APPLICATION OF SYSTEMS ANALYSIS METHODS TO FRACTURE CONTROL

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ABSTRACT

Methods of systems analysis are outlined and used to describe complex materials degradation problems. Two example illustrations are provided.

KEYWORDS

Fracture, fatigue, corrosion, materials reliability, materials degradation, non-destructive inspection, materials performance optimization.

INTRODUCTION

Materials technology, both in development of new and improved materials and in its application in engineering design, is a dynamic area subject to resource availability considerations as well as world economic and political pressures. On the sociological side, a more knowledgeable and discerning public demands the high quality it knows is available through current technology. On the economic side, both resource availability and competitive pressures among domestic and foreign industries require efficient use of fabricating systems and of materials. Large engineering systems are often called to operate under adverse environmental conditions which lead to deterioration of the materials of construction. The number of potential materials deterioration modes is large and individual disciplines providing the information required to assure reliable performance throughout the life of the structure are highly diverse. Inputs are often required from stress analysts, metallurgists, corrosion chemists, and specialists in the fatigue and fracture areas. This specialized information must be expressed in the respective paradigms of the designers, builders, and operators. Thus, superimposed on the pure technical problem of failure control, are additional problems in information management, communications, and organization. *Fracture control* is defined in this paper as the ensemble of procedures and technologies used to prevent failure in load-bearing structures and machines whose materials of construction are subject to deterioration.

Contemporary approaches to failure control can best be characterized as *eclectic* The information required to develop failure control plans is broad-based, a total system comprising many subsystems of relevant disciplines. As failure control technology moves into the next decade, it will be necessary to develop a philosophy of the total systems approach to failure control and to structure the system in order integrate the subsystems.

The General Systems Approach

The purpose of systems engineering is to solve problems beyond the scope of any one individual or discipline. It is essential to look initially at the problem generally in terms of objectives and constraints without becoming involved in detail. The system analyst then proceeds to add detail through logic modeling. This provides the advantage of precisely defining the information required and adds efficiency to problem solving.

Operation research and *systems analyses* are the most important offsprings of the systems approaches. Operations research comprises a diverse set of "*cookbook*" approaches to narrow and specific problems.

Systems analysis represents the same approach when the problem is generalized to larger systems and used for administrative purposes. The techniques available include statistics, simulation and Monte-Carlo methods, linear programming, guessing theory, decision theory, games theory, simulated games, cybernetics and information theory. In constructing systems analysis as a discipline, the systems theorist draws heavily on these disciplines.

For those components of a load-bearing system which operate under load, there are two distinct design criteria to be considered - *strength-based design* or analysis of the behavior of the structure according to its constitutive equations and *failure-based design*. Strength-based design is a well established discipline dating back several centuries to Robert Hooke (1676) and Thomas Young (1773). Modern computational facilities yield high confidence levels in this part of the design analysis. Failure-based design on the other hand dates back only a few decades to A.A. Griffith in the 1920's.

Failure based design recognizes the basic fact of life that materials contain flaws or that flaws may be introduced in service. These flaws and their effect on materials performance must be characterized. Thus, an integral element in assuring the integrity of load-bearing structures subject to degradation of their materials of construction involves inspection. The inspection process is carried-out during fabrication, before the structure is put into service and periodically during its service life.

Interelations among failure control disciplines can be represented in a general form using the central formula of systems analysis, the block diagram with arrows representing inputs and outputs. Three types of operations, conversion operations, logical operations, and correction operations may be combined and multiplied to any level of complexity. Common types of such operations include the transformation block in which input x is converted to output y by specified conversion rules (Fig. 1a).

In the decision block, input x is tested and converted to either y or z according to stated rules (Fig. 1b).

