development, manufacturing and testing activities of the various SPACELAB Systems.

Numberous parallel activities are being performed in different European Research Centers, Universities and Industries to study and to develop the experiments to be flown with the SPACELAB.

In addition programmes of Applied Space Research have been initiated in many countries, sponsored by the National Research Agencies, to support research activities in advanced fields related to the design problems of Aerospace Vehicles.

ITALY is particularly active in the SPACELAB Program and related activities; as Member State participating to the European Space Agency (ESA), Italy, shares the second largest contribution to the SPACELAB Program after Germany, with about the 18%.

The largest italian aerospace company, AERITALIA, is responsible, within the ERNO Consortium, for the analysis, design, manufacturing and testing of two of the major SPACELAB Systems; the Module Structure and the Thermal Control of Module and Pallet.

The Payload activities have recently been initiated, in Italy, with a study for an Astronomical Facility for observation of Ultra-violet and X-rays. AERITALIA is acting as Industrial Prime Contractor coordinating all the engineering efforts in support of the scientific team of astronomers in charge of the Facility definition.

The "Consiglio Nazionale delle Ricerche" (C.N.R.) responsible for the promotion of the Government supported Researches in Italy, has sponsored, in addition, several researches to stimulate the Space Activities, with the aim to involve, into the advanced problematics posed by the Space Programmes, the Italian Universities and Research Centers, in close collaboration with the Aerospace Industries.

An example of these collateral activities is the "Research on Fracture Mechanics of Pressurized Space Structures subjected to Acoustic Fatigue"* that the "Istituto di Ingegneria Aerospaziale of the Politecnico di Milano" the "Istituto di Aeronautica of the University of Pisa" the "Istituto di Progetto di Aeromobili of the Politecnico di Torino" and the "Space Sector of AERITALIA" have recently initiated.

1. Introduction

Recent advances in space activities have introduced a new class of problems in the design of space vehicles. Among the more challenging ones are fracture mechanics and fatigue, that will be adressed in the present paper.

A brief outline of the SPACELAB Program and in particular the description of the main features of the Module Structure design characteristics is given, to provide a better insight into the above problems.

The Spacelab design is considered as a reference sample for a broader discussion of advanced aerospace vehicle design problems.

Particular enphasis is given to the "design against structural defects" approach; a general review of the fundamental concerning fracture mechanics and fatigue, as well as, non distructive inspection methods is presented.

The impact on the fracture mechanics and fatigue structural design of advanced aerospace vehicles is discussed to provide an insight into the today available design methodologies in these particular fields.

As a result some of main areas that require further investigations are enphasized and accordingly the guidelines for an "ad hoc" theoretical and experimental research is outlined. The late start of the activities prevents us to present results.

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* C.N.R. Contracts n. SAS 760031, 760030, 760032, 760040.

2. The European Spacelab Program

2.1. Basic Feature

SPACELAB is a Space Laboratory designed for the best utilization of the payload capabilities of the Space Shuttle, it has been conceived with an extremely flexible design to allow the performance of a large variety of experiments in space; it is planned to operate for missions lasting from seven up to thirty days.

SPACELAB will offer the international community of users an efficient and versatile general purpose mean to conduct the next generation of manned space research and exploration activities.

The SPACELAB is made up of two basic elements: the "Pressurized Module" and the "Unpressurized Pallet" (Fig.2.1a).

The "Module" (Fig.2.1b) is a cylindrical compartment that provides to the experimenters and to their equipments an environment equal to the sea level earth conditions, apart the absence of gravity. Inside the Module standard elements for experiment support, such as floor, racks, airlocks, heat exchangers, cold plates, as well as basic services such as power, environmental control and data management are provided.

The "Pallet" is a platform to support experiments directly exposed to the space environments.

These two basic elements designed with a modular concept can be used separately or in conjunction giving rise to different configurations.

2.2. Module Structure System Description

The primary structure of the Module comprises the cylindrical shells and the conical end closures, forming the pressurized compartment of the SPACELAB (Fig.2.1b); this primary structure provides the habitation environment for the crew and the structural tie between the experiment equipments and the ORBITER.

The cylindrical elements have each a length of about 2.7 meters and a diameter of about 4 m; the overall length in the short module configuration is about 4.2 meters and in the long one about 6.9 meters. The forward located element is named the "Core Segment" and contains the subsystem equipments occupying about the 40% of the rack area (the remainder 60% is devoted to the experiment installation). The other one is named "Experiment Segment" and is fully dedicated to the experiment installation.

In top of each cylindrical element is located a flange of 1.3 meters in diameter to accomodate the top airlock or the viewports and windows.

The cylindrical shell is made up of integrally numerically machined waffle pattern panels (Fig. 2.1d)) of aluminuim alloy 2219, welded together longitudinally and welded circumferentially (Fig. 2.1e) at the ends to forged rolled rings.

The two main rings incorporate a bolted flange and stiffening circumferential ribs, that at fitting locations have outer cap members to carry the bending moments; interposed between the panels are two longerons to transfer the fitting reactions into the shell.

The conical end closures have a semivertex angle of 60° and are terminating with flanges of 1.3 meters in diameter to accomodate on the forward the tunnel and on the rearward the airlock.

The conical shell is made up of numerically machined panels of the same aluminium alloy welded together longitudinally and welded circumferentially to the forged rolled rings (Fig.2.1f and g).

The forward end-come interfacing with the tunnel provides, by means of feedthrough panels, the ingress of signals, power and other utility lines coming via the utility bridge from the ORBITER; it has as well a view-port in top.

The aft end come has provision, through a flange for the 1.5 m Aft Airlock and provides, by means of two feedthrough panels the connection of utility lines running to the pallet; it has a view-port in top to visually control the experiments on the pallet.

The module elements are joined by bolted flanges with interposed seal elements; a single row of bolts, accessible from outside, ensures the tightness of the joints. The Gask-O-Seal device with double butyl seals molded into an aluminium base ring is adopted; under the pressure derived from assembly the elastomer is deformed to fill the seal cavity thus ensuring the tightness.

The Module is supported in the ORBITER cargo bay at four points providing a statically determinate attachment system to preclude coupling between the SPACELAB and the ORBITER.

The main fittings (Fig.2.1c)(reacting X and Z loads)are attached to the aft ring of either a short or long module. The stabilizing fitting (reacting Z loads only) is attached to the forward ring of either a short or long module. The keel fitting (reacting Y loads only) is attached to either the aft ring of a short module or the aft ring of the core segment of a long module.

Each cylindrical element has provision for attaching all the four fittings which are removable and interchangeable.

Current design is now titanium alloy integrally machined elements shaped to be bolted, without perforation of the main shell, on the circumferential flange ribs. The connection with the ORBITER support is provided by inconel pins. Two diagonal struts provide stabilization on the frame plane.

A longitudinal arm connects the rings at the two extremes of the module and a shear tie element provides continuous connection between the arm lower slab and the module longerons.

2.3. Structural Design Problems

The mechanical load conditions, of an aerospace vehicle, of the category to be flown in conjunction with the Space Shuttle, can be classified under the following general heading: - trasportation, manouver and gust loads, internal pressure loads, acoustic loads, crash loads.

In addition the meteorite impact effect as well as the environment (see [2]) effect on structure must be assessed.

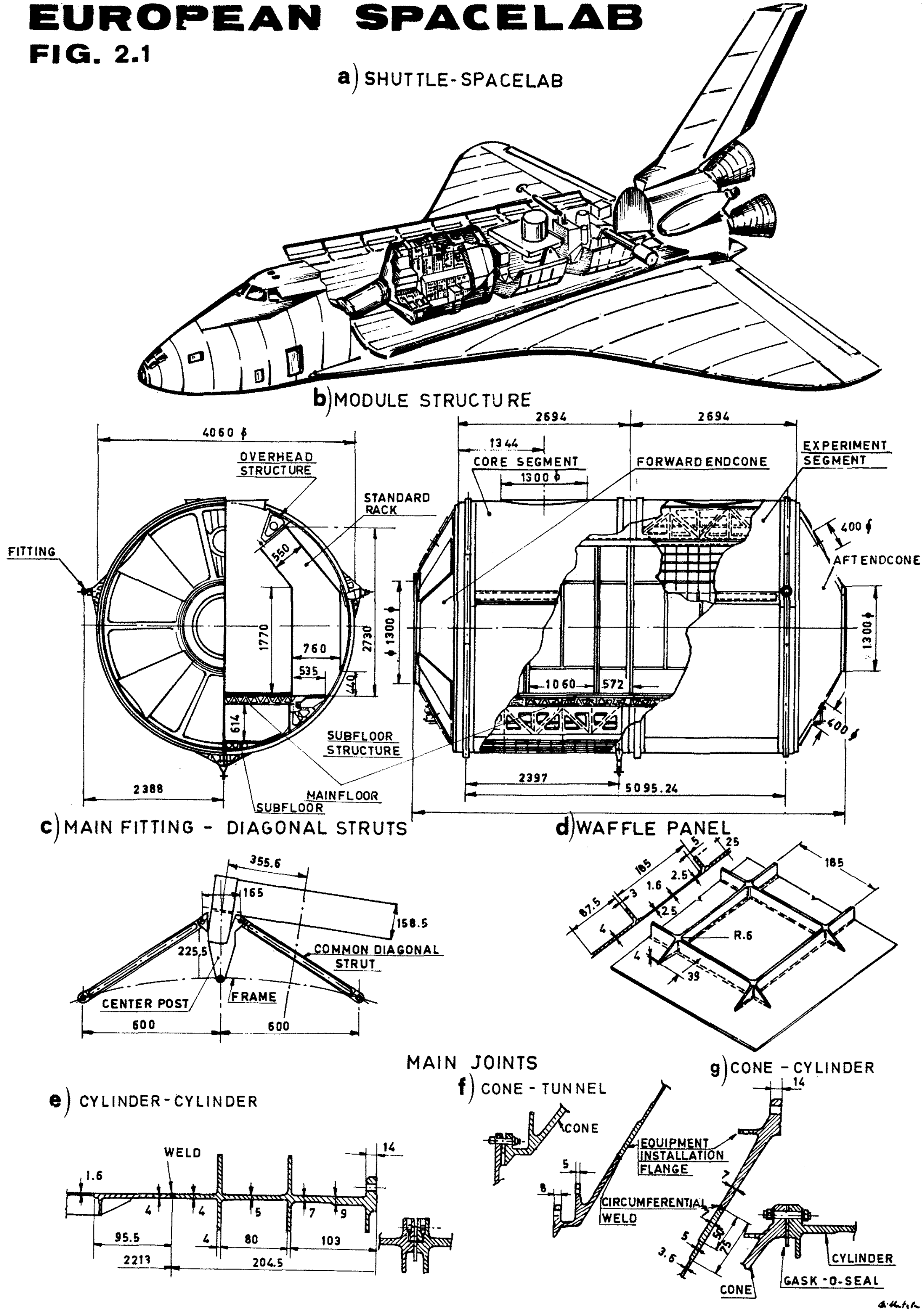
The structure is requested to suffer no failures under the maximum expected load for each condition, as well as to withstand on the loading conditions derived from a fixed number of missions, with specified safety and reliability requirements. Such requirements, in relation to the various functions requested to the component may have different levels.

The safety design criteria adopted utilize a deterministic approach, based on safety factors, (Tab.2.1) in order to obtain from the maximum expected limit loads the ultimate loads.

As concerns allowable loads, safe-life concepts are applied to all structure components that are critical to the integrity of the vehicle or to the personal integrity with a deterministic multiplication factor of the service life. In addition,

EUROPEAN SPACELAB

FIG. 2.1



a) SHUTTLE-SPACELAB

b) MODULE STRUCTURE

c) MAIN FITTING - DIAGONAL STRUTS

d) WAFFLE PANEL

MAIN JOINTS

e) CYLINDER-CYLINDER

f) CONE - TUNNEL

g) CONE - CYLINDER

fail-safe concepts, when applicable and convenient, are introduced.

COMPONENT	FACTORS		
	YELD	ULTIMATE	PROOF
General structure	1.0	1.4	--
Main propellant tanks:			
Combined loads and pressures	1.1	1.4	
Pressure alone	---	*	1.05
Pressurized windows, doors, and hatches	---	3.0 *	2.0
Pressurized structure:			
Combined loads and pressures	1.0	1.5	---
Pressure alone		**	
Pressure vessels (other than main propellant tanks)	---	2.0 *	1.5
Pressurized lines and fittings:			
Less than 1.5 in. in diameter	---	4.0	1.5
1.5 in. in diameter or larger	---	2.0	1.5

*In addition to including the design factors in this table, designs for major load carrying structure, windows, doors, hatches, and tanks should use fracture-control procedure to account for sharp cracks, crack-like flaws, and other stress concentrations in a manner that ensures the structural life meets mission requirements.

** Factor applied to limit load at limit pressure

TABLE 2.1 DESIGN FACTORS (from [2])

The safety concepts actually applied are based on a long experience, principally deriving from the aeronautical activity. More comprehensive and fully statistic safety approaches, even if theoretically attractive, are not applicable up to day, because of the lack in the necessary statistical data, in particular for all that concern space vehicles.

A characterizing problem in assessing the ability of the structure to withstand the applied loads lies in the presence of flaws as cracks that may grow during the service life, due to the effects of the repeated nature of the loads (manouvers, gusts,...) and may reduce the capability to withstand loads (static or sustained).

The unavailable presence of flaws and cracks, together with the stringent weight requirements demand the "safe crack growth life" concept to be applied.

From NASA SP-8057 we report: "For structure utilizing a safe-life design concept,..., any flaw that cannot be detected in a regular inspection should not grow enough before the next scheduled inspection to degrade the strength of the structure below that required to sustain loads at temperatures defined by the limit load and critical temperature envelopes.

Analysis of flaw growth should account for material prospecties, structural concepts, and operating stress levels throughout the structure including adverse effects from variations in operational usage and environments".

The foundamental tool in analyzing a flawed or cracked structure is represented by fracture mechanics, through which an assessement is made of the critical crack length and of the service time required to reach such critical sizes.

Fatigue analysis methodologies provide a valuable mean for assessing the areas where cracks may growth.

3. Fatigue and Fracture Fundamentals

3.1. Introductory Remarks

The life of an initially damage free structural element under complex loading condition may be described as consisting three stages. In the first, the incubation stage, the loading variability causes an accumulation of the damage leading to the initiation of the damage;in the second the fatigue crack propagates owing to the repeated loading; in the third fracture occurs as the crack has grown to a dimension that is critical for the maximum applied load.

In the first stage no degradation in strength takes place and "classical" approach (tipically notch strength analysis, [ref.1]) are adequate to assess such a strength. In secondary a progressive strength reduction takes place with the increasing of the crack length; the fracture mechanics technologies are a suitable tool to assess the strength of the cracked component.

If the designer strives to provide a service life which is only a part of the first stage no cracks or flaws* are to be considered in the fracture and the "classical" fatigue approach can be used in the design and analysis methodologies. Following such an approach life calculations are based on the usual S-N curves; the Miner rule, at most corrected for the residual stresses effects, is used to predict life under variable amplitude loadings and empirical coefficients are allowed to correct the elastic stress concentrations and to assess environmental effects.

The same approach can be used if the designer is only interested in evaluating the crack free life of the component, or in preventing the occurence of crack like defects.

On the other hand if a crack free structure cannot be assured in the course of the operational life, the type of approach demands essentially fracture mechanics based design and analysis methodologies.

This kind of approach is requested essentially owing to the potential existence at a given stage of the operational life of damage in the form of flaws or cracks. Such flaw or crack have been known to escape detection during manufacture and acceptance inspections; they might be introduced by inadvertent damage, during manufacturing and service or they may result from fatigue or stress corrosion.

The designer assumes that the largest cracks or flaws that can be missed during an inspection, is indeed present in the structure at a given stage of operational life.

Fracture mechanics analysis and data are then applied to predict flaw growth and structure residual strength under the load and environment conditions expected in the operative life fraction chosen as inspection interval.

Fracture mechanics based approaches need to be implemented by an important engineering tool: nondestructive inspection (NDI) methods. The largest flaws or crack missed through NDI action are a basic input in the fracture mechanics analysis and in the establishement of inspection intervals.

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* A "flaw" is concerned with the material or structure discontinuities due to production processes. A "crack" is due to damage accumulation in the material or to flaw growth under static sustained or repeated loads. When these can reach their "critical lenghts"they are termed defects.

3.2. Fatigue life (incubation stage) analysis method.

The assessement of the fatigue life of an aerospace-vehicle structural component goes through several stages, as it is shown in fig.1, [ref.2]

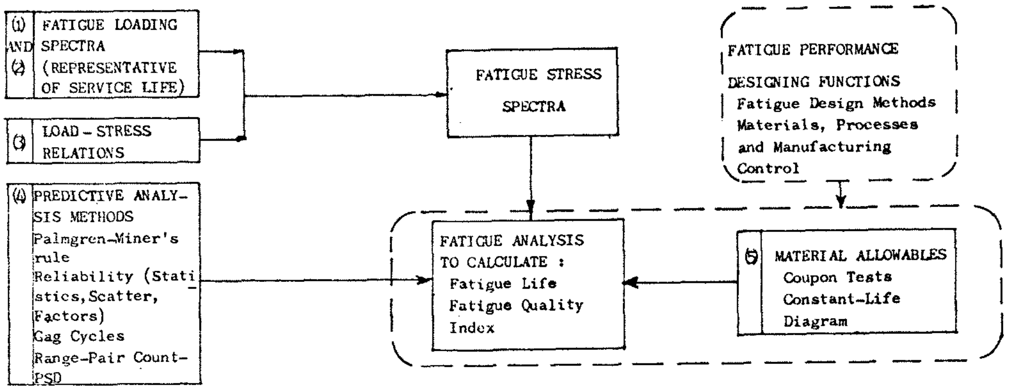


FIG.3.1 Elements for Fatigue Design and Analysis

Service loading arises from a variety of source such as gusts, manouvers, landing, ground taxi, acoustic excitation, pressurizzation, etc.

For an accurate evaluation of the fatigue life, loading spectra representative of the operational life are essential; in particular the variation in loading from ground taxi to flight and back to ground taxi must be taken into account in the correct sequence. The ground air ground (GAG) load variation is one of the most important loading cycle contributing to the fatigue damage of the structure.

In general the service load are random; therefore the achievement of a fatigue loading spectrum are to be based on statistical analysis. Two different approaches are presently used to describe the service load histories, namely: Counting Methods, The Power Spectral Density (PSD) Method.

The aim of counting method is to give a statistical distribution of characteristic magnitudes of load time histories, such peaks, level crossings or load ranges.

In relation to the magnitude adopted for the counting procedure different counting methods exist [ref.3]. Among these the range-pair-range count method is throught to give more relevant information from a fatigue damaging point of view as compared to other methods. In fact, it permits identification and definition of the GAG load cycles as well as any other significant secondary load excursion [ref.3]. Therefore its use for the reduction of load time histories to fatigue spectra is recommended.