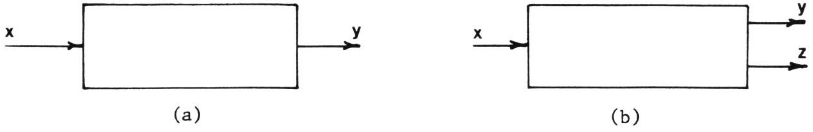

Fig. 1 Transformation and decision operations

In the feedback block, input y is modified as a function of output x (Fig. 2)

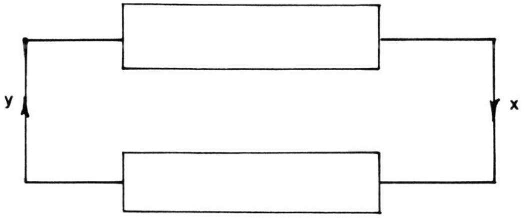

Fig. 2 Feedback operation

Each of the elements in the failure analysis and control system can be identified in terms of the operation it performs. They can be combined in an appropriate fashion to effect the required analysis.

Structuring of the Qualitative Model

In this section we will develop a basic generalized structure for the failure analysis and control system and express this in terms of a simple block diagram. The systems approach adopted here comprises four phases. Initially, in the *informational input phase*, the system is defined from an operational or functional viewpoint rather than in mechanistic terms. This can include selection of the key system output(s) required to characterize its behavior or performance or to effect judgements or decisions. This can include comparison of the observed behavior with design objectives and overall cost implications. Management value judgements and attitude toward risk may be involved. In addition, the set of key inputs over which control can be exerted are defined thereby completely describing the system in terms of its inputs and outputs. In the next phase of system development, the *deterministic phase*, crucial variables are identified and the problem is structured and modeled. In the *probabilistic phase*, uncertainty about crucial variables is encoded and the profit lottery calculated. The *informational output phase* involves validation and implementation of the model.

The result of the informational input phase is a comprehensive description of the problem in terms of its inputs and outputs.

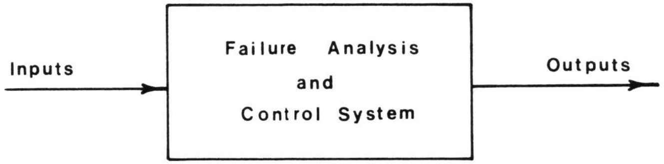

Fig. 3 Definition of the system in operational terms

The elements of the failure analysis and control system include the:

- *loading condition characterization, the*
- *flaw characterization, and the*
- *material failure resistance characterization and cost functions.*

A loading condition characterization involves determining the effect of load on the structure. Load-deflection, pressure-strain, and other similar calculations based upon the constitutive relationships are, in effect, transformation operations. Similarly the flaw growth laws which characterize the material failure resistance are also transformation operations. The term degradation is used to describe this type of transformation. In a failure control system, flaw characterizations by inspection are accompanied by a corrective action such as repair or scrapping. The term *upgradation* has been coined for the inspection/correction transformation. Three basic transformations are summarized in Table II.

TABLE II Transformation Operations

Stress analysis
Degradation - flaw growth
Upgradation - inspection/correction

TABLE III Decision Operations

K_{Ic}	*Plane strain fracture toughness*
K_c	*Fracture toughness*
Δk_{th}	*Threshold stress intensity factor for fatigue*
Δk_{Iscc}	*Threshold stress intensity factor for stress corrosion*

In addition to transformations, materials science and fracture mechanics provide a basis for certain logical operations. These include the use of critical values of the stress intensity factor including the fracture toughness K_c, the threshold stress intensity for fatigue crack growth Δk_{th}, and the stress corrosion cracking threshold Δk_{Iscc}. In such a decision box a parameter is monitored (the stress intensity) and a decision made as to whether a particular failure mechanism is operative. These decision operators are listed in Table III.

Examining the transformation operations in more detail, they clearly separate into two categories. The response of a well-characterized structure to a load is characterized by its constitutive equations. These are based upon equilibrium theories of classical thermodynamics and may be considered as reversible or quasi-static processes. On the other hand, the degradation mechanisms are clearly irreversible. Thus the qualitative model should recognize this distinction and separate them into two modules.

Many deterioration mechanicsms, such as fatigue and stress corrosion, depend upon the loading conditions and require information from the constitutive equation block. Similarly, as the severity of corrosion of fatigue attack increases, the flawed areas attain a size where they may modify the geometry upon which the stress analysis is based. Thus, the irreversible phenomena act as a feedback block which controls the constitutive equations (Fig. 4).

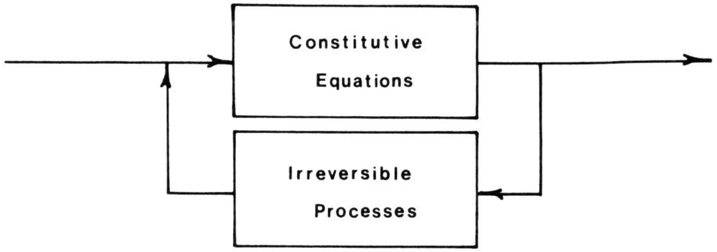

Fig. 4 Feedback operation in a failure analysis and control system

Here top-down modeling has clearly separated the phenomena according to fundamental concepts and established the information flow on a basis analogous to control theory. Regulation of the system network by the feedback of information produced in it is the core of cybernetics. A higher level of system is thus derived through this approach than is possible with simply the bottom-up building block approach.

Expanding the irreversible process block to show the degradation and upgradation processes gives the block diagram in Fig. 5.

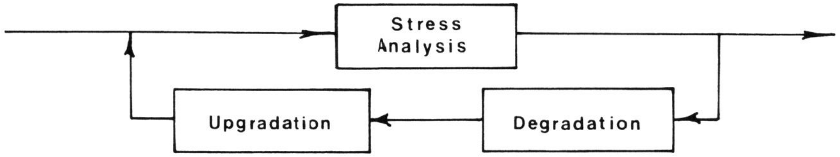

Fig. 5 Basic failure control flow diagram

This diagram illustrate the basic flow of information in the failure analysis and control system. It is the fundamental system upon which more elaborate systems can be built to incorporate economic and administrative factors and multiplicities of failure modes.

Case Study: Inspection Interval Optimization

A simple implementation of the systems approach involves optimization of the interval of inspection during the design lifetime of a component by quantification of the degradation and upgradation blocks. A simple model illustrates the use of the methodology. The problem is one of pitting corrosion and for purposes of illustration, a low reliability case is examined. The equivalence of terminologies in the materials science, systems, and mathematical disciplines is shown in Fig. 6. In this problem, a flaw-size (pit-depth) density function:

$$f(a) = \exp\left\{-\exp\left[-(a-3)\right] - (a-3)\right\}$$

where a (in mm) is the pit depth is transformed by a flaw growth law

$$\delta = \delta(T)\ (t/T)^{0.25}$$

where δ is the pit depth growth increment at time t and T is the service life. The upgradation or censoring operation is described by

$$\alpha(a) = \exp\left[-5.0\left(\frac{a-2}{7}\right)\right]$$

where α is the probability of non detection and the assumption that units with detected flaws larger than the tolerable size are replaced by units of the original quality. The failure criterion corresponds to a critical pit depth determined from fracture mechanics or, in this case, by penetration of the containment vessel wall, $a_f = 7$ mm. A tolerable flaw size is determined from the flaw growth law and is the flaw size which at the normalized time t/T in the service life would grow to the failure size a_f at t/T = 1.

Upon effecting the transformations[1] Fig. 7 is obtained. In this case, inspection at the usual time t/T = 0.5 gives a probability of survival of 0.34. However, inspection at t/T = 0.09 corresponds to the maximum survival probability of 0.65. Similar effects are observed in high reliability systems although the factors of improvement are generally greater. Also when multiple inspections are considered, reliability enhancement through inspection optimization can be even greater.

Case Study: Material Property Optimization

This example involves the case of rotating component in an adverse environment. It is subject originally to pitting corrosion and, as the pits deepen, to corrosion fatigue and, ultimately, to fast fracture. The logic model derived for the degradation box is shown in Fig. 8 . In this case the phenomenon switches from one degradation mechanism to another based upon threshold stress intensities in the decision blocks. Material parameters for a hypothetical, but representative, material are given in Table IV .