The PSD method is another suitable tool to analyze randomly varying loads, expecially gust and acoustic loads. The basic assumption is that the random load may be considered a random stationary Gaussian process. Such a process is fully described by its power spectral density function through which the statistical distribution functions for level crossing and peak loads can be obtained [ref. 4]. The PSD function can be obtained from the following relationship

$$\Phi(\omega) = \lim_{T\to\infty} \frac{|X(\omega)|^2}{2T \cdot 2\pi}$$

$x(\omega)$ being the Fourier trasform of the load time history.

The fatigue loading spectra, together with the relationship, between the loads and stresses are used to define the fatigue stress spectra. Load-stress relationship are based on stress analysis supplemented with suitable stress concentration data; stress analysis con vary from simple "engineering" stress load relations to very sofisticated computer based approaches in relation to the stage of design.

In determining stress spectra the effect of structure elasticity must be allowed. In particular it must be considered when the frequency content of the applied load is significant in relation to the excitation of one or more elastic degrees of freedom of the structure.

Acoustic excitation is noteworthy in this respect owing to its broad band frequency content.

The PSD method is an appropriate approach for such problems; the PSD function of the structural response (and therefore all the statistical quantities relevant to stress spectrum preparation) can be obtained from the PSD function of the load and the transfer function of the structure, which is related to its vibration modes.

Such an approach is valuable only if a limited number of elastic degrees of freedom are excited because the computational effort and its inaccuracy increase with the number of degrees of freedom excited.

When a large number of degrees of freedom must be allowed, other approaches seem to be preferible; noteworthy in this respect is the "Statistical Energy Analysis (SEA)" method [ref.5].

In these cases, however no well established procedure is untill now available.

The fatigue stress spectra and the material allowables in the form of S-N curves are the imput data in fatigue analysis; here N ought to be the number of cycles for crack initiation at the load level S. The S-N curves to be used should be drown from tests of the same structural configutation and for the same combinations of mean and alternating stress as those for which calculation is desidered. Further as considerable scatter is present in fatigue test data, such curves ought to be relative to a given probability of crack occurrence defined with a prescribed level of confidence.

These informations are rarely available in sufficient details, particularly for mayor components. Consequently calculations are performed using S-N data for simpler specimens taken from literature. Of particular importance in this aspect are S-N data drown from specimens that embody significant features of the actual structural component, noteworthy specimens of riveted, bolted or welded joints or specimens with geometric discontinuities representative of the structure under investigation.

Among such data a set can be chosen in the more convenient way if the fatigue quality index of the construction is known. This index can be ascertained by comparison of the specimen fatigue data with the results of fatigue tests on complex components well representative of the structure under investigation. This procedure which tends to quantify the fatigue quality of the construction through an "effective stress concentration factor" is also a valuable procedure to ascertain the adequacy of the design in respect of fatigue.

The fatigue calculation of the service life under these stress spectra involves the use of some damage analysis. The well-known Palnigren Miner hypothesis is the most commonly used. The rule states that failure will occur when $\Sigma n_i/N_i = 1$ where n_i is the number of cycles spent at a stress level S_i and N_i is the number of stress cycles required to cause the failure at the stress S_i, found on the appropriate S-N curve.

Miner's rule usually fails to predict the life quantitatively particularly for structures undergoing complex load time history.

Systematic tests (see for instance [ref.6]), in fact, have shown that $\Sigma n/N$ at failure depends on the sequence in which loadings are applied, on mean stress and on whether or not negative loadings are included in the spectrum. A possible improvement in life evaluation might be obtained modifying empirically the right hand side of the rule on the basis of the type of spectrum.

Even if the Miner's approach suffers the above said limitations, it is usually preferred to the other proposed damage rules [ref.7] which are more complicated but not necessary more accurate when their prediction are compared against data taken from different sources.

A basic explanation of the variation in $\Sigma n/N$ at failure as a function of the parameters cited can be found in the residual stresses that take place in zones of stress concentration owing to the different load levels in the spectrum. Sufficiently high loads to induce local yielding, when removed, leave residual stresses. In the case of a high-low tensile load sequence, compressive residual stresses induced by high load, interact with the stress induced by low load, diminuishing the stress amplitude and/or modifying the mean stress.

Such an interaction has benefical effects on the fatigue life. The opposite situations takes place when a high low compressive load sequence is applied.

Although substantial improvement in the accuracy of Miner's rule prediction can be obtained computing the actual stress spectra taking into account the residual stresses, design tools based on such procedure have not yet obtained general acceptance.

Miner's rule is therefore corrently employed in its original form at most with a suitable modification of the figure in the right hand side.

The outlined procedure furnishes a tool to assess the fatigue life of a structural component when the stress history can be described with sufficient accuracy through blocks of stresses. In the case of acoustic excitation the stress history is best described by a continuous probability distribution function. In this case the Miner's approach may be applied with minor modification only when the structural response is prevailingly unimodel [ref.8]. In the case of multimodel response the problem is more involved and no general agreement procedure is at present available.

In the case of a complex structure fatigue damage may growth in a large number of zones each with its own local stress problem. The fatigue life evaluation of complex structures therefore demands a large computational effort, which in some circumstances may even fail to produce accurate results.

Such a failure may depend on the difficulty to describe accurately the load conditions and the corresponding local stress systems as well as to obtain appropriate S-N curves which adequately account, on statistical basis, the inherent scatter which affects fatigue data.

This state of affairs demands that all the computational data on the fatigue endurance must be substantiated by suitable fatigue tests. In particular a general agreement exists that the best extimate of the fatigue life is to be gained from a fatigue tests of a complete structure under programmed load simulating those expected in service. The design of such test in one of the basic challenge in the fatigue technology of aerospace structures and its correct accomplishment is a fundamental warranty of a reliable fatigue life estimation. The objective of the test is to demonstrate a fatigue life M times the expected operational life. The minimum ammissible value of the coefficient M is, however, difficult to define due to scatter in fatigue data, and difficulties in simulating the actual operative load conditions.

Current practice is toward an estimate of M on the basis of past experience with similar structural configurations [ref.9].

3.3 Fracture Mechanics

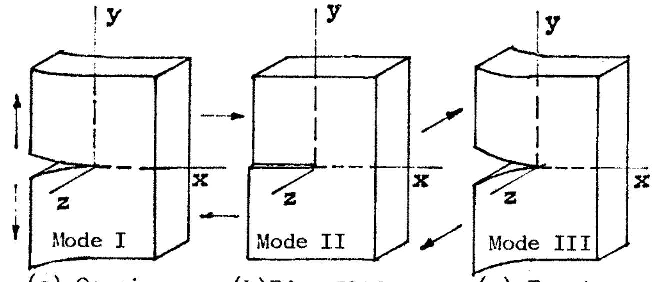
The processes involved in the growth of cracks or flaws from an initial dimension up to the fracture are very complicated and not well fully understood. Despite this rather discouraging assessment a body of knowledge has been established through which the designers can approach the problem of fracture-safe design with sufficiently rational procedures.

The basis of these procedures lies in a rationale for the analysis of fracture developed on the work of Griffith and Irwin which has come to be known as "Fracture Mechanics", [10-11].

The fundamental basis for this discipline is the consideration of the elastic stress state in the neighbourhood of a defect with an ideally sharp edge. Two fundamental types of potential defects are usually taken into account: the through crack (TC) and the part through crack (PTC). Even if the starting point to analyze both the types of defects is the same, a separate discussion of the two cases is useful as some significant differences exist.

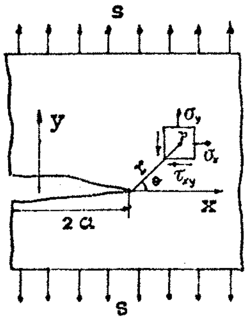
3.3.1. Through crack. Three basic modes of crack surface displacements which can lead to crack extension can be considered, fig.2. In the opening mode the crack surface moves a part simmetrically with respect to the cracked surface. Because of space limitations attention will be confined only to the opening mode of separation owing to its great importance in all the structural situations encountered in aerospace vehicle which demand fracture-safe design. It should be realized, however, that the essential results and conclusions associated with the opening mode displacements also apply to the other two modes.

With reference to a structure containing a through crack which undergoes the opening mode displacement the relationships (shown in fig.3) are pertinent as far as the elastic stresses at point close the crack tips are concerned.



(a) Opening (b)Edge Sliding (c) Tearing

FIG. 3.2



$$\sigma_y = K.\sqrt{\frac{1}{2\pi r}}\cos\frac{\theta}{2}\left(1+\sin\frac{\theta}{2}\sin\frac{3\theta}{2}\right)$$

$$\sigma_x = K.\sqrt{\frac{1}{2\pi r}}\cos\frac{\theta}{2}\left(1-\sin\frac{\theta}{2}\sin\frac{3\theta}{2}\right)$$

$$\tau_{xy} = K.\sqrt{\frac{1}{2\pi r}}\cos\frac{\theta}{2}\sin\frac{\theta}{2}\cos\frac{3\theta}{2}$$

$$K = C\ S\ \sqrt{\pi a}$$

FIG.3.3 Stress State in the Near of a Crack Tip.

In these expressions only the first term of a series expansion is shown; the other terms do not need to be considered as the calculated local stress distribution is dominated by the singularity $r^{-1/2}$ descending from the infinitely sharp crack tip hypothesis.

As it results the stress distribution is always the same and its intensity depends only on the quantity K named "stress intensity factor". K can be put in the following form:

$$K = C\ S\sqrt{\pi a}$$

where S is a reference stress uniquely related to the applied loads, a is the half-crack length, C is a function of the geometry of the cracked body and of the load configuration.