TABLE IV Material Parameters used in the Simulation

Fatigue: $\frac{da}{dN} = C(\Delta k)^m$, m=5.4 and C=1.51 x 10^{-12}(ΔK in MN-$m^{-3/2}$, $da/_n$ in m/cycle)

Initial Flaw Size (i.e. surface condition): $a_i = 0.0685$ mm

Threshold Stress Intensity (Fatigue): $\Delta K_{th} = 7.0$ MN - $m^{-3/2}$

Corrosion: $\frac{da}{dt} = K_1 K_2 t\ (K_2 - 1)$, k_1 and K_2 are material constants -
$k_1 = 0.75$ and $K_2 = 1.016 \times 10^{-8}$ mm/sec

These parameters were each varied separately over a range of values while the remaining parameters were kept constant. Their effect on the life of the component is shown in Fig. 9. Here, the high sensitivity of the lifetime to corrosion (K_1) and fatigue (K_{th}) is clearly demonstrated while the, surface finish for example has a little effect. Such sensitivity analyses are useful for determining where to place immediate emphasis in materials development or maintenance to obtain maximum return.

CONCLUSION

Systems analysis principles assist in structuring complex fracture control problems and render them amenable to treatment using the techniques of reliability engineering. These include probabilistic treatment and multiparameter analyses.

REFERENCE

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ACKNOWLEDGEMENTS

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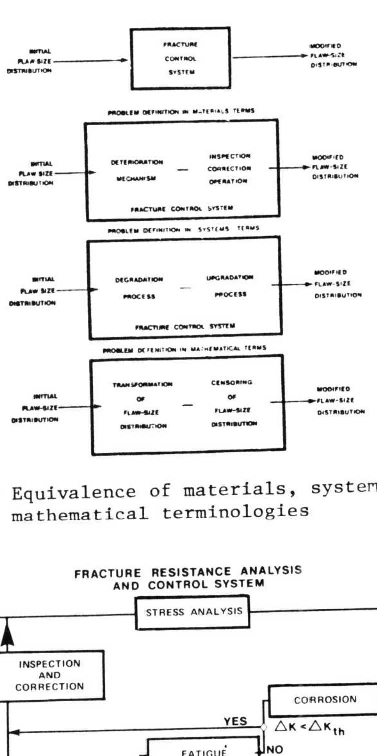

Fig. 6 Equivalence of materials, systems and mathematical terminologies

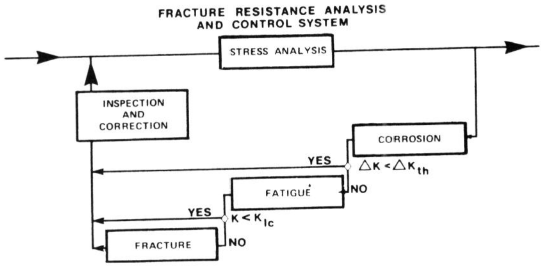

Fig. 8 Logic model for the degradation stress analysis, and inspection correction box

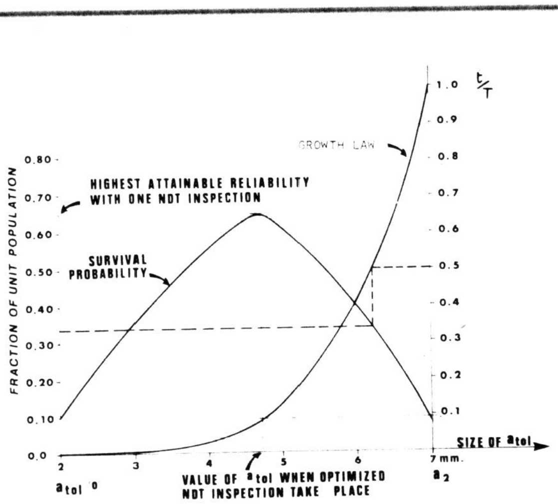

Fig. 7 Graphical illustration of the optimization of the inspection interval

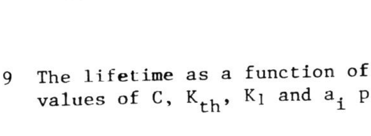

Fig. 9 The lifetime as a function of the normalized values of C, K_{th}, K_1 and a_i parameters