Determination of explicit form of C for any given cracked body configuration require an exact solution of the corresponding elasto-static boundary value problem, discussion of which is beyond the scope of the present paper. General approaches to this problem can be found in [12]. Solutions of this problem for body and load configurations relevant to several design problem have been found and appropriate references are collected in [13]. Among such solutions of particular interest the one for an infinite sheet subjected to uniformly distributed stress S characterized by C = 1.

The basic idea of the Irwin approach is the existence of a critical value of the stress intensity factor characteristic of the material in correspondence of which the crack extends incontrollably. This value is usually a labelled Kc and sometimes called fracture toughness.

Clearly the existence of a critical value Kc gives the possibility to derive a critical stress-crack size relationship for any structural configuration for which C is known.

The Irwin approach, being based upon an elastic analysis, furnishes valid results only in the case of brittle materials. However the material used in the aerospace construction, typically the aluminium alloy, do not behave in a purely elastic manner on fracturing, so that previous analysis is largely approximate except when plain strain conditions are present at the crack tips.

If these conditions are satisfied, a minimum value of Kc is obtained which is effectively a material constant. This critical value is called the plain strain fracture toughness and is indicated with the symbol K_{IC}.

Plane-strain conditions are promoted by very thick-section plate. On the contrary in the case of very thin sheet, plane stress conditions prevail at the crack tips and the fracture toughness Kc results considerably higher than K_{IC}. With intermediate thickness, the stress state becomes significantly mixed (plane strain and plane stress) and the thoughness assumes intermediate values.

The basic reasons of K_C thickness dependence are to be found in the plastic zone which takes place at the crack tips whose dimensions are critically dependent on stress state. A discussion on this topic is beyond the scope of the present paper; reference to [14] are recommended to interested readers.

At this stage of the discussion some further insight are to be gained as far as the application is concerned of the K_C concept to the aerospace structures, typically made of thin gages elements. To this end reference can be done to a typical test in which a thin sheet structure which contains a crack is loaded monotonically at a moderate rate. As the load is increased, the crack is often observed to grow slowly and stably (if the load is not increased, the crack does not grow); this process, usually called slow stable tear, continues up to maximum load is reached at which unstable growth occurs and the structure collapses. The test previously described, indicates the presence of several significant variable in the process of thin sheet fracture: the initial crack length, the final or critical crack length, the load for tear initiation, the maximum load. Therefore a not unique definition of K_C is possible. It is usually accepted that for design purpose K_C would involve the initial crack length and maximum load. For material characterization, however, other correlations may be acceptable (e.g., load and crack length at instability). Another important question lies in the dependence of K_C (whichever definition is chosen) from the panel width. This state of affairs depends certainly on the existence of a plastic yield at the crack tip, a condition not taken into account in the crack tip stress relations shown in fig.3. A possible improvement may be obtained if a correction for crack tip plastic zone can be found. A somewhat rational, if not rigorous method for correcting for small scale yielding at the crack tip has been proposed by Irwin [15]. Following this method, the actual stress in the elastic-plastic solid corresponding to a half crack length, a, is imagined to be equivalent to the stress that would arise from an effective half crack length

$$a_e = a + r_y$$

in a perfectly elastic material; the measure of the plastic zone, has been roughly obtained starting from the elastic analysis, in the form:

$$r_y = \frac{1}{\pi n}\left(\frac{K}{\sigma_y}\right)^2$$

where n varies between 2 to 6 depending on the stress state at the crack tip.

Using such an approach K_C is obtained from test results from the following relationship

$$K_C = C\ S_C\sqrt{\pi\,(a + r_y)}$$

The body of ideas previously discussed, usually called "Linear Fracture Mechanics (LFM)" works well only if sufficiently small plastic zones are present at the crack tip. On the contrary when considerable crack tip plasticity is observed, typically found in medium low , strength ductile materials, difficulties of different nature arise in the application of LFM.

As far as material characterization is concerned unduly large and wide specimen size become necessary; as far as the evaluation of an effective structural situation is concerned the LFM approach can produce unrealistic results. Further LFM does not account the phenomenon of slow stable tear, particularly important with thin sheet construction.

In order to circumvent these limitations several different proposed methods of determining fracture toughness of a given material and the residual strength of a given structure in situations where crack front plastic yield is appreciable (semibrittle fracture) are currently under investigation (14). Among these methods the Crack Growth Resistence Curves (R-curves) has received consideration as far as its application to aerospace structure is concerned [2,16].

Such a method takes into account the slow stable tear phenomenon and clarifies the influence of the width on K_C.

3.3.2. Part Through Crack (PTC). The part through crack pattern usually taken into account in critical flaw dimension evaluation consists of a planar discontinuity extending into the thickness direction and oriented normal to the primary stress axis. The crack size is described by its surface length 2c and depth a. The two dimensional flaw system is usually represented as a regular semi-ellipse with 2a and 2c dimensions corresponding to the minor and major axes respectively.

The surface flaw has been considered a potential defect of prevalent importance in many classes of structures, particularly welded, both pressurized and non pressurized or weld defects are common origins of surface flaws in welded joints. Other origins of surface flaws are inclusions and corrosion pits in stressed surface exposed to corrosive environments. Much analytical research has been conducted on the surface flaw to obtain a stress intensity solution. This research effort has conducted to approximate formulations of the problem which are based on the stress intensity solution around the perimeter of a burred elliptical sharp crack in an infinite elastic solid under uniform normal tensile stress. Such a solution is described by: $K = \sigma\sqrt{\pi a} \cdot M/\Phi$

$$M = \left[\left(\frac{a}{b}\right)^2 \sin^2\beta + \cos^2\beta\right]^{1/4}$$

where β is the angle measured from the minor axis to a specific point on the periphery, Φ is the complete elliptic integral of the second type. Using the truncation concept of Irwin [17], the infinite solid is truncated into two halves, through the introduction of a front surface correction factor M_1. The semi-infinite solid can be truncated to have finite dimensions (width and thickness), through the use of similar correction factors. Therefore, finally the stress intensity factor for the surface flaw can be expressed as

$$K = \sigma\sqrt{\pi a} \cdot M_1 \cdot M_2 \cdot M_p \cdot \varphi_1 \cdot M/\Phi$$

where M_2 is a factor which accounts for the influence of the back free surface, φ_1 is the finite width correction and M_p the plasticity correction factor.

A detailed discussion of the front and back surface coefficients and M_p factor are given in [2,16].

For purpose of critical flaw dimension evaluation has become very popular an expression proposed by Irwin [17] who had assumed that the combined effects of the front and the back surface would be approximately 10 percent. With this assumption $M_1 . M_2 = 1.1$ the previous equation in the depth direction can be rewritten as $K = 1.1\,\sigma\sqrt{\pi a/Q}$

where $Q = \left[\Phi^2 - 0.212\left(\frac{\sigma}{\sigma_y}\right)^2\right]^{-1/2}$

the Irwin flaw and plasticity factor was obtained estimating M_p, where for plane strain conditions, with $n = 4\sqrt{2}$ and putting $\varphi_1 = 1$.

The previous relationship is currently used to predict surface flaw fracture through the following equation: $K = K_{IE}$

where K_{IE} is the toughness pertinent to the surface flaw. The range of applicability of such a equation is schematically shown in fig.4 [16]. Zone 1 failure is controlled by yield and ultimate strength of the material; Zone 2 failure is well predicted by the present approach; Zone 3 is characterized by rapid drop off the stress. Such a zone requires formulation and use of a more accurate back surface factor [2].

A similar analysis, based on appropriate values of the free surface M_i factors, can be used to treat other types of flaw surface, like the corner flaw or surface cracks emanating from a bole [2].

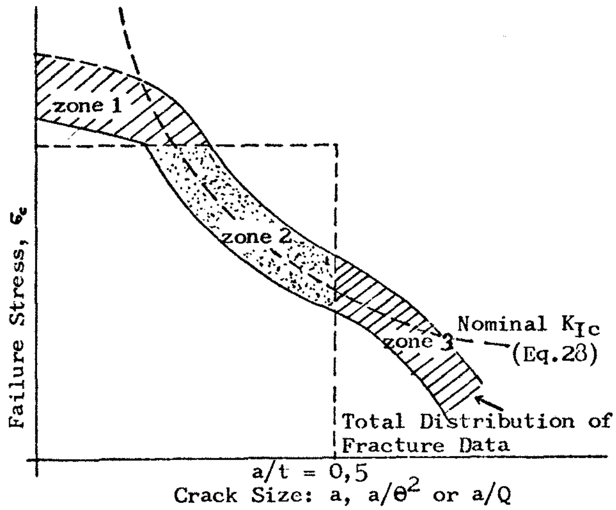


FIG.3.4 Stress vs.Size

3.3.3. Precritical Crack Growth. A fundamental need in the design fracture safe structures is to evaluate the growth characteristic of preexisting flaw or crack at operating stresses throughout an assigned fraction of the space vehicle lifetime. Precritical crack growth may depend on two main causes: cyclic-load-induced crack growth, growth-upon-loading. The basic ideas on these points are briefly discussed.

3.3.4. Cyclic-Load-Induced Crack Growth. The growth of a crack under constant amplitude fatigue loading is controlled by the range of the stress intensity factor ΔK at the crack tip [19]. Generally when test results are plotted as the increment of crack growth per cycle against ΔK a situation is obtained as the one shown in fig.5.

In the medium ΔK range, da/dn varies linearly with ΔK on a log-log plot. When the maximum cyclic stress intensity approaches the critical value K_C, the growth rate increases beyond the values of the linear behaviour. On the contrary at relatively small stress intensity factors, the growth rate diminuishes approaching a threshold value of stress intensity below which measurable crack growth would not occur.

A number of laws have been proposed to describe the K-rate relationship. The simpler one is the Paris law which describes the K-rate relationship by the simple power equation $da/dn = C\,\Delta K^m$ [19]: this law furnishes a good fit of the crack growth data in the linear range.

To accomodate the K_C influence and to provide for observed stress ratio, R effects, Forman [20] proposed the following relationship:

$$\frac{da}{dn} = C\,\Delta K^m \big/ \left[(1-R)K_c - \Delta K\right]$$

which works well in the medium and high ranges.

Colliprist [21] has developed a four parameter K-rate relationship which fits well the data in all the three ranges. The K-rate relationship can be used to calculate the growth of both through and part through cracks. For through cracks its application is straight forward; in the case of PTC crack propagation must be evaluated at each point of the flaw periphery utilizing the local value of the stress intensity factor in form given in the previous section.

The above discussed relationships are valid in the case of constant amplitude loading; in the case of variable amplitude fatigue loading a linear cumulative damage hypothesis (Miner's rule approach) is used [22]; such an approach furnishes conservative estimate of the crack growth time as it disregards the retardation effects due to the high-low sequences of load [22].

As far as the problem is concerned of evaluating the crack growth under acoustic loads, presently only a limited amount of data are available limitedly to through cracks [23, 24]. The need of further investigations in this field is pressing as far as the safe life design of an aerospace vehicle is concerned.

3.3.5. Growth upon Loading. Flaw or crack estension resulting from a single increasing load application has been already cited in a previous section as the "slow stable tear" phenomenon. The most promising approach for quantitative analysis of this type of crack growth appears to be the crack growth resistence curve.

Another type of phenomenon that demands consideration of growth upon loading is sustained load growth of a precracked structure in a given environment [16].

This type of crack growth depends on the simultaneous presence of tensile stress and a specificig corrosive medium; it can be considered a particular aspect of the stress corrosion phenomenon which is usually assumed to include crack initiation as well as subsequent growth under sustained load.

Use of the stress intensity solutions to describe such a phenomenon has been found promising: the time to grow to failure can be plotted versus the initial to critical stress intensity ratio through an unique curve, for a given environment. Such a curve shows the existence of a threshold stress intensity level below which time-dependent precritical flaw growth will not take place [16].

The growth upon loading may play a significant role in crack growth evaluation under spectrum or random loading. The omission of such phenomenon in the growth analysis may result in overlooking a most significant portion of the flaw growth behaviour.

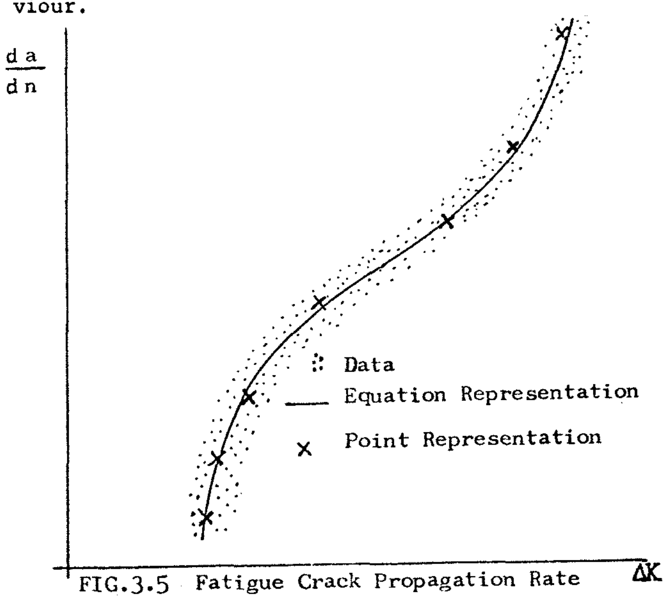


FIG.3.5 Fatigue Crack Propagation Rate Representations

4. Non Destructive Inspection Methods

4.1. General Remarks

Non destructive inspection methods provide the mean to detect the presence of a flaw, that is to say an inhomogenity, a discontinuity, a local singularity, with a specified reliability.

According to the philosophy of NDI [6] the methods must basically ensure that "flight structures" are identical to the structures submitted to fatigue and quality tests. This means that the raw semifinished materials must undergo NDI so as to assure a predetermined standard of quality and that fabrication process and assembly should not induce defects liable to invalidate the quality test performed on the prototype which would jeopardise the prediction of fatigue life.

All methods have their own limitation because of their basic physics, mechanical arrangements, type of apparatus type of materials tested, accessibility to the point where a crack is starting or propagating and these limits are combined with human limitations of the testing personnel such as their degree of interest, experience, fitness and intellect; consequently, the success of any NDI cannot be 100% reliable i.e. either all flaws are not detected or too many "flaws" are indicated which do not exist. In the first case the result is a technical risk, in the second the method may be uneconomical.

Therefore every organization has to build its own reliable detection limits in connection with the product, the operating condition.

A close relationship exists between the NDI methods enabling the identification and localization of "flaws" and the fracture mechanics enabling through analysis to assess when a flaw may be considerated as a "defect".

It is clear that it is necessary to determine the definition of the maximum initial defect permitting the expected service life to be achieved. This determination is very complex and requires close and continuous cooperation between stress engineers, fracture mechanics specialists, experts in materials technology, experimental laboratory experts and finally NDI specialists.

The NDI methods are today very numberous and are based on very diverse physical principles. Some of these methods are routine methods at shop and laboratory levels both in manufacturing and servicing facilities. Other methods, referred to as advanced methods, are still in the development phase and routine application can barely be foreseen at this time.

It may be said that almost every measurement of physical constants in metals has given rise to a particular NDI method and that local or overall variability of these physical constants may be correlated with elastic and ultimate properties of metals. The five most commonly used methods for non-destructive evaluation of materials may be classified as follows:

- radiographic, magnetic particle, liquid penetrant, eddy current, ultrasonic.

Each of these methods shows in itself a great variety of modes of application and practically every method is available in a very diverse variety of hardware and software. Other techniques are currently undergoing development and many show promise as standard methods of the future. These include optical and acoustic holography, acoustic emission and thermal methods. Other methods, such as X-ray diffraction, will probably remain confined to laboratory uses.

With the development of new ratio-sources nuclear techniques, once restricted to laboratory use, are becoming available for quality control in the field.

To ensure that NDI cover his vital role in the development of any aerospace project it must be verified (7) that the following points are correctly implemented within the organization.

- Information and motivation of management at all levels as to the real value and capability of NDI.
- Education of the design engineer both from the standpoint of fracture mechanics and from the standpoint of designing the component so that it can be inspected.
- Further education of the NDI personnel so that the various NDI methods can be properly applied, overall NDI coordination and planning and proper understanding by personnel of the nature and purpose of the inspection.
- Application of NDI techniques during initial fabrication, in production, and in failure analysis for service reliability.

4.2. Comparison of the Non Destructive Inspection Methods Crack Detection Capabilities.

The reliability of the most widely applied Non Destructive Inspection Methods on the basis of the minimum detectable flaw size has been investigated recently at AERITALIA S.p.A. as an ESA research study. The type of flaw considered is an ideal surface crack.

The minimum detectable crack size for each method has been selected at about 90% of detection probability and 95% of confidence level, by carefully weighting the reliability curves relevant to laboratory tests, reported from different sources. The surface of the part has been assumed to be fairly smooth.

All the cracks represented by points on the left side of the each curve are undetectable because their small size defies the method sensitivity; all cracks falling on the right side are detectable.

In fact, the practical conditions for the inspection (such as part geometry, surface roughness environment, etc.) affect sensitivity to a large extent.

The sensitivity of the various methods may be quite lower when they are emploied for maintename inspection at depot level, due to the adverse factors consequent to the conditions under which inspection is carried out.

5. Impact of Fatigue and Fracture Mechanics on the Structural Design. Fracture Control

5.1. Typical aspects of the advanced vehicle Structure Design.

Two main peculiar conditions intervene to make difficult the application of the fracture mechanics both connected with the typical thickness and materials to be used. One is the near plain stress condition in a through crack and the not negligible effects of the plastic zone at the apex of the flaw or crack. The other is connected with the nature of the fatigue loads, that are not constant in amplitude if not random, and in particular require an analysis of the dynamic response of the structure as concerns acoustic environments.

Owing to the intensity and spectrum of the acoustic input, the effect on the crack propagation of such a dynamic response, in combination with the other loading conditions, must be properly investigated. Because of the geometrical properties of the main structural components the contribution of the acoustic noise to the crack propagation emerges as an area that particularly requires insight in the safe life assessment.

Besides the safety requirements related to the various types of applied loads and the predicted environment, a further safety requirement is that the structure, which is subjected to internal pressure, must have a Leakage Before Burst (L.B.B.) and not a Burst Before Leakage (B.B.L.) behaviour.

In the thickness field involved in a pressurized aerospace vehicle, see [26], the L.B.B. or B.B.L. behaviour is affected mainly by the ratio between crack length 2c and material thickness t and by the ratio between t and the crack depth a. Roughly speaking as these two ratios increase, the structure tends to pass from LBB to BBL behaviour (Fig. 5.1).

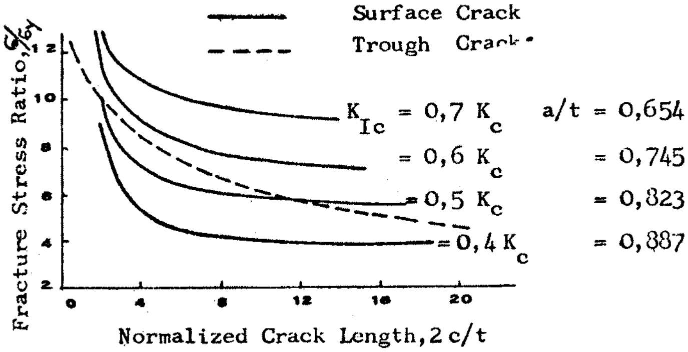


FIG.5.1 LBB and BBL Behaviour (from[27])

The described problems of the structural design require a correct use of the fracture mechanics concepts as well as a development of a series of tests in order to obtain:

- the data that are necessary for the application of the fracture mechanics to the particular design.
- the data for the qualification and the acceptance of the final product.

5.2. Design Development Tests.

5.2.1. Implications of Fracture Mechanics and Acoustic Noise. Also in the case of advanced aerospace vehicle design the development tests can be classified into material characterization, qualification and acceptance tests. Owing to the importance of fracture mechanics and acoustic noise they must contain particular topics as the toughness and the crack propagation tests among the characterization one's,the acoustic noise response tests among the qualification one's and the proof tests among the acceptance one's in order to evidentiate cracks having unacceptable lengths.

5.2.2. Material Characterization Tests. They are the experimental determinations of the "allowable mechanical properties" and in particular of the fatigue characteristic and of the fracture properties. As concerns fatigue, from [26] we report: "The fatigue characteristics of structural materials shall be determined by test. These tests shall be made in the combined environment used for design representing static loads, dynamic loads, temperature, vacuum, and corrosion. Provision shall be made to reduce allowable stresses to account for scatter in the test data.

The test loading conditions, environments, and stress states should represent as accurately as possible those expected during the service life of the structure".

Therefore, beside the life tests on the structures fatigue tests on specimens are necessary in order to evaluate the fatigue properties of the materials.

The main fracture properties are:

- Fracture toughness (K_{IC}, K for appropriate thickness)
- Resistance to initiation and propagation of fatigue and environmentally induced cracking (K_{SCC} - Stress corrosion cracking).
- Threshold values of stress intensity under sustained load and cyclic loading (K_{Th} Threshold limit for specific environment)
- Crack propagation characteristic (crack growth for sustained loading and for local cycle).

From [26] we report:

"Flaw-growth characteristics and the threshold stress intensity of materials should be determined by tests when the materials are used for structural components designed for safe-life. A sufficient number of specimens having flaws of various sizes and simulating the parent metal, weldments, and heat-affected zones of the pressure vessels should be tested to allow meaningful statistical values of fracture toughness to be established.

Therefore, it is necessary to make tests on specimens, including pre-flawed specimens, welded joint specimens, repair specimens in order to verify the adopted fracture analysis methods and to evaluate the adequacy of the inspection methods and requirements.

Therefore, in particular tests shall be conducted, to demonstrate that undetected flaws in the structure will not propagate to a critical size during service life, and fracture critical locations in the structure shall be identified and the time of crack initiation and the crack propagation characteristics shall be evaluated.

5.2.3. Acceptance Tests. Among other tests, the proof test, that concern the pressurized components, are particularly interesting from a fracture mechanics point of view. From [25] we report:

"All pressure vessels and pressurized structure intended or flight use shall be proof-tested.....
Pressure vessels and main propellant tanks shall be tested at proof pressures.
When it has been shown by test that the pressure vessel materials exhibit a decreasing resistance to fracture with decreasing temperature, the proof test shall be conducted at a temperature equal to or below the lowest expected operating temperature.
The time for pressurization to the proof-pressure level and the time the pressure is sustained at that level shall be held to the minimum consistent with test-system limitations. Depressurization time shall also be held to a minimum.
Tests shall be conducted to verify that the probable failure mode in service will be leakage rather than catastrophic fracture when assurance of safe-life cannot be provided by proof test."

Proof-tests conditions may account for all significant factors including combined loads, repeated load cycles, acceleration effects, sustained loading, temperatures and thermal stress effects, environmental effect.

The proof-test is assumed to be the most reliable non-destructive inspection technique available to ensure that there does not exist in the structure any initial flaws of sufficient size to cause failure during operating conditions.

Because of the loading condition during the proof test which are not able to take into account the time history of the various external loading, the proof tests can be utilized only in order to obtain data on the cracks or flaws included in the structure, but it is impractical to obtain in a direct way indications on the life expectancies.

In addition, the disuniformity of the stress distributions during a proof test provides a different capability of the proof tests in order to reveal the presence of cracks in the various parts of the structure.

5.3. Fracture Control

5.3.1. Need of Fracture Analysis

Theoretical analysis, tests and non-destructive inspection involved in the fracture mechanic problems require a great lot of time and are very expensive. Furtherly all these operations besides engineering interest several technological department and in particular the Product Assurance.

Therefore, a design "fracture control" is necessary, in order to evidentiate the part that need a fracture mechanics analysis. A "fracture control plan" is adopted to do it and to perform the fracture analysis if it is necessary, in order to obtain that the structure can withstand all the loading conditions with the required safety levels and with the controlled design cost.

"Fracture Control" is a new engineering discipline that has become into use to describe the design approach that seeks to prevent structural failures due to initiation or propagation of cracks or crack-like defects during fabrication, testing and service life.

The driving criteria to accomplish this objective for the new generation of space structures, are outlined in a NASA basic document that describes in a systematic way the procedures of design, fabrication, environmental control, inspection, maintenance, repair and verification, required to establish an adequate "Fracture Control Plan".

The basic assumption substantiating the need of such a plan is the understanding that the flight hardware is not defect free; the complexity of the structure, the multiple pre-launch testing, the long duration repeated use, offer indeed many opportunities for the generation and propagation of cracks in critical parts of the structure.

In spite of the advancements in the non destructive inspection methodologies, a finite probability always exists, for the large and complex structures, of test or operational failure due to the presence of undetected defects.

The "Fracture Control Plan" largely adopted now--a-day in Aerospace Industries, is a consistent mean to focuss the engineering and workmanship attention on the problem of the existence of such defects in the structures, with the aim to reduce the probability of failure of Spacecrafts.

Several technical specilities having different responsabilities in the project of a vehicle (fig. 5.2), including design, analysis, tests, materials, fabrication, non destructive inspection, are organized through the F.C.P. in a system that foresees a series of checks that allow the Project Management to timely resolve the critical problems discussed in the appropriate review meetings.

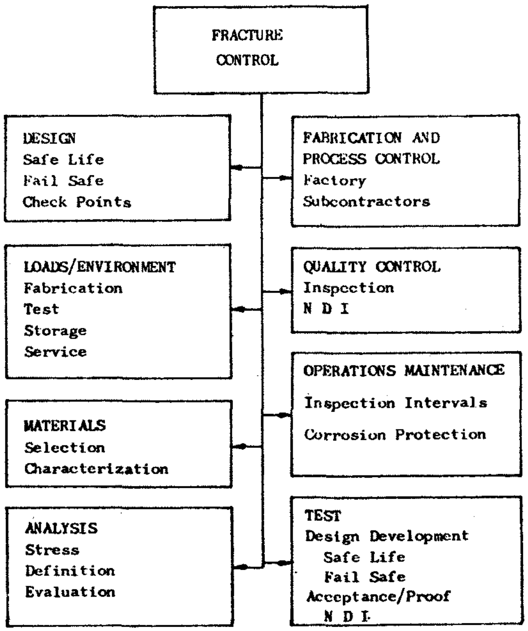


FIG.5.2 Technical Specialities Involved in the F.C.P.

Early evidentiation and evaluation of the fracture problems in essential for initiating corrective actions in terms of design configuration changes, structural materials selection and fracture control approach. A correct planning of all the fracture control activities is needed to ensure the integration with all the other design requirements.

A Fracture Control Board is established with engineering, product assurance, system integration and test, operation responsible representatives for verifying that design and construction meet the agreed specified requirements.

The identification of parts or components selected for Fracture Control on the basis of criticality for the flight-worthness and susceptibility to cracking or fracture, is required as a basic element for the establishment of a consistent and correct "F.C.P.".

For the SPACELAB Program for instance a logic diagram (Fig.5.3) has been established on the basis of the NASA recommendation, according to which the parts after fracture mechanics analysis are categorized to be either:
Non fracture critical; Fracture critical; Unacceptable due to fracture criticality.

A part or component is fracture critical if its fracture will cause:

- Loss of crew life or loss of vehicle.
- Loss of mission (loss of major subsystems that would render the Spacecraft non habitable or would reduce the experiments data retrival).

Rigid fracture control procedures are required for the parts labelled "Fracture Critical"; each of these parts shall be traceable from design to operation through a system of documents, procedures and records. For each "Fracture Critical Part" it is required: an analysis of flaw growth, a specific process control, an adequate inspection procedure and detailed quality control requirements.

MODE	LONGITUDINAL (g)	LATERAL (g)	VERTICAL (g)
Marine	±0.5	±2.5	±2.5
Air	±3.0	±1.5	±3.0
Ground			
Truck	±3.5	±2.0	+6.0
Rail (humping shocks)	±6.0 to ±30.0	±2.0to±5.0	+4.0to+15.0
Rail (rolling)	±0.25 to ±3.0	±0.25to±0. 75	+0.2to+3.0
Slow-moving dolly	±1.0	±0.75	+2.0

The load factors in this table apply to the transport vehicle axes.
These are shock conditions and should not be treated as quasi-steady accelerations.

TABLE 5.I TRANSPORTATION LIMIT-LOAD FACTORS (from [26])

5.3.2. Fracture Control Plan Components. Design. For each critical selected part or component of an aerospace structure an evaluation has to be made to determine whether a safe life or a safe life fail safe design approach is more appropriate, accounting for the the requirements of safety, structural weight, inspectability, maintainability as well as cost.

For the SPACELAB Module for instance the structure shall be designed in such a way that any flaws having length lower than threshold of NDI used in regular inspection, cannot grow enough, before next inspection, to become critical, taking also into account the LBB requirements.

AREA	LONGITUDINAL	VERTICAL	LATERAL
Crew and passenger compartments	+20	±10	±3
Cargo and equipment areas	+10	+5	-
Large mass equipment support structure	+9 -1.5	-2.0 +4.5	+1.5 -1.5

TABLE 5.II CRASH LOAD FACTORS (from [26])

Load and environments. The cummulative static and dynamic loading, anticipated in the various phases of the service life must be defined for each struc-

tural part or component considered fracture critical. The loading spectra must include: - ground and flight phases (see for instance Tab.5.1, Fig.5.4, Fig. 5.5.) such as ground tests, storage, transportation, ground handling, pre-launch, launch axent, entry, atmosphere flight, landing;
- internal pressure data;
-acoustic input data (see for instance fig.6).

In addition, only as static loads, that due to crash must be considered (see for instance tab.5.II).

The plasticity effects have to be accounted for with existing modern methods. When adequate theoretical techniques are not existing or esperimental correlation theory is inadequate, the analysis shall be supplemented by tests.

Fabrication and Process Control. All parts selected for fracture control have to be clearly identified throughout the fabrication cycle.

Process control procedures have to be defined to prevent physical conditions that could contribute to crack initiation of growth.

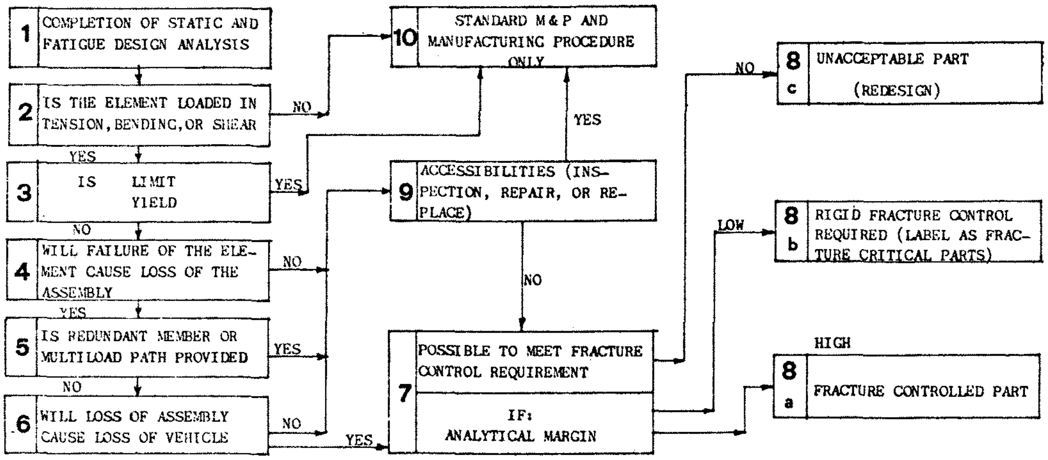


FIG. 5.3) SPACELAB - Fracture Control Plan.

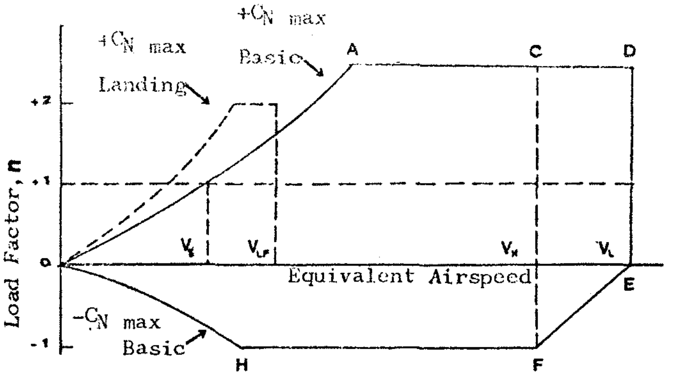


FIG.5.4 Symmetrical Maneuver Envelope (from[26])

Materials. Of particular relevance is the selection of the materials to be adopted, that have to be accomplished accounting for their fracture properties (K_{IC}, K, K_{SCC}, K_T,....)

Analysis. Analysis shall be performed to verify the structural adequacy of all components selcted for fracture control, to establish the critical crack lenght, to evaluate the flaw growth behaviour, to identify the inspection methods and the maintenance and repair guidelines.

The classical analysis procedure based on initial crack length assumptions and on linear elastic Fracture Mechanics have to account for the correct effective sequence of events, the know material properties and stress spectra.

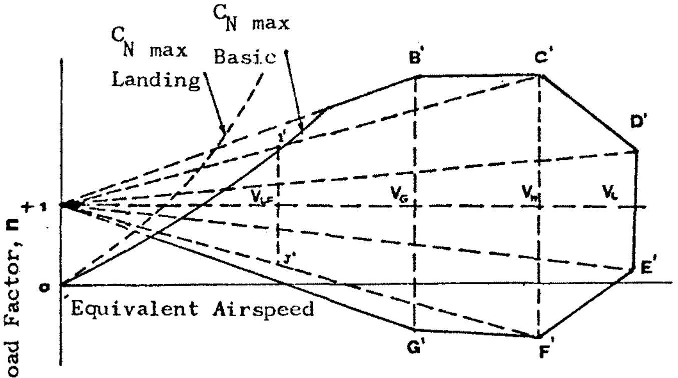


FIG.5.5 Symmetrical Gust Envelope (from [26])

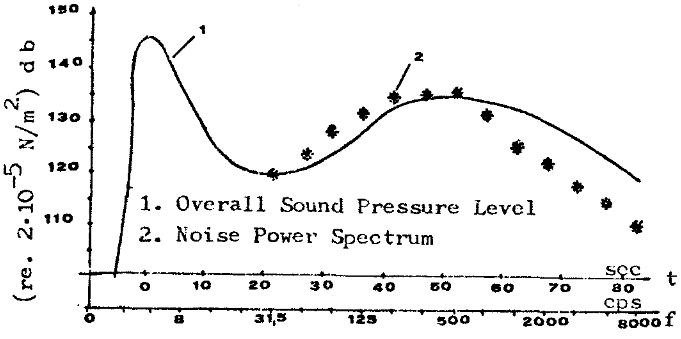


FIG.5.6 Acoustic Environment in the Cargo Bay.

Quality Control. The quality control system shall ensure that materials and parts are conform to fracture requirements, that no damage or degradation has occurred during manufacturing, processing and operation, and that high confidence exists that no defects are present that could cause failure.

Appropriate non destructive inspection techniques shall be selected for inspection of critical components to verify compliance with the requirements. The capability of the NDI technique to reliably detect critical flaws in fracture control components shall be determined experimentally.

Operations and Maintenance. The required inspection intervals for the critical components, under fracture control, have to be established on the basis of the crack growth analysis and the results of development tests.

Minimum inspection interval in set to either 1/4 of the calculated crack growth life or 1/2 of design life whichever is less.

Inspection methods and procedures shall be defined to meet these objectives.

Repairs will be allowed only when the structural capability is not degraded and test results of repair have demonstrated.that no reduction of material properties introduced.

Tests. In their purposes there are the selection the characterization of the materials in particular as concerns fracture mechanics the qualification of the structure from several points of viewand in particular as concerns fatigue, life and acoustic noise dynamic response; the acceptance of the products in particular as concerns the existence of initial flaw or cracks.

6. Remarks on the Scope and the Program of a Theoretical and Experimental Research

6.1 Research Requirements

From the previous analysis it emerges that the existing design methodologics for safe life space structures may need some further development.

For example, it would be extremely useful to have relatively simple and reliable methods for predicting the dynamic response of the structure to random acoustic loads, to evaluate the rate of evolution of cracks.

One of the inputs of such methods, i.e.the acoustic loads, have to be described in statistical terms, with a certain degree of uncertainty;on the other hand, their output, i.e. the structure stress response, is also required in some statistical form.

The classical modal analysis of the complete structure,in conjunction with finite element idealization, may be a very powerful tool for the lower frequencies, but usually becomes exceedingly expensive and time consuming for the higher acoustic frequencies, which would require a very fine mesh to obtain the needed accurancy.

The partition of the whole structure into smaller sections with appropriate boundary conditions,which is quite common in static analysis, may be successfully applied to compute the mode shapes and frequecies, in the upper frequency band, at a much lower cost. But it seems that it is not applicable to compute the response to random acoustic loads,since it does not take into account energy transfers between the sections trough their boundaries, and with the reverberating cavities.

Besides the output of any kind of response analysis suffers the uncertainties in the knowledge of the pressure field and of the damping factors.

Then the simpler procedures of Statistical Energy Methods (SEM), even if they are generally less accurate, may be a good answer to the need of simple and yet realistic methods for obtaining a statistical prediction of the structure response to an acoustic pressure field.

But though it is not realistic to pretend a high accuracy, the accuracy of SEM must be carefully assessed, when they are applied to the particular shapes and load conditions of space structures.

Obviously this requires further investigation;for instance, a good compromise could be a procedure using modal analysis, with finite elements idealization of appropiate sections of the structure, and SEM to evaluate statistically the energy flows between such sections.

As another example, the design of LBB structures needs some further investigation on the evolution of part-through cracks starting with various shapes. In particular, the retardation of the crack growth trough the thickness of a plate, which is likely to occur when the crack adge approaches the free real surface, may require some specific theoretical and experimental research.

Besides it seems that the LBB concept itself might be somehow refined or detailed.

In fact, Leakage Before Burst does not merely mean "a certain amount of leakage just before burst",then the simple requirement that a part though crack has to cut the whole thickness of a plate before becoming critical may not be enough.

On the other hand the above requirement might also be too severe, because the instable propagation of a partthrough crack may reach a stable through crack configuration.

Theese are merely examples but it is clear that a specific research is needed, covering a wider area.

6.2 Research Program

To fulfil this need a research is now starting in our country, supported by the Consiglio Nazionale delle Ricerche (C.N.R.).

It is intended to be an engineering research,covering both theoretical and experimental subjects, developed by University and Industry,in cooperation

The participation of University and Industry in the same research program is needed for the relative wideness of the investigation, requiring both theoretical and technological experience.

The final aim of the research program is to contribute to the improvement of our know-how on the design of pressurized space structures, with special reference to LBB behaviour.

The main flaw lines of such program are concerning the growth of cracks and flaws, in the stress field due to random acoustic loading plus other typical loading conditions, and to the behaviour of a space structure, in the presence of cracks grown to a certain level; a third line, strictly connected with the first two, concernes the critical appraisal of the NDI techniques most suitable to detect the flaws or cracks pertinent to aerospace structure, that may grow to a critical langth during one mission.

A preliminary flaw diagram of the complete research program is reported in Fig.6.1. Due to the complexity of the research, the definition of its details must be gradual; so the program could be more or less slightly changed, ore more specialized on some subject, according to the results of research itself.

The work done at present on that program besides organization and management, is mainly the collection of available methodologies and data, plus a certain amount of modal analysis of stiffened panels,within the band of acoustic frequencies.

The latter has shown that modal separation may be critical, both numerically and experimentally, in those bands where the free vibration frequencies are very close.

In such cases the usual definition of vibration

modes may be somehow meaningless, and a more suitable approach to response analysis must be used.

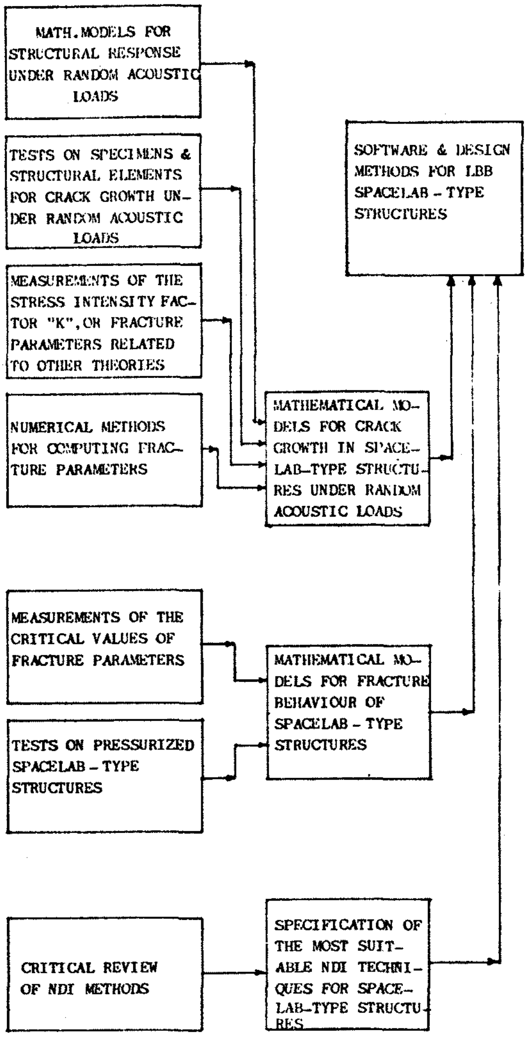


FIG.6.1) The Research Program

Finally, the philosophy of the entire research will be that of utilizing at best the available informations, for that the following steps have been specified for the investigation:

a) acquisition and filtering of the available knowledge, through a critical survey;

b) performance of experimental work in such areas where the available knowledge is not enough;

c) syntesis of the available knowledge,complemented by new contribution where necessary, in an operational software;

d) performance of tests to evaluate the reliability of the above software;

e) specification of new research areas eventually needed for the achievement of the goals.

In other words, the available materials, as experimental data, mathematical models, software etc., will be used as far as possible, after careful verification of its applicability.

When necessary this will be integrated by experimental and theoretical research.

References

[1.] KUHN P.: Notch Effects on Fatigue and Static Strength.Current Aeronautical Fatigue Problems. Pp.229÷264.Pergamon Press, Oxford 1965.

[2.] LIN A.F.: Fracture Control Method for Space Vehicle. Vol.I NASA CR-134596. August 1974.

[3.] VAN DIJK G.M.: Statistical Load Data Processing. 6th ICAS Symposium, Miami 1971. NASA SP 309.

[4.] RICE J.R.: Selected Papers on Noise and Stochastic Processes. Nelson Wax Editor, Dover. New York 1954.

[5.] UNGAR E.E.: Statistical Energy Analysis of Vibrating Systems. J.Eng.Ind., Trans.ASME, vol.89, Series B 1967, pp.626÷632.

[6.] SCHIJVE J.: Endurance under Program.Fatigue Testing. Full Scale Fatigue Testing of Aircraft Structures. Plantema and Schijve Editors. Pergamon Press, New York 1962,pp.763÷780.

[7.] LEVE H.L.: Cumulative Damage Theories. Metal Fatigue Theory and Design. Edited by A.F.Madayag. John Wiley & Sons, New York 1969. Pp.170÷203.

[8.] POWELL A.: An Introduction to Acoustic Fatigue. Acoustical *Fatigue in Aerospace Structures. Edited by Trapp & Forney.* Syracuse University Press, Syracuse, New York 1965.Pp.1÷19.

[9.] HARDRATH H.F.: Fatigue and Fracture Mechanics. J. of Aircraft. Vol.8, 1971. Pp.134÷ 135.

[10.] GRIFFITH A.A.: The Phenomenon of Rupture and Flow in Solid. Phil.Tran.of the Royal Society of London. Ser.A, vol.221, 1920, pp.163÷198.

[11.] IRWIN G.R.,KIES J.A.: Fracturing and Fracture Dynamics. Welding Journal, Research Suppl., Febr.1962. Pp.95_s÷100_s.

[12.] Methods of Analysis and Solutions of Crack Problems.Vol.I, II. Edited by G.C.Sih. Noordhoff Int.Pub., The Netherlands, 1973.

[13.] ROOKE D.P., CARTWRIGHT D.J.: Stress Intensity Factor Solutions. Fracture Mechanics of Aircraft Structures. Edited by H.Liebowitz. AGARD-AG-176, 1973. Pp.592÷600.

[14.] EFTIS J., JONES D.L.,LIEBOWITZ H.: Basic Concept in Fracture Mechanics. Fracture Mechanics of Aircraft Structures.Edited by H.Liebowitz. AGARD-AG-176, 1973. Pp.32÷73.

[15.] IRWIN G.R.: Plastic Zone near a Crack and Fracture Toughness. Proc.7th Sagamore Conf., Syracuse Univ.1960.

[16.] EHRET R.M.: Fracture Control Methods for Space Vehicles.Vol. II-NASA CR-B4597, August 1974.

[17.] IRWIN G.R.: Crack-Extension Force for a Part-Through Crack in a Plate. Trans.of ASME, Series E, J.of Applied Mech.,vol. 84, n.4, 1962, Pp.651÷654.

[18.] ADAM H.P.: Fracture Controll of Metallic Pressure Vessels. NASA SP-8040, 1970.

[19.] PARIS P., ERDOGAN F.: A critical Analysis of Crack Propagation Lows. Trans.of ASME; Series D., J.of Basic Engineering vol.85, 1963, pp.528÷534.

[20.] FORMAN R.G.,KEARNY V.E., ENGLE R.M.: Numerical Analysis of Crack Propagation in Cyclic-Loaded Structures. Trans.ASME Series D, J.of Basic Engineering, Vol.89, n°3 1967,pp.459÷464.

[21.] COLLIPRIEST J.E.: An Experimentalists's View of the Surface Flow Problem. The Surface Crack: Physical Problems and Computational Solutions. ASME, 1972, pp.43÷62.

[22.] SCHIJVE J.: The accumulation of Fatigue Damage in Aircraft Materials and Structures. AGARD-AG 157, 1972.

[23.] SMITH S.H.: Fatigue Crack Growth *under Axial Narrow* and Broad Random Loading. Acoustical Fatigue in Aerospace Structures. Edited by Trapp & Forney Syracuse University Press, Syracuse, New York 1965, pp.331÷360.

[24.] BYRNE K.P.: Bending Induced Crack Propagation in A 4% Cu-Al Alloy with Reference to Acoustically Propagated Fatigue Cracks. Journal of Sound and Vibration, 1975,pp.337÷355.

[25.] MIL-STD 721: Definition of Effectiveness Terms for Reliability, Maintenability, Human Factors Safety.

[26.] NASA: Space Vehicle Design Criteria (Structures)Structural Design Criteria Appicable to a Space Shuttle. NASA SP-8057 January 1971.

[27.] Th.W.ORANGE, T.L.SULLIVAN and F.D.CALFO: Fracture of thin Sections Containing through and Part-through Cracks.NASA T.N. D-6305, April 1971.

[28.] RICE R.C., DAVIES K.B., JASKE C.E. & FEDDERSEN C.E.: Consolidation of Fatigue and Fatigue-Crack-Propagation Data for Design Use. NASA CR-2586, October 1975.

[29.] NASA: Space Shuttle System Payload Accomodations Handbook. Vol.14 - Rev.C.

[30.] E.BOLIS Ed.: Non Destructive Inspection Practices. AGARD-AG 201, 1975.

[31.] SMITH A.M. Ed.: The Role of Testing in Achieving Aerospace System Effectiveness. AIAA System Effectiveness and Safety Technical Committee, January 1973